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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT 320

Propulsion and Energetics Panel Working Group 23 on

Guide to the Measurement of the Transient Performance of Aircraft Turbine Engines and Components

(Guide pour la mesure des performances en transitoire des turbomachines Aéronautiques et de leurs composants)

This Advisory Report was prepared at the request of the Propulsion and Energetics Panel of AGARD.

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North Atlantic Treaty Organization
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Summary

The objective of this report is to provide the user with a guide for the measurement of *transient* aerothermodynamic performance parameters of aircraft gas turbine engines or components. It is hoped it will be helpful to a variety of gas turbine users — including engine developers, test agencies, certifying authorities and operators of overhaul facilities and aircraft.

This report may be treated as an extension of AGARD Advisory Report AR-245, which was prepared as a guide to the recommended practices for the measurement of steady-state pressures and temperatures, and AGARD AR-248, which treated other steady-state parameters important to gas turbine performance assessment. This current report includes discussion of recommended procedures for the transient measurement of pressures, temperatures, flows, component geometry including rotational speed and clearances, thrust, torque, and the use of the engine control system for transient parameter measurements. Examples of typical transient measurement techniques are presented for each parameter. A section on data acquisition and processing is also included.

A transient is defined in this report as a deliberately included variation of machine operation from one steady-state condition to another. Examples of test procedures fitting this definition and appropriate to potential users of this report are listed. Higher frequency dynamic measurements, in which the spectral behaviour characteristics are usually required, are excluded.

This report includes a comprehensive discussion of the concepts and procedures for the uncertainty estimation of transient measurements. The report concludes with a detailed discussion of two examples — (i) the measurement of compressor ratio and air flow at surge, which would be of primary interest to engine designers and developers, and (ii) a measurement of engine acceleration time, which would be of particular interest to engine overhaul facilities and operators.

Sommaire

Le présent rapport a pour but de fournir à l'utilisateur un guide sur la mesure des paramètres de performance aérothermodynamique en *transitoire* des turbomachines d'aéronef ou de leurs composants. Nous espérons qu'il pourra aider les divers utilisateurs de turbines à gaz, y compris les entreprises de mise au point de mouteurs, les organismes d'essais, les autorités chargées de l'homologation ainsi que les exploitants d'installations de révision et d'aéronefs.

Le présent rapport peut être considéré comme un prolongement du rapport consultatif AR-245 de l'AGARD, qui a été préparé sous la forme de guide des pratiques recommandées pour la mesure des pressions et des températures en régime permanent, et AGARD AR-248, qui traitait d'autres paramètres en régime permanent qui sont importants pour l'évaluation des performances des turbines à gaz. Le présent rapport comprend une étude des procédures recommandées pour la mesure transitoire des pressions, des températures, des flux, de la géométrie des composants, y compris de la vitesse de rotation et des tolérances, de la poussée, du couple et de l'utilisation du système de commande moteur pour la mesure transitoire de paramètres. Des exemples de techniques typiques de mesure transitoire sont présentés pour chaque paramètre. Une section porte également sur l'acquisition et le traitement des données.

Un phénomène transitoire est défini dans le présent rapport comme étant une variation délibérément induite dans le fonctionnement d'une machine, d'un régime permanent à un autre. Des exemples de procédures d'essais qui répondent à cette définition et qui sont appropriés aux utilisateurs éventuels du présent rapport sont énumérés. Les mesures dynamiques à fréquence plus élevée, dans lesquelles les caractéristiques spectrales de comportement sont habituellement nécessaires, sont exclues.

Le présent rapport comprend une étude complète des concepts et des procédures d'estimation d'incertitude des mesures transitoires. Il se termine par une étude détaillée de deux exemples: (i) la mesure du taux de compression et du débit d'air au pompage, qui serait d'un intérêt primordial pour la conception et le développement de moteurs, et (ii) la mesure du temps d'accélération moteur, qui serait d'un intérêt particulier pour les installations de révision de moteur et les exploitants.

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Contents

Nomenclature

Parameters	Definitions	Text Reference[1]
a	Velocity of sound	Eq. 4.2-2
a	Constant	Eq. 4.4-17
A	Area, Geometric	Eq. 4.2-2
A_p	Swirl-chamber inlet port area	Eq. 4.4-13
AR	Blade aspect ratio	Eq. 4.4-2
b	Elemental bias error	Eq. 3-1
b	Constant	Eq. 4.4-17
B	Total bias error	Eq. 3-1
B	Flux density	Page 4-171
c_p	Specific heat at constant pressure	Eq. 4.3-1
c_v	Specific heat at constant volume	Eq. 4.3-1
$C_{\Delta P}$	Correction between PS31 and P3	Eq. 5-1
C_w	Flow coefficient	Eq. 4.4-11
C_x	Correction factors	Eq. 4.4-6
d	Diameter	Eq. 4.3-3
D_o	Orifice diameter	Eq. 4.4-11
D_s	Swirl chamber diameter	Eq. 4.4-12
e	Emissivity	Eq. 4.3-4
EMF	Electromotive Force	Eq. 4.5-1
f_N	Nyquist frequency	Page 3-11
f_o	Breakpoint frequency	Eq. 4.4-5
f_R	Resonant frequency	Eq. 4.2-1
f_S	Sampling frequency	Page 5-5
F	Centrifugal force	Eq. 4.5-1
Fa	Thermal expansion factor	Table 4.4-2
FG	Gross thrust	Eq. 4.6-1
FN	Net thrust	Eq. 4.6-2
FR	Ram drag	Eq. 4.6-2
FS	Scale force	Eq. 4.6-4
G(f)	Power spectral density of noise	Eq. 5-2
h	Damping ratio	Eq. 4.6-7
h_c	Convective heat transfer coefficient	Eq. 4.3-3
H	Enthalpy	Eq. 4.4-20
H(f)	Sinusoidal frequency response transfer function of filter	Eq. 5-2
i	$\sqrt{-1}$	Eq. 3-16
I	Moment of inertia	Eq. 4.4-1
k	Thermal conductivity	Eq. 4.3-3
K	Order of curve fit	Eq. 3-12
K_a	Calibration constant	Eq. 3-16
K_s	Spring rate	Eq. 4.6-6
L	Length	Eq. 4.2-2

[1] Equation, Table or Figure of first use

L_C	Blade mean chord	Eq. 4.4-2
m	Mass	Eq. 4.3-7
M_i	Primary measurand to determine s	Eq. 3-3A
Ma	Mach number	Eq. 4.3-1
n	No. of pulses per revolution	Eq. 4-5-2
n	nth component	Eq. 3-3A
nm	No. of tests to define average value of a primary measurand	Glossary
N	Rotation speed	Eq. 4.5-2
N	Number of repetitions of the defined measurement process	Eq. 3-1
N_B	Number of blades	Eq. 4.4-2
P	Pressure	Eq. 3-3D
P_R	Pressure ratio	Eq. 2-1
P_{RW}	Pressure ratio at the engine operating point	Eq. 2-1
P_S, PS	Static pressure	Table 2-3
P_T, PT, P	Total pressure	Table 2-3
P_v	Vapour pressure	Table 4.4-2
q	Heat flow rate	Eq. 4.4-20
$q(i\omega)$	Fourier component of Q(t) at ω	Eq. 3-19
$Q_I(t)$	Instrument input as a function of time	Eq. 3-19
$Q_O(t)$	Instrument output as a function of time	Eq. 3-22
r	Radius	Eq. 4.4-2
r	Recovery factor (thermocouple probes)	Eq. 4.3-1
R	Gas constant	Eq. 4.4-20
R_d	Reynolds number	Table 4.4-2
s	Elemental precision index - estimate of standard deviation	Eq. 3-1
S	Total precision index	Eq. 3-1
SEE	Standard error of estimate	Eq. 3-12
SH	Specific (or Absolute) humidity	Table 4.4-2
t	Time	Eq. 3-18
t_{95}	95th percentile point of the Student's "t" distribution	Eq. 3-1
T	Temperature	Table 2-3
T	Elapsed time	Eq. 3-23
T	Torque	Eq. 4.4-1
$T(i\omega)$	Transfer function	Eq. 3-16
U	Uncertainty of measurements	Eq. 3-29
UADD	Additive uncertainty	Eq. 3-1
URSS	Root-sum-square uncertainty	Eq. 3-2
v	Velocity	Eq. 4.4-2
V	Voltage	Eq. 4.3-13
V	Volume	Eq. 4.4-20
V_i	Volume between measurement device and engine inlet	Eq. 4.9-14
V_i	Value	Eq. 4.9-1
W	Mass flow rate	Eq. 2-3
X, Y	Derived or inferred parameter	Eq. 3-3A
Ya	Adiabatic expansion factor	Table 4.4-2
Y_K	Conduction error	Eq. 4.3-3
Y_R	Radiation error	Eq. 4.3-4
Y_T	Time constant error	Eq. 4.3-8
Y_V	Velocity error	Eq. 4.3-1
Z	Compressibility factor	Table 4.4-2
α_e	Blade effective angle of attack	Eq. 4.4-2

β	Phase lag	Eq. 4.3-15
β	Frequency ratio	Eq. 4.6-11
β	Area ratio	Table 4.4-2
δ	Natural log of amplitude ratio	Eq. 4.6-8
γ	Ratio of specific heats	Eq. 4.3-1
ϵ_L	Lag error	Eq. 4.2-5
ϵ_R	Oscillatory error	Eq. 4.2-6
η	Efficiency	Eq. 4.4-2
θ	Angular displacement	Eq. 4.4-1
μ	Absolute viscosity	Table 4.4-2
ν	Kinematic viscosity (μ/ρ)	Fig. 4.4-9
ξ	Damping constant	Eq. 3-17
ρ	Density	Eq. 4.4-2
σ	Stefan-Boltzmann constant	Eq. 4.3-4
σ	Standard deviation	Fig. 3-1
τ	Time constant, response time	Eq. 3-16
ϕ	Sonic-flow function	Table 4.4-2
ψ	Generalized engine performance parameter	Fig. 2-10
ψ	Phase angle change due to filter	Table 4.9-1
ω	Angular frequency	Eq. 3-16
ω_n	Natural (resonant) frequency	Eq. 3-17

Subscripts

abs	absolute
amb	ambient
av	average
A	air
B	bead (thermocouple)
calc	calculated
cor	corrected
C	common
D	duct
F	fuel
FR	afterburner fuel
H	high pressure rotor
i, j	primary measurands
I	input
J	junction (thermocouple)
L	low pressure rotor
M	metal
n	natural
N	Nyquist
O, o	output, value at time = 0, reference
p	phonic wheel
P	probe
rad	radiation
ref	reference
s	sample
S	static
w	wire
W	wall

WP	operating, or working, point
X, Y	derived or inferred parameter

Superscripts

SS	steady state
T	transient

Descriptive Symbols

A/B	Afterburner
AC	Alternating current
A/C	Aircraft
A/D	Analogue to digital
ADC	Analogue to digital convertor
AIS	Analogue input system
AR	Aspect ratio
ATF	Altitude test facility
BP	Bypass
BCD	Binary coded decimal
CARS	Coherent anti-stokes Raman scattering
CDP	Compressor discharge pressure
CIVV	Compressor inlet variable vanes
CLP	Collective pitch
DAS	Data acquisition system
DC	Direct current
DVM	Digital voltmeter
EGT	Exhaust gas temperature
FADEC	Full authority digital electronic control
FCU	Fuel control unit
FFT	Fast Fourier transform
FM	Frequency modulated
FOD	Foreign object damage
GL	Ground level facility
HP	High pressure
HPC	High pressure compressor
ID	Inside diameter
IFM	Interface module
IMRA	Infra-red monochromatic radiation and absorption
LDA	Laser doppler anemometer
LOD	Light off detector
LP	Low pressure
LVDT	Linear variable differential transformer
L2F	Laser-two-focus anemometer
NPI	Nozzle position indicator
OD	Outside diameter
PCM	Pulse code modulated
PLA	Power lever angle
PPH	Pounds per hour
Prop	Propeller
RF	Radio frequency
RPM	Revolutions per minute
RTD	Resistance temperature device

RTVD	Rotary variable differential transformer
RVT	Rotary variable transducer
TEC	Test environmental control
VDU	Visual display unit
VIGV	Variable inlet guide vanes
VSV	Variable stator vanes
ZOC	Zero, operate, calibrate system

Glossary

(The definitions in this glossary are based, generally, on those of AGARD Report AR245. Some additions and adjustments have been made to clarify the application of specific terms to transient measurements.)

Accuracy	The closeness or agreement between a measured value and a standard or true value; uncertainty as used herein, is the maximum inaccuracy or error that may reasonably be expected (see measurement error).
Acquisition Time	The time taken for a track and hold circuit to acquire the input signal (cf. Figure 4.9-26).
Aliasing	Introduction of error into the computed amplitudes of the lower frequencies of a Fourier analysis of a function carried out using discrete time samplings whose interval does not allow the proper analysis of the higher frequencies present in the analyzed function.
Analog Output	Measurement system output which is a continuous function of the measurand.
Aperture Time	The time interval during which the hold system is exposed to the measurand for the purpose of data acquisition (cf. Figure 4.9-26)
Average Value	The arithmetic mean of nm readings. The average value is calculated as: $\bar{x} = \text{average value} = \frac{\sum_{i=1}^{nm} X_i}{nm}$
Bias (B)	The difference between the average of all possible measured values and the true value. Also called the systematic error or fixed error which characterizes every member of a set of measurements.
Blockage	The ratio of the frontal area of a probe or a set of probes at a given station to the total flow area at that station.
Blockage Effects	General term referring both to measurement errors and real component performance effects caused by probe blockage.
Calibration	The process of comparing and correcting the response of an instrument to agree with a standard instrument over the measurement range in a specified environment.
Calibration "On-Line"	Calibration of a measurement system, in situ, during the period that data is being taken.
Calibration Drift	When an instrument is recalibrated, this refers to the recording of the difference between the present calibration before adjustment and the previous calibration. It is a measure of the stability of the instrument between successive calibrations. (Instrument Stability)

Calibration Hierarchy	The chain of calibration which links or provides the trace of a measuring instrument to a national standards institution.
Calibration Uncertainty	The estimated error in the output values shown in a calibration record.
Compensation	The utilization of supplemental devices, materials or processes to minimize known sources of error.
Conduction Error	The error in a temperature transducer due to heat conduction between the sensing element and the mounting of the transducer.
Confidence Interval	A range within which the true value is expected to lie with a specified confidence.
Conversion Time	The time taken for an Analogue to Digital converter to digitise a given signal.
Cut-off Frequency (f_c)	That frequency where the signal attenuation exceeds a prescribed value (e.g. 3 dB).
Damping	Action or influence that extracts energy from a vibratory system in order to suppress the vibration or oscillation.
Damping Factor	The ratio of the amplitude of any one damped oscillation to that of the following one.
Damping Ratio	The ratio of actual damping to the damping required for critical damping.
Defined Measurement Process	A detailed description of a measurement including: objective, test procedure, elemental measurement systems including calibration hierarchy and methods, and mathematical models.
Differential Amplifier	An amplifier whose output is proportional to the difference between the voltages applied to its two inputs.
Drag Coefficient	Coefficient used to calculate the fluidynamic drag force imposed on an object immersed in a flow stream.
Droop Rate	The change in output voltage while a track-and-hold system is in the hold mode (cf. Figure 4.9-26).
Elemental Error	The bias and/or precision error associated with a single component or process in a chain of components or processes.
Estimate	A value calculated from a sample of data as a substitute for an unknown population constant.
Excitation (electrical)	The external electric voltage and/or current applied to a transducer.
Filtering	Elimination of disturbing signals that are superimposed on the signal of interest.
Isolation	Isolation is a reduction in the ability of a system to respond to an excitation.
Isolation Amplifier	An amplifier used to minimize the effects of a following circuit on the preceding circuit.

Kiel Probe	A total pressure sensor in which a shield is placed around the sensor to increase the tolerance to changes in air angle. Includes generic forms of the original Kiel Frobe design.
Laboratory Standard	An instrument which is calibrated periodically at a national standards institution. The laboratory standard may also be called an interlaboratory standard.
Map, Performance	One or more curves of a gas turbine component performance parameter or parameters presented as a function of one or more other parameters. For example, compressor pressure ratio is presented as a function of referred compressor inlet flow and referred compressor rotor speed.
Match	A term used to denote the process of causing a gas turbine engine component to operate at a particular point or points on its performance map, usually by the control of one or more operating parameters such as rotor speed, and sizing of the downstream geometry.
Mathematical Model	A mathematical description of a system. It may be a formula, a computer program, or a statistical model.
Measurand	An elemental physical quantity which is the objective of a specific measurement.
Measurement Acquisition	The recording and/or display of information coming from a sensor.
Measurement Channel	The route followed by a signal from a sensor to the recording media.
Measurement Error	The collective term meaning the difference between the true value and the measured value. Includes both bias and precision error - see accuracy and uncertainty. High accuracy implies small measurement error and small uncertainty.
Multiplexing	The recording of signals from multiple sensor inputs on to a single recording channel.
Noise	Noise is any undesired signal
Nozzle, Exhaust	Device for providing a desired match of upstream components of a gas turbine engine and for converting the engine exhaust energy into th[illegible]n an efficient manner.
Nyquist Frequency	If a continuous bandwidth-limited signal contains no frequency components higher than f_c , then the original signal can be recovered without distortion if it is sampled at a rate equal to or greater than the Nyquist Frequency = $2f_c$.
Outlier	A data point which does not seem consistent with the rest of the data. A "wide" or "rogue" point. Various schemes for treatment or rejection of outliers are used.
Parameter	An unknown quantity which may vary over a certain set of values. In statistics, it occurs in expressions defining frequency distributions (population parameters).
Parameter, Derived	A performance parameter calculated from two or more primary parameters. Pressure ratio is an example of a derived parameter.
Parameter, Inferred	A parameter having either primary or derived parameters as inputs and obtained as a result of calculations involving modelling and/or fitting of experimental data.

Component efficiency is an example of an inferred parameter.

Parameter, Primary	An expression of the physical state actually being measured. Primary measurement systems have a single measurand as an input and deliver a single (may be time-varying) output which is interpretable using a single calibration factor to convert to engineering units. Pressure is an example of a primary parameter.
Perturbing	The technique used to determine sensitivities of one dependent variable to other independent variables. The value of one independent variable is changed slightly and the change in the dependent variable is noted. This is often done where the partial derivatives are too complex to evaluate.
Precision Error	The random error observed in a set of repeated measurements in a Defined Measurement Process. This error may be the result of a large number of small effects.
Precision Index	The precision index is defined herein as the estimate of the standard deviation for a set of nm measurements. $$s = \sqrt{\frac{\sum_{i=1}^{nm} (x_i - \bar{x})^2}{nm-1}}$$
Pressure, Total	(Stagnation, Impact) The pressure sensed by a probe which is at rest with respect to the system boundaries and which locally stagnates the fluid isentropically.
Pressure, Static	(Stream) The actual pressure in a fluid independent of its state of motion. The pressure that would be measured by a pressure sensor moving with the fluid.
Probe	An assembly containing a single sensor or combination of sensors, such as temperarure or pressure sensors.
Pulse Code Modulation	Modulation in which the peak-to-peak amplitude range of the signal to be transmitted is divided into a number of standard values, each having its own code; each sample of the signal is then transmitted as the code for the nearest standard amplitude (abbrev. PCM).
Pulse Rise Time	The interval of time required for the leading edge of a pulse to rise from some specified small fraction to some specified larger fraction of the maximum value.
Rake	A probe assembly containing two or more similar sensors or combinations of sensors, or an aerodynamic probe consisting of a single support with an array of sensors attached.
Random Error	Random part of the measurement in a Defined Measurement Process (see Precision Error).
Recovery Factor	The ratio of the actual to the total thermal energy that will be available from the isentropic deceleration of the gas stream at the temperature measuring junction.
Resonance	A resonance of a system in forced vibration exists when any change in the frequency of excitation causes a decrease in the response of the system.

Root-Sum-Square (RSS)	The method of combining bias errors and precision errors. Note that in this document, lowercase notation always indicates elemental errors, e.g. s and b for elemental precision and bias, and uppercase notation indicates the Root-Sum-Square (RSS) combination of several errors, e.g. $$S = \pm\sqrt{\Sigma s_i^2}$$ $$B = \pm\sqrt{\Sigma b_i^2}$$
Sample Size	The number of repeated observations or measurement used to estimate a given statistic.
Sampling	The selection, for a given parameter, of an acquisition frequency and a measurement time, dependent on the physical process and the performance of the measurement system.
Sensor	That part of the instrument intended to sense or respond directly to the physical quantity being measured.
Settling Time	The time for the output of a track-and-hold system to settle to its final value following the end of the aperture period.
Signal Conditioning	Operations that are necessary to make the sensor output signal compatible with the recording devices.
Signal Processing	All the operations on the signal between the output of the sensor and the conversion into engineering units.
Signal-to-Noise Ratio	The ratio of the amplitude of a desired signal at any point to the amplitude of the noise signals at that same point (for random noise, the rms value is usually used).
Standard Deviation	A measure of the dispersion of a frequency distribution. See Precision Index: s is an estimate of σ calculated from a sample of data.
Standard Error of Estimate	The measure of dispersion of the dependent variable (output) about the least-squares line in curve fitting or regression analysis. It is the precision index of the output for any fixed level of the independent variable input. See Equation 3-12.
Student's "t" Distribution	The ratio of the difference between the population mean and the sample mean to the sample standard deviation (multiplied by a constant) in samples from a normal population. It is used to set confidence limits for the population mean; t_{95} percent confidence range. It depends on the number of degrees of freedom or sample size. For large (>30) samples, t_{95} has a value of 2. For small sample sizes, it is much greater than 2.
Switching	Connection by electric or electronic devices of several instrumentation channels to a single amplifier.
Systematic Error	see Bias
Time Constant	The time required for an instrument to indicate 63% of the final reading of an input

signal.

Traceability	The ability to trace the calibration of a measuring device through a chain of calibrations to a national standards institution.
Transfer Function	The mathematical relationship between the output of a system and its input.
Transducer	A device which converts the measurand into an electrical signal.
Transient Condition	A transient condition is one in which a variation of machine operation from one steady state condition to another steady state condition is deliberately induced (e.g. engine acceleration).
Uncertainty	The error reasonably expected from the defined measurement process. Usually expressed as UADD (Additive Uncertainty) or URSS (Root-sum-square uncertainty) at confidence levels of 99% and 95% respectively.

$$UADD = \pm(B + t_{95}\frac{S}{\sqrt{N}})$$

$$URSS = \pm\sqrt{B^2 + \left(\frac{t_{95}S}{\sqrt{N}}\right)^2}$$

Variance (σ^2)	The square of the standard deviation; it is a measure of the scatter or spread of a data distribution. It is estimated by

$$s^2 = \frac{\sum (x_i - \bar{x})^2}{nm-1}$$

from a sample of data.

Working Standard	An instrument that is calibrated in a laboratory against an interlaboratory or transfer standard and is used as a standard in calibrating measuring instruments.

List of Acronyms

AEDC	Arnold Engineering Development Center (USA)
AGARD	Advisory Group for Aerospace Research & Development (NATO)
AIAA	American Institute of Aeronautics and Astronautics
AIR	Aerospace Information Report
ANSI	American National Standards Institute
ARC	Aeronautical Research Council (UK)
ARP	Aerospace Recommended Practice (USA)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
CEPr	Centre d'Essais des Propulseurs (France)
IPTS	International Practical Temperature Scale
ISA	Instrument Society of America
ISO	International Standards Organization
NACA	National Advisory Committee for Aeronautics (USA)
NASA	National Aeronautics and Space Administration (USA)
NATO	North Atlantic Treaty Organization
NIST	National Institute for Standards and Technology (USA)
NRCC	National Research Council (Canada)
PEP	Propulsion and Energetics Panel (AGARD)
RAE	Royal Aerospace Establishment (UK)
SAE	Society of Automotive Engineers (USA)
SI	Système International (System of units of measurement)
TUAF	Turkish Air Force Overhaul Base
UETP	Uniform Engine Test Program (AGARD Project)
USAF	United States Airforce

Editor's Note

In its conception and format, this report was very much a collaborative effort by all members of AGARD Working Group 23. However, the task of the actual writing inevitably fell on a few contributors with special expertise. It is with much pleasure that I take the opportunity here to acknowledge the dedicated and extensive contributions of the following committee members: W.G. Alwang, S. Bitter, A.H.A. Halfacre, J.D. Harris, R. Jacques, P.H. Papadakis, and N.J. Seyb. Without their continued interest, their knowledgeable inputs, and their infinite patience with the editor, this report would not exist. B.D. MacIsaac of GasTops Ltd., of Ottawa, provided valued comments and contributions, particularly to Chapter 4.7. R.E. Smith, Jr., reviewed the final manuscript with detailed, and much appreciated, care and greatly assisted the editorial process. Francois Dubé of the National Research Council of Canada provided the particular analyses shown in Figures 5.2-10 to -13; Nicole Cardin and Michèle Charron of the same organization prepared the texts and figures for printing. Finally, I would like to thank the Chairman of WG23, D.M. Rudnitski, for his persistence in the execution of this project and his generous support at all times.

1. INTRODUCTION

1.1 BACKGROUND

The accurate quantification of the steady-state operating conditions of engines and components is a very necessary part of gas turbine research and development. However, for many years it has been recognized that the operating conditions within each component also need to be understood when moving between steady-state operating points. Control systems may then be tuned to enable a safe and swift response to changes when demanded. The measurement of transient rig and engine parameters during such manoeuvres can involve significantly different methods of instrumentation, recording and analysis from the steady-state measurements of similar parameters.

AGARD Advisory Report No. 245 on "Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components" (Reference 1.1), provided a rigorous treatise on the steady-state determination of pressure and temperature. The authors of AR-245 considered that the other steady-state engine performance parameters, such as thrust, airflow and fuel flow were treated adequately in AGARD AR-248, "The Uniform Engine Test Programme" (Reference 1.2). The authors of AR-245 agreed, that when dealing with component tests, temperature and pressure were the two most difficult, but critical measurements, that needed to be accurately determined. AR-245 was specifically aimed at the engine *development* phase, where the development team was mainly concerned with isolating and correcting deficiencies in engine performance.

1.2 OBJECTIVE

The objective of this document is to provide the user with a guide for the measurement of *transient* aerothermodynamic performance parameters of aircraft gas turbine engines or components. Topic areas covered include typical types of transients, sensed parameters, frequently used sensors and transducers, and the desired level of accuracy. Data acquisition and reduction procedures, measurement uncertainty and worked-out examples are presented as aids for the user. For the experienced user, it is hoped that this document will act as a reference manual on particular aspects that may require clarification.

In this document, the 'user' is defined as a fully qualified engineer. Technicians, with specialized training and suitable experience, will also find the information quite useful, as the examples in particular, are meant to complement technical operating instructions.

In keeping with the concept of a 'user's guide', the specific objectives of a transient investigation will be closely related to the type of user. Four broad categories of user can be identified:

- o Engine developer/designer
- o Test agency/test subcontractor
- o Certifier/licensing authority or aircraft customer
- o Operator/aircraft user

Engine developer/designer

Of the four categories above, the *engine developer* will usually have the most comprehensive requirements since the developer will be dealing with a potentially unknown, new test article and, hence, will need to investigate a large range of transient characteristics. These requirements will cover the effective behaviour of each component (aerodynamic and mechanical) and determine safe handling/operating margins including safe rates of change. The development of the control system and variable geometry schedules will also form a major part of transient testing as will accelerated life cycle assessment programmes. Obviously, there will be many other requirements for detailed transient testing, some of which will be directly related to a specific engine - aircraft installation or flight environment.

Test agency/test subcontractor

The *test agency* or *test subcontractor* will normally have at its disposal a dedicated and comprehensively developed test facility backed up by an in-depth knowledge of test procedures. It will thus be capable of undertaking, on behalf of the engine developer, certifier or operator, a wide range of investigations.

Certifier

The *certifier* or equivalent agency will normally be interested in carrying out limited but well defined tests. These tests will need to be very carefully controlled to the high standard demanded by the *licensing authority*. The test article in this case usually has a well understood transient behaviour history and is only required to demonstrate a compliance with certification requirements.

Operator

Most *operators*, both civil and military, have a vital interest in engine performance testing as pre-delivery and post-overhaul handling checks are an essential requirement. The test procedure will normally be specified in the "operating manual" produced by the manufacturer and, in part, take the form of a handling check. These tests must rely on a limited number of instruments and the test procedure may vary from customer to customer and engine to engine. In some cases, throughout the production life of a particular engine, operational problems may arise and it is often necessary for the operator to carry out diagnostic tests in the field using simple test facilities, production engine instrumentation or instrumentation inserted through existing engine openings.

1.3 SCOPE

The scope of this document is limited to transient tests on engines that would be carried out in ground-based test facilities; these could be ground-level test beds (commonly referred to as sea-level cells) or altitude chambers. Although rig tests are not specifically addressed, in general many of the techniques described are applicable. Flight tests are not considered as this would considerably broaden the scope.

Thus far, the word *transient* has been used without definition. In general terms, measurements fall into one of three different classifications that describe the degree of unsteadiness of the measurand: steady-state, transient and dynamic. The classifications used in this report are consistent with those of AGARD AR-245 (Reference 1.1). The definitions of these classifications are reprinted below for completeness.

Steady-state conditions are those where the machine is running at a nominally fixed operating point and the measurand is essentially constant with time. Even in steady-state conditions it must be recognized that there may be substantial unsteadiness due to the presence of rotor passage wakes, turbulence etc., which could significantly influence the performance and calibration characteristics of the probe system itself. Also, the machine under test cannot be held at a precisely constant condition and so over a period of time a sequence of slow variations must be expected. These factors should be considered when assessing the uncertainty of the results.

Included in this concept of steady-state conditions is the requirement that the machine should be allowed time to reach equilibrium conditions in terms of stable aerodynamic and/or structural temperature gradients, and stable component operating point or engine match point, before the definitive measurements are recorded.

The term ***transient conditions*** are those in which a variation of machine operation, from one steady-state condition to another, is deliberately induced (e.g. engine acceleration). The discussion in the following sections is aimed at describing instrumentation capable of accurately quantifying transient behaviour. The instrumentation system must be capable of detecting the boundaries of instability (e.g. surge, rotating stall, etc.,) and changes in performance due to transient operation.

Dynamic measurements are those in which the measurands are varying at a high frequency and for which an instantaneous point measurement or spectral behaviour characteristics are required to adequately define the parameter. Special instrumentation is usually required for this purpose. The specific problems associated with the measurement under dynamic conditions will not be considered in this document.

Although this document is specifically aimed at *transient* assessment, steady-state measurements are generally a pre-requisite in defining the bounds of the transient manoeuvre. Consequently, steady-state measurement systems will be discussed to some degree.

Consideration was given to include vibration and acoustic sensors, but as the bandwidth of the data fall into the dynamic range, they fall outside the scope of this report. Nevertheless, vibration and acoustic sensors can be important for all four classes of user.

This document purports to be a guide to assist a user in obtaining meaningful transient measurements from turbomachinery under test. Detailed descriptions of sensors and their application, along with expected measurement uncertainty, should enable each class of user to select the most appropriate sensor for a given situation. Although inferred, test planning, test procedures and system setup are not specifically addressed. These are recognized as very important elements of any test programme which are generic in nature, but application specific. The use of component and engine models can be a powerful tool to define estimates of expected results for measurement range and frequency content. However desirable, time and available resources did not permit these important issues to be included in this document.

1.4 HOW TO USE

This document provides guidelines along with worked examples on the application of measurement systems to transient data capture. The text is organized to provide the user with a self-contained document that should be read essentially in its entirety. Some emphasis has been placed on measurement uncertainty and is the subject of theoretical treatment in Section 3. For a first review only the introduction in Section 3 need be covered prior to entering Section 4, the heart of the report. The more experienced user, seeking reference material only, can refer to a particular chapter to obtain detailed information on a particular measurand or application concept, such as measurement uncertainty methodology. In the sections dealing with the individual measurands, worked-out examples have been provided which illustrate typical procedures for application. For consistency, two typical examples of test procedures of common interest, one for an engine developer and the other for an engine operator, are fully defined in Section 5, and are used to demonstrate the instrumentation details, including measurement uncertainty, in each section as appropriate. In this manner, detailed treatment of the measurands, globally used in Section 5, can be found in the individual sections. The glossary and nomenclature from AR-245 (Reference 1.1) have been used but modified, where appropriate, to avoid potential confusion with multiple terminology.

The organization and content of Sections 2 through 5 are summarized as follows:

Section 2 - General requirements for measurement of engine and component transients
Section 2 lays out the groundwork of requirements for transient measurements. it is a general summary of the engine test process that serves as a reminder of the many and often competing factors that go into planning a test programme. Described are typical types of transients, the requirements for the engine test facility, examples of test methods, and the general parameters to be recorded during a transient. A general quantitative definition of a transient in terms of frequency response and discrete time sequences is not possible as it is parameter and event dependent. Also introduced is the concept of a defined measurement process, which, if followed in the planning stages, will greatly enhance the probability of success.

Section 3 - Measurement uncertainty methodology
A section is devoted to a theoretical treatment of Measurement Uncertainty Methodology (Section 3), an essential step in the planning process. The model describes a process that can be used for instrumentation design. Application of measurement uncertainty to real engineering problems is already a matter of considerable debate in the steady-state measurement community, and no doubt will provide even more discussion amongst experts in its application to transient measurements. A clear understanding of bias and precision errors, combined with the stated experimental objectives, should determine the relative or absolute accuracy of the parameters. A method is proposed that depends on separating the error sources into steady-state and transient components, which, when combined, will yield the total uncertainty.

Section 4 - Transient measurement systems
Section 4 is the bulk of the report, and is meant to stand alone. Starting out with general definitions of measurement systems, including the integration of data in space and time, the novice and the expert alike are then given detailed information on pressure, temperature, fuel and air flow, geometry, force and torque, and control system parameters. Generally a uniform format has been adopted for each sensor type, where possible, that covers basic theory, advantages and disadvantages,

signal conditioning, calibration procedures, and specific design examples. There is no general agreement in the industry on a unified approach to dealing with transient measurements in the context implied in Section 3. Each sensor technology is handled a bit differently but all have some form of transient response model. A chapter on data acquisition and processing completes this section. Each sensor type, with its own unique signal conditioning, produces a voltage level that is routed to the data acquisition system; from this juncture, data handling, processing, time correlation and display are considered as a common requirement for any transient measurement problem.

Section 5 - Examples of a measurement system uncertainty analysis for two test cases

Two design examples of instrumentation systems, required for two different types of tests spanning the range of interest, are described in Section 5. The first example, applicable to both engine developers and overhaul agencies who have a requirement to determine compressor pressure ratio at surge, is a complex one requiring specialized instrumentation. The second example is directed at an engine overhaul agency or operator who, as part of an acceptance test, must record the acceleration time from idle to 100% of rated engine thrust. This is a common test procedure employing conventional instrumentation.

This section guides the reader in implementing the complete process, from the statement of need, through sensor selection, test techniques, measurement uncertainty, up to data display. In following the procedures developed for these examples, and referring back to Section 4 for details on the individual measurands, the user should gain a thorough understanding of the process, and be able to apply the methodology to any parameter.

1.5 REFERENCES

1.1 *Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components*, AGARD Advisory Report No. 245, June 1990

1.2 *The Uniform Engine Test Programme*, AGARD Advisory Report No. 248, February 1990

2. GENERAL REQUIREMENTS FOR MEASUREMENT OF ENGINE AND COMPONENT TRANSIENTS[1]

2.1 INTRODUCTION

In assessing the suitability of a powerplant to provide the energy to enable an aircraft to meet its mission requirement, two important aspects must be considered:

(a) The powerplant's performance at steady state conditions (i.e. its thrust and fuel consumption at a fixed flight condition and power lever setting).
(b) The satisfactory behaviour of the powerplant while undergoing a change in flight condition or power lever setting or both (i.e. transient operation).

As stated in Section 1, it is item (b), transient operation, which is the main subject of this report. However, before proceeding further it is necessary to outline the character of the measurand and range of conditions anticipated so that the requirements of the measurement techniques and instrumentation can be established.

In AGARD-AR-245 (Reference 2.1) it was found convenient to consider three arbitrary operating conditions - steady state, transient and dynamic. As all flow systems exhibit a degree of unsteadiness, completely separate and unambiguous definitions of these three states are not possible. However, for the purposes of this guide to transient measurement techniques, the definition from Section 1.3 is used throughout the report, viz.:

Transient conditions are those in which a variation of machine operation from one steady state condition to another steady state condition is deliberately induced (e.g. engine acceleration).

Implied in this definition is an imposed (measured) rate of change of input control or environment. The response of the machine is measured by a sensor-transducer system which will not respond immediately to the measurand. This time related response is usually quantified by an instrumentation "time constant" or "frequency response". Also, the data acquisition system will impose further time related response characteristics, sampling rate requirements and frequency range limitations.

The total elapsed time spanning the transient also needs to be considered. The main response to a transient input (e.g. throttle movement) will take place over an initial short period but performance changes will continue to take place until full steady state equilibrium has been achieved. This may take several minutes. Thus it will be necessary to refer to the objective of the test to ascertain what defines the transient duration.

So that the reader of this report will have a clear understanding of the conditions covered by the above definition an expanded discussion of the concept of transient operation is given below.

Consider the operating condition where the input control setting is changed from one steady state setting X, to another, Y (Figure 2-1(a)). This will induce changes in the measured output parameter as shown in Figure 2-1(b).

Using pressure as an example, the three conditions - steady, dynamic and transient - may be defined with reference to Figures 2-1(a) and 2-1(b) as follows:

Steady state (mean) pressure
The pressure obtained at a constant/fixed control setting after the pressure fluctuations have been smoothed either by a data acquisition system which has a long time constant or through a defined data reduction/analysis process.

Dynamic (fluctuating/oscillating) pressure
These are pressure perturbations about the mean value and which may vary in both magnitude and frequency as a function of time. For dynamic measurements an instantaneous point value or spectral behaviour characteristics are required to adequately define the flow. To be properly transduced the measuring system range of flat response must be wide enough to encompass the full frequency range of the fluctuations.

Transient pressure
A pressure which varies as a result of a control action such as a fuel spike, slow/fast slam acceleration/deceleration or as the result of some other specific event, e.g. surge. It is normally a non-repetitive function of time and represents a transition from one operating point to another. To be accurately transduced the response time of the measurement system must be such

[1] Tables and Figures begin on page 2-13

that it is possible to evaluate and follow the "mean" pressure level throughout the transient period as illustrated in Figure 2-1(b). It is therefore essential in all transient investigations to record all measurements against a common time base.

From the above discussion it will be seen that it is not realistic to quote a specific frequency boundary (or more appropriately response time) which would encompass all types of transient operation, as the frequency boundary would depend on the objective of the test, the event under consideration, engine dimensions, etc. Hence each set of test conditions must be considered on its merits and reviewed to define the appropriate measurand requirements.

2.1.1 Planning the Test and Instrumentation

The starting point of a transient performance investigation must be a clear statement of the objectives of the test. These could take various forms:

Examples of General Objectives for Transient Tests

o to determine the time dependance of the measured quantity;

o to determine the peak value or stability margin;

o to relate two or more quantities or events with respect to time.

Using the specified objective it will be possible to define the instrumentation configuration, data acquisition requirements, test procedures, and data reduction and analysis methods to be followed. An essential part of this pre-test planning is to review the path chosen and to confirm that the collected data, when finally analysed will be of sufficient quality to meet the customer's original objective. This assessment will usually involve a pre-test uncertainty analysis as described in Section 3.

The nature and objectives of the investigation will be closely related to the type of user:

The *development engineer* will need to define the transient conditions under which it is required to investigate the test article behaviour. This may well include specifying the following conditions:

o simulation of flight environment
o engine power manoeuvre
o test geometry requirement

Having specified the transient conditions the next step is to identify the transient measurements necessary to investigate the test article behaviour during the transient and to estimate the anticipated rates of change of both input control and output response. The strategy should be such as to ensure that enough information is collected to give an understanding of the machine characteristics in order to make it possible to develop the test article.

When the general list of measurement parameters have been identified it will be necessary to specify the more precise and detailed measurements needed to achieve the general parameter. If, for example, fuel flow is the general measurement objective it will be necessary to identify the measurements needed to achieve this objective:

Fuel mass flow -
o volume flow rate
o meter calibration
o density
o fuel temperature

The process of specifying the detailed list of measurements will have identified the instrument response rates and measurement process needed to achieve the data. The quality of the items in this process now need to be specified and an uncertainty analysis carried out to ensure that the output meets the accuracy requirements necessary to understand and develop the machine characteristics. The uncertainty analysis will reveal:

o if the test objective is satisfied
o if the measurement process needs improvement
o if the process can be relaxed with a cost benefit
o the sample rate necessary to capture the frequency of the event

There is often an added complication that sensors are shared between the steady state and transient measurement systems. Where this is the case it will be necessary to assess the impact on each system of the dual role.

It should be emphasised that the steps outlined above are dependent on the test objectives and therefore the process will have to be repeated for each case. It is also generally true that test objectives have a significant effect on:

o choice of parameters
o range of measurement
o instrumentation response rates required.

In the case of a *test agency* a similar situation to the engine developer exists and therefore the procedure above applies equally well in meeting the test objectives. However, there are sometimes added problems, for example, the measurement process might be split between the agency and the engine manufacturer.

Where this is evident it is important to consider the calibration needs of the split responsibilities. Often the sensor is in the domain of the engine manufacturer and the electronic conditioning and data gathering equipment is the responsibility of the agency.

If tests are being done in more than one facility, care is needed to ensure compatibility and traceability to enable true cross correlations to be made. Sometimes, testing on more than one facility will be the only way of determining "unkown bias", e.g. "bed" vs "outdoor".

The *certifier/licensing authority* has the task of determining that the test vehicle meets whatever certification requirements are laid down for the particular application. He is not as interested in the detail a developer may require since he is not attempting to determine component performance boundaries that need extending but simply checking that set requirements are met. However, the need for a good understanding of the whole transient measurement field is important in order to ensure that each new vehicle is properly tested.

The *engine operator* again has a different transient test requirement. The most likely test is a pass-off test for engines that have been overhauled, or a test to confirm a prohlem reported in service. The operator is unlikely to have a sophisticated instrumentation need or capability. He will be reliant on production instrumentation standards plus the capability to insert sensors into the engine through normally blanked openings. Often the sensor is in the domain of the engine manufacturer and the electronic conditioning and data gathering equipment is the responsibility of the agency.

2.2 THE NEED FOR TRANSIENT MEASUREMENTS

The number and type of transient tests and associated measurements (Reference 2.2) will depend upon the user's objectives as described in Sect on 2.1. The most comprehensive range of transient test requirements would include, for the engine developer:

- o verifying engine operability/handling.
- o determining engine structural changes during transient operations.
- o verifying engine control settings and schedules.
- o analysing differences between actual engine behaviour and the design cycle model.
- o accelerated life cycle assessment.

2.2.1 Verifying Engine Operability & Handling

During transient engine operation the effective operating point of each component will move away from its steady state condition. The magnitude of these excursions will depend upon many factors, but they may be large enough to extend beyond stable operating boundaries with a corresponding effect on engine stability. The most well known illustration of a transient trajectory is an acceleration - deceleration excursion on a compressor map, Figure 2-2. The rate of acceleration of the engine will be limited by the surge margin. One important transient test will therefore be to establish the minimum margin between the transient operating line and the surge line. If, unfortunately, engine surge should occur, assessment of the post stall behaviour and recovery procedure may be necessary and, if so, the appropriate instrumentation and data acquisition system will need to be defined. Similarly engine starting boundaries, relight envelope, afterburner operation, and thrust reversal, etc., will also form part of transient handling investigations.

2.2.2 Determining Engine Structural Changes

Another major aspect of transient testing is the detection and assessment of the effects of geometrical changes due to the influence of differential temperatures, loads etc. These changes could affect both the aerodynamic performance and the mechanical integrity of the engine. These structural changes are over and above the changes due to steady state operation and should include the influence of active controls.

Measurement techniques to cover such items as variations in blade tip and seal clearance, actuator movements, etc., will be described in Section 4.5.

2.2.3 Engine Control System Development

Engine control systems require development testing in order to maximise engine performance capabilities without transgressing damaging operational limits. These control systems can vary in complexity from the relatively simple mechanical through hydromechanical to fully variable digital electronic systems. The ease with which electronic systems can be tailored to

maximise engine performance, by software changes to the control laws, means transient tests are an important step in the development of the control unit-engine combination. These tests may be used to explore, for example:
- o surge free operation
- o widest relight envelope
- o minimum acceleration time
- o optimum afterburner augmentation
- o buzz and screech-free afterburner operation

Testing of mechanical or hydromechanical systems should follow similar practices although their flexibility is unlikely to match that of the electronic variety.

2.2.4 Validation of Engine Cycle Model

At some stage in an engine design and development programme a mathematical model of the cycle, including both aerodynamic and mechanical simulation, will be devised. The purpose of these theoretical models is to enable cycle manoeuvre and transient operation studies to be carried out with a minimum of engine testing and to study the effect of component characteristic changes on the engine performance. These engine modelling exercises, in the main, are undertaken in parallel with engine development and could have a significant input into, for example, control system design and development. As experimental testing proceeds, the mathematical model can be updated and revised to make it more representative of actual (real) engine behaviour. As with all mathematical models care must be taken in interpreting the results as the simulation can only be as good as the model, which at the best is a simplified representation of the real engine.

2.2.5 Accelerated Life Cycle Testing

Testing of this type will normally take the form of repeated engine cycles, relatively rapidly, through a series of carefully controlled predetermined operating conditions. The control scheduling, instrumentation and data recording systems will all need to have transient capabilities. It is important for such tests to be representative of actual engine usage in the field so that maintenance schemes can be configured to achieve minimum ownership costs within safe working practices.

2.3 TYPES OF TRANSIENT CONDITIONS IN AIRCRAFT ENGINE TESTING

The various forms of transient investigations described in Section 2.2 could be carried out in a range of different external engine environments. Five such sets of environments are described below in Sections 2.3.1 to 2.3.5.

Note that in all transient events structural thermal gradients will be introduced and considerable changes in clearance, etc., will continue to occur long after the input disturbance has ceased. Thus engine or component performance will continue to change until equilibrium is achieved or, in the case of cyclic events, a hysteresis is established.

2.3.1 Steady Environmental Conditions, Homogeneous Intake Flow, Transient Engine Operation

Tests within this type of environment could be as follows:
- o Acceleration and/or deceleration between a range of engine power ratings in a fixed mode (e.g. dry or reheat) or combined with a change of mode (e.g. dry to reheat to dry).
- o Starting from rest (or windmilling) to idle covering a range of steady environmental conditions (e.g. starting after a cold soak) and restarting in simulated flight conditions (e.g. windmilling, starter assisted, immediate relight before deceleration of spool).
- o Shut down from high operating point to rest or windmilling (e.g. avoidance of engine damage due to structural changes resulting from thermal gradients).
- o Effects of, and recovery from, compressor surge. Violent loads resulting from engine surge may contribute towards engine damage. Also following surge a special sequence of control operations may be necessary to re-establish stable engine running.
- o Influence of sudden changes in engine power demand. This manoeuvre is similar to the first type except it often includes an engine geometry change (e.g. thrust reversal or vectoring, main shaft power as in helicopter lift off or turboprop reverse thrust).

2.3.2 Steady Environmental Conditions, Non-Homogeneous Intake Flow, Transient Engine Operation

This type of environment is of interest when it is required to simulate the inflow distortion due to operation behind a non-symmetrical intake, or due to high incidence flight, etc. The transient testing procedures and objectives would be similar to those of Section 2.3.1. However a more comprehensive array of instrumentation may be essential to quantify the influences of the non-uniform flow, although data storage/channel availability may be a limiting factor.

2.3.3 Transient Inlet and Exhaust Conditions, Fixed Power Setting

Transient change of environmental condition can be caused by a wide range of factors and will cover a significant band of magnitudes and of rates of change. These causes could be; aircraft incidence variation, speed or altitude change, plume crossing (rocket weapon exhaust), hot gas re-ingestion (VTOL or thrust reversals, or helicopter or turboprop operation). The simulation of these types of manoeuvre in test facilities is difficult, in particular rates of change in temperature are difficult to control to prescribed schedules.

In altitude facilities special care is required to compensate for plant operating characteristics. The plant settling times must be monitored to verify satisfactory stability of both inlet and exhaust conditions.

2.3.4 Variation of Bleed and Auxiliary Power Extraction, Homogeneous Inlet and Exhaust Conditions and Fixed Power Setting

As well as transient conditions related to variations in main engine parameters, auxiliary engine services can also induce transient response and behaviour. The type and range of testing in this field will be very much dependent upon the engine type and application.

2.3.5 Combination of the Above Described Cases

In engine operation the above described conditions seldom occur in isolation and a combination of several of the above conditions is the more likely. Concurrent cases are seldom of the same effective order of magnitude or rate of change but the detrimental effects on engine performance and stability are additive. Generally, neither test capability nor measurement capability exists to impose simultaneous realisitic combinations of these four transient conditions. It has been shown to be acceptable to test the conditions separately, and estmate the combination effect by superposition.

Combination cases will therefore not be evaluated in this report but the possibility of combination cases or events should be borne in mind when planning a test.

2.3.6 Single Event Tests

Single event tests which are required for certification, safety, and structural integrity, although they may exhibit aspects of transient behaviour, are not treated in this report. These tests include such events as ice ingestion, bird ingestion and blade-off.

2.4 GENERAL REQUIREMENTS FOR AN ENGINE TEST FACILITY

2.4.1 Introduction

The objectives, needs and requirements for measurements related to the various types of transients have been outlined in Sections 2.1, 2.2 and 2.3. For any particular test the objectives will have been defined by the customer (engine developer through to engine operator) and from this specification the required test programme, instrumentation configuration, type of test facility and analysis methods necessary will be defined. Note that it is important to ensure that the complete chain from objective to analysed results is compatible and of adequate standard to meet the customer's requirements with an acceptable level of confidence.

In this section some typical test facilities suitable for transient measurement will be described, flight testing being excluded. Also, some comments regarding the test vehicle itself and some typical test procedures will be outlined in order to provide a background to the following Sections 3 to 5. It is not the intention to describe in detail methods of testing, but only to give sufficient outline so that a suitable instrumentation configuration and data acquisition system can be designed.

2.4.2 Station Identification Codes

In order that a universal and systematic set of station identification codes be used it is recommended that those of References 2.3 and 2.4 be adopted. The reader is also referred to Reference 2.1 from which Figure 2-3 has been taken. Note also that Reference 2.1 recommends sensor station identification nomenclature.

In some test cases it will be necessary to identify conditions external to the engine which may not be described in the above references and, if so, clear definitions will need to be made when planning the tests. Also station numbering (and geometric position) will be necessary in other external systems, e.g. fuel supply lines, at which measurements are made. Another example could be stations in a mechanical linkage in which case sufficient detail must be included so that proper accounting for flexure, thermal expansions, lost motion etc, can be made.

2.4.3 The Test Facility

There are four main forms of test facility;

(i) Ground level bed - with or without aircraft intake,

(ii) Altitude test bed - with or without aircraft intake,

(iii) Ground level static - engine in aircraft,

(iv) Flight test - flying test bed or designated aircraft. (Not discussed in this report)

Each of these test facilities has its own related advantages and disadvantages. The user-defined objectives will help in selecting which type of test facility is needed and is the most cost effective for the programme envisaged. Some of the characteristics of the different test facilities are listed in Table 2-1 and typical engine installations are shown in Figures 2-4 (altitude test facility (ATF)) and 2-5 (ground level cell (GL)). An equivalent arrangement for a turboshaft engine is shown in Figure 2-6. The capabilities of some typical test facilities are given in Table 2-2.

2.4.4 Test Cell Environment (and its instrumentation)

It will normally be the requirement of the test cell to simulate as nearly as possible a realistic/representative engine environment (or some classical external conditions), at inlet and exhaust to the engine and have instrumentation capable of measuring these conditions. Typical test facilities are discussed in the previous section (2.4.3). The engine itself is usually installed on some type of frame which is allowed to move as freely as possible over short distances so that the frame load can be measured using load cells. In the case of power turbine engines, shaft power is the primary measurement and thus thrust measurement is not normally required.

Unfortunately, as with all installations, the test cell itself will have some influence on the performance of the bare engine and so corrections will need to be made. These corrections could be due to flow induced around the engine in the confined space of the cell or "drag" from lines providing services to the engine. In the case of steady state testing, corrections and allowances, either from calibration or theoretical assessments, can be made. During transient testing there will be additional influences due to the unsteady nature of the flow. It is normal practice to apply any calibration/corrections determined in steady state testing to the results obtained in those transient manoeuvres where no direct transient measurement can be made.

These "cell effects" and methods for accounting for them are discussed in detail in Section 4.6 as related to thrust and torque measurement.

2.4.5 Test Vehicle and Instrumentation

Once the range of measurements needed to meet the users objectives have been established, careful positioning of the sensors within the engine is essential. The different types of user will need differing instrumentation arrays; for example, the developer/designer will require a comprehensive array while the engine operator may require only a very simple arrangement, defined in the operating manual as being necessary to monitor a handling check following engine overhaul. A typical array of instrumentation for a comprehensive investigation (e.g. a surge margin assessment by an engine developer) is outlined in Table 2-3. In some cases a video camera and recording, including the associated common time base, can provide valuable information.

In positioning instrumentation, due account must be taken of the fact that as well as varying with time, fluid flow profiles will vary spatially as the input controls impose the required transient manoeuvre. Figure 2-7 illustrates the change in fan exit profile at four different power settings along the steady state running line. It should be noted, however, that a flow profile variation during a transient may be significantly different from that at the corresponding steady state point. Thus, if, for example, a wall static pressure at a station is being monitored due allowance must be made for this variation in profile.

With transient investigations it is essential that account be taken of the lags or delays in the complete instrumentation system and that the response rates are adequate. Also the instruments must have adequate operating range to cover the full extent of the transient excursion and the instruments themselves must be sufficiently robust to minimise mechanical hazards while not creating excessive flow disturbance. Where pressure measurements are concerned it is not always possible to have the transducer position at the point of measurement due to physical restraints. In these cases careful design of the sensor-transducer combination is essential (see Section 4.2), or an allowance must be made to account for the distortion of the measurand.

In addition to fluid flow measurements a whole range of geometric measurements will be necessary. A knowledge of the changes in blade tip or seal clearances due to differential thermal growths is essential to investigate performance penalties and establish safe running limits. Similarly measurements of actuator and linkage movements will be necessary.

Also, as the engine control system has a major influence on the engine stability, detailed consideration may need to be given to monitoring the behaviour of the control system itself, i.e. its many inputs, internal 'software', control outputs, etc.

An essential aspect of instrumentation selection is ensuring that the sensor-transducer system is capable of responding correctly to the measurand and that the Data Acquistion System (DAS) faithfully records the transducer output. In this respect, when signal digitisation is used it is essential to choose a sampling rate appropriate to the expected event and its rate of change. These aspects are discussed in detail in Section 4.9.

Details of the instrumentation (sensors, transducers, data acquisition) and other special features (lags and response rates) are discussed in Sections 4.2 to 4.9.

2.5 EXAMPLES OF TRANSIENT TESTS

The purpose of this section is to describe, in outline only, some typical tests undertaken during a transient programme so that the instrumentation/data acquisition system designer can have a background view of the information/measurement required.

It is usually a requirement, wherever possible, to make the transient instrumentation capable of covering the requirements of steady state testing.

Seven different types of transient tests are listed below and each of these will require a different array of instrumentation which in some cases could be relatively rudimentary should that prove adequate to meet the specified test objectives. These seven types of transient test are described in outline in Sections 2.5.1 to 2.5.7. One of these, 'surge margin assessment (for an HP compressor)', is more fully described in Section 5.2 to illustrate a suggested procedure for the selection of instrumentation array. Table 2-4 suggests lists of typical measurands which may need to be recorded during this and other kinds of transient investigations described in Section 2.5.

Types of transient tests described in the subsections below:

- o Surge margin assessment.
- o Starting and relight.
- o After-burning ignition.
- o Control system development.
- o Thrust modulation and reversal, including turboprops.
- o Clearance and structural investigations.
- o Overhaul, pass-off and diagnostic tests.

Certification or specification testing may encompass all or some of these transient tests.

2.5.1 Surge Margin Assessment

During an aircraft mission the engine will be required to operate over a range of settings and will encounter a series of rapid accelerations and decelerations and/or changes in environmental conditions. The track of engine operation is often illustrated as a trajectory on a compressor performance map (Figure 2-2) in which the performance at any instant in time, during the operating transient, is plotted on the steady state compressor characteristics. In certain circumstances the transient operating line may cross a component stability boundary. This instability can vary from small scale flow unsteadiness, with only small performance penalties or mechanical hazard, through to major flow reversal (surge) and significant possibility of mechanical failure. As well as surge, rotating stall and blade vibration could be considered as major stability limits.

Surge margin can be defined in several different ways (see Figure 2-8).

$$\text{Surge margin} = \frac{\Delta P_R}{P_{aw}-1} \qquad \text{2-1}$$

at either constant flow or speed,

or

$$\text{Surge margin} = \frac{\Delta P_R}{P_{Rw}} \qquad \text{2-2}$$

also at either constant flow or speed,

or

$$\text{Surge margin} = \frac{(W/P_R)_{WP}}{(W/P_R)_{surge}} - 1 \qquad 2\text{-}3$$

It is important to note that many factors can affect the apparent or real surge margin of a compressor. Some of these factors are indicated in Figure 2-9 and it is important to consider their implication when determining a surge margin and quoting its value. Particular attention is drawn to the problems determining meaningful station averages in the case of split flow fans or in the presence of distorted flow.

One technique for assessing surge margin is to supply a fuel spike in the combustion chamber thus raising the back pressure on the compressor forcing it up an effectively constant speed line and hence into surge. Table 2-3 illustrates the typical list of measurands that would be monitored by an engine developer conducting a surge margin assessment transient test.

To illustrate the procedures which are recommended later in this report, for the selection of instrumentation, data acquisition system, test procedure and analysis methods, the assessment of surge margin of an HP compressor is taken as an example and explained in greater detail in Section 5.2.

2.5.2 Starting, Relight and Shutdown

Starting and relighting tests are often conducted in altitude test facilities to determine the boundaries of the envelope and the control system laws needed to expand the envelope to its maximum limits. In an altitude cell the environmental conditions can readily be adjusted or kept constant and the engine starting or relighting sequence initiated to determine engine behaviour. Adjustments to flight conditions on the engine control system can therefore be made to maximise the operating envelope. Successful relight or starting is usually determined by measurements of engine shaft speeds, fuel flows and jet pipe temperatures.

2.5.3 Afterburning Ignition

A significant amount of testing is required to establish and expand the useable augmentor operating envelope. Light up transients are evaluated to assess ignition time, flame stability and propagation, thrust jump, control system performance and the resulting impact (back pressure) on engine compression system components. Augmentor fuelling transients must be accomplished without significant impact on engine operation and within the required acceleration and deceleration times. Cancellation and flameout transients are investigated relative to control responses and liner pressure loads.

2.5.4 Engine Control System Development

The configuration of a control system can vary from a pure mechanical system through a hydromechanical to fully automatic electronic system. The controller itself performs the vital function of sequencing events during a transient operation and takes its inputs not only from the pilot's throttle but also from a wide range of sensed parameters. Built into the system is a series of magnitude and rate of change limits so that engine instability and mechanical hazards are avoided. A block diagram of a typical control system is shown in Figure 2-10 and an idealised engine operational cycle in Figure 2-11.

During the design and development of a control system the boundary limits to be imposed by this system must be established. To support this activity both mathematical modelling (of the engine/control system and software) and transient engine testing is essential. Obviously, in carrying out these tests the appropriate input and output parameters and also some internal parameters of the control system must be recorded. Further details relating to "control system parameter" are given in Section 4.7.

2.5.5 Thrust Vectoring and Reversal (including turboprops)

The reversal of the propeller (prop) pitch under power conditions creates considerable stresses on the engine. The process of pitch reversal puts the engine through the conditions of full forward load, no load in fine pitch and then full reverse load. It is then subjected to the reverse sequence. In the development cycle, tests are performed to observe overspeed margin, droop in prop speed, surge margin and stability of the regulation of accessories (the engine being fully loaded for these particular tests). During endurance running on a block test over some 100 hrs., the engine is subjected to a prop pitch reversal every hour. The tests highlight reduction gearbox and prop bearing endurance.

Vectoring or reversal of turbojet thrust can be used for vertical or short takeoff and landing, maneuvring, or for reduction in landing roll. This type of engine operation is largely transient in nature and can often involve reingestion of engine exhaust flows with consequent stability problems (References 2.2 and 2.5). An example of such a transient could be the requirement for rapid engine deceleration on wheel to ground contact during a vertical landing. Because this type of engine operation involves flows which are external to the engine, representative modelling of the aircraft installation is essential. Therefore testing in a prototype aircraft may be the only option. However, for those cases where the flow deflection angles are small it may be possible to undertake testing in a standard test facility (Reference 2.2). The exact instrumentation layout will be dependant on the objective of the test but, as well as engine mounted instrumentation, measurement of flow conditions external to the engine will often be necessary.

2.5.6 Clearance and Structural Investigations

During transient engine operation it will be necessary to not only measure control actuator movements but also those displacements resulting from differential temperature induced expansions and forces.

Typical amongst these displacements is compressor blade tip clearance as illustrated in Figure 2-12. The monitoring of seal clearances will similarly require measurements of the separation between stationary and moving parts. Methods of measuring clearances are discussed in detail in Section 4.5.4 where methods ranging from "touch probes" and "capacitance probes" to X-ray systems are discussed. Obviously, many other parameters such as structural temperatures, engine operating conditions, etc., will need to be recorded during these transient clearance investigations.

Other forms of displacement measurement are those associated with control system actuators, flow areas, etc., and these are discussed in Section 4.5.3.

2.5.7 Overhaul, Pass-off, Diagnostic and Acceleration Tests

One very important type of transient test is the handling check required after engine overhaul. The test procedure will usually be carefully defined and probably based on a limited set of measurements using only those sensors permanently incorporated in the engine and test bed (or specially provided for pass off testing).

These tests could be limited to thrust and fuel consumption at specified spool rotational speeds. Alternatively they may require accel/decel tests, in some cases, incorporating an inflow pressure distortion.

Also during aircraft service, engine operation problems can sometimes arise and the engine operator may wish to carry out some diagnostic testing in order to pin point the cause of the problem. Such testing will often follow simple transient testing procedures and have to rely on simple instrumentation which can be introduced through existing access ports. With testing of this type it is important to be aware of the same requirements that apply to transient testing in general and to take all reasonable precautions with instrumentation, data recording and interpretation, otherwise misleading conclusions could result. Where a "good" procedure can not be adopted or where instrumentation/recording compromises are made these should be clearly stated.

2.6 PARAMETERS TO BE MEASURED DURING A TRANSIENT

2.6.1 Measurements

The objectives of each particular proposed investigation will determine the parameters that need to be recorded, the test procedure to be followed, and the accuracy of the required measurements. Each class of user will normally have a different set of requirements and instrumentation options. The performance parameter desired may be a primary parameter obtained through a direct recording of the measurand. Alternatively, it may be derived from two or more primary parameters or inferred following an analytical process incorporating measured data (see Sections 3.2 and 4.1.7).

A simple example of an inferred measurement is the estimation of compressor mass flow using the known (measured steady state) characteristic and the values of pressure ratio and rotational speed recorded during a transient. In some cases direct measurement may not be possible and, then, an inferred value is the only alternative.

In addition to all the problems associated with steady state measurements, transient investigations must correctly sense and record the variation of each parameter to a common time base. Thus each sensor, transducer and data recording system must have a rapid response capability of known (calibrated) characteristics; these aspects will be discussed in detail in Section 4.

In all cases uncertainty analysis will establish which parameters have the greatest influence on the uncertainty of the final result and will provide valuable guidance as to which measurement procedure will be the most cost effective in meeting the test objectives.

Also, where possible, the instrumentation system should be designed to serve both steady state and transient investigations.

The following is a list of the measured parameters considered in this report, all measurements being related to each other through a common time base.

Pressure (Section 4.2)
- o Gas
- o Liquid

Temperature (Section 4.3)
- o Gas
- o Liquid
- o Solid body

Flow (Section 4.4)
- o Gas
- o Fuel and oil
- o Velocity and Mach number (derived)

Geometry (Section 4.5)
- o Rotational speed
- o Throttle/actuator position
- o Structural movements and clearances
- o Areas

Thrust and Torque (Section 4.6)
- o Thrust
- o Torque

2.6.2 Calibrations

All sections of the data acquisition system from sensor through to data reduction (output in engineering units) will contain errors. Hence, where possible, calibrations, on line or off line, must be undertaken and allowed for in data reduction systems. Also precision errors must be considered (see Section 3) and these may be assessed from data gathered from earlier (similar) engine transient testing, specially devised calibration tests (time constant determination) or an appropriately planned test procedure designed to reduce and quantify precision error.

The detectors used to measure the fundamental flow parameters of pressure and temperature will not respond immediately or exactly to the measurement; a lag in response and distortion of the signal is inevitable. In the case of pressure measurement the geometry of the sensor/tubulation and the transducer frequency response characteristics will need to be considered when assessing the behaviour of the system. Similarly for transient temperature measurement the geometry of the sensor and the heat transfer characteristics of the thermocouple or RTD must be considered.

In the case of transient measurement, calibration correction to the initially recorded value of the measurement will depend to a major extent on time related behaviour of the measurement itself; this considerably complicates the application of a calibration correction process.

It is desirable to design instrumentation which directly measures and faithfully responds to the measurand and in this way minimise the calibration corrections or inferred assumptions. However, in practice, limitation of resources and access to the engine can lead to many compromises but nevertheless valuable data can be obtained provided care is taken with data interpretation. All of these aspects will be discussed in greater detail in the sections related to each type of sensor.

2.6.3 Sampling in Space and Time

In some cases it may be adequate to investigate the local behaviour of a measurand or assume that the local measurement can be related to the steady state mean. However, where the area mean of fluid flow at an interface plane is required, an array of sensors will be necessary. In this case there arises the problem as to the number of sensors required to limit the uncertainty to the required level, the method of averaging, etc. Obviously the shape of the flow profile will have a significant influence and it should not be assumed that transient flow profiles are directly related to or similar in shape to the equivalent steady state profile.

Similarly, with geometric measurements, it may not be wise to assume uniform or symmetrical levels of displacement or lost motion. It may therefore be necessary to undertake measurements at an array of positions.

Sampling with respect to time is a fundamental requirement of any transient investigation. In some cases it may be necessary to merely establish which element in a sequence of events occurs first and may therefore be judged to be the fundamental cause of an instability. On the other hand more detailed information in the form of magnitudes, rates of change, etc will be required.

The objective and form of testing will have established the requirements of the data acquisition system and in particular whether analog or digital (or both) should be used. In the case of sequential sampling and digital recording, scanning sequences and rates must be chosen very carefully if a true representation is to be recorded. While the above comments have been addressing the recording phase of the investigation similar effects must be considered during the signal reconstruction and data analysis phase. Aspects of sampling in space and time are discussed further in Sections 3, 4, and 5.

2.6.4 Quality, Editing and Uncertainty

In any experimental measurement (or theoretical prediction) a degree of uncertainty will inevitably exist in the final results quoted. It is therefore necessary to attempt to quantify the uncertainty level and thus ensure that the quality of the measured results are adequate to meet the objectives of the programme. Whereas the methods of uncertainty analysis of steady state measurement have been firmly established (Reference 2.6), the corresponding methods for transient analysis are in their infancy. Section 3 of this report provides a discussion. As with all experimental data there will often be some unexplained recordings (i.e. outliers) and it is usually desirable that those values outside the uncertainty limits should be removed from the data base or replaced with an assumed value. This subject (outliers/editing) is discussed in Section 3.

2.7 DEFINED MEASUREMENT PROCESS

2.7.1 Introduction

It is the intention of this section to provide guidance and to outline a seque: :e for planning a test programme starting with the objective of the test through the selection of instrumentation and acquisition system, definition of test procedure to analysis of the results. It is particularly important in planning any programme that all phases and elements are considered and related to one another so that any weak links or excessive expenditure can be identified and eliminated. In the following four subsections 2.7.2 to 2.7.5 these aspects are discussed in more detail.

2.7.2 Objective of Tests

At the beginning of any investigation it is essential that the objective of the test be clearly defined and any limitations (e.g. resources, engine access or time scale) be identified. It is against these objectives and limitations that all following aspects of the test plan must be judged. Detailed consideration of the objective will then permit the definition of the measurements required, their range and type, the facility requirements, the instrumentation configuration, the accuracy of measurements necessary, the test procedure and data acquisition system and analysis methods etc. It may be, for example, that the transient testing forms part of a wider steady state programme. In this case it may be possible to select a sensor configuration which, while compromised, may be adequate to meet the objectives of the total programme.

2.7.3 Definition of Instrumentation and Acquisition System

Once the desired range and quality of measurements required has been established the instrumentation arrays and configuration in both the facility and test vehicle must be defined. Obviously the type of facility and its sophistication must be capable of meeting the test objectives and one in which "cell effects" are well understood.

In planning the instrumentation layout it is often not possible to make a direct measurement of the particular parameter required. In that case the data must be inferred from measurements of related parameters. Also it may be possible to derive the data using alternative procedures taking measurements from different sensors and often with recourse to the engine cycle mathematical model. Thus, particularly with transient experimentation, it will be necessary to carefully consider the possible alternatives in order to choose those which are most cost effective.

Included in instrumentation definition must be all aspects of data acquisition from sensor through transducer, signal conditioning, analogue to digital convertor, recording methods etc. Such aspects as sensor positioning and array, pressure and temperature ranges, frequency response and rise times, scan rates, calibration, etc., for the total measurement and data acquisition chain must be considered. Further discussion of the capabilities of the alternative forms of instrumentation and data acquisition is given in Section 4.

2.7.4 Definition of Test Procedures

The test procedure will obviously depend upon the type of testing being undertaken and the response expected from the vehicle under investigation. For example, when developing a new engine or system the test plan could be based on the known behaviour of previously tested vehicles. More often however transient tests are made to investigate a particular engine characteristic and in this case the test procedure can be planned around the known behaviour. So, because of the wide field included in transient testing, both aerodynamic and mechanical, it is not possible to summarise typical testing procedures. At this stage further requirements of the data acquisition procedure will become apparent, e.g. scan rates and repetition testing, if the transient event is to be properly captured. Finally, before committing to test, it is worth undertaking a pretest uncertainty analysis, as described in Section 3, in order to highlight any unforeseen deficiencies in the measurement system, testing procedure, including the proposed analysis methods.

2.7.5 Analysis

Analysis methods will vary widely depending on the test objective. They may be a simple reconstruction and display of the measurands, related to each other through a common time base, so that the sequence of events can be established. On the other hand quantified stability margins (eg surge margin) or rates of change may be required. Methods of handling the data (acquisition, processing and conversion to engineering units) are discussed in Section 4.9. The additional problems of editing data, interpreting arrays of sensors, or assessing profile effects when only a limited number of sensors are installed, are vital aspects of the analysis methods which are discussed in the following sections.

Also, as the final data analysis methods will be dependant on the test objective and they will have a significant impact on the overall measurement procedure, it is important that the final analysis methods adopted are considered in planning the programme and when undertaking a pre or post test uncertainty assessment.

2.8 REFERENCES

2.1 *Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components*, AGARD Advisory Report No. 245, June 1990.

2.2 Wantland, E.C., *Turbine Engine Operability Test and Evaluation Techniques*, AIAA-91-2277, 1991.

2.3 Aeronautical Recommended Practice, ARP 246B, (Aug 1 76) (RA Jul 91).

2.4 Aeronautical Recommended Practice, ARP 755A (April 15, 1974).

2.5 Lotter K. and Kurz, W., *Aerodynamic Aspects and Optimisation of Thrust reverser Systems*, AGARD-CP-150, 1974.

2.6 Abernethy, R.B. and Thompson, J.W. Jr., *Uncertainty in Gas Turbine Measurements*, USAF AEDC-TR-73-5 (AD-755356), February 1973 (Revised January 1980).

Table 2-1 Transient Engine Test Facilities

Facility	Advantages	Disadvantages
Ground level test bed	• Moderate Cost • Comprehensive instrumentation • Good DAS • Adequate for major part of test programme	• Real flight environment not possible
Altitude test facility	• Comprehensive instrumentation • Classic environmental condition can be created and measured • Good DAS • Can test beyond aircraft envelope	• High cost • Limited simulation of rate of change of environment possible • Difficult to maintain constant inlet & outlet conditions
Ground level in A/C	• Moderate cost • Real engine environment for static A/C	• Limited range of tests and conditions • Limited instrumentation • Difficult and limited DAS
Flying* test bed	• Moderate standard of instrumentation • Close to real environment • Moderate to good DAS	• High cost
Flight* test	• Real environment	• High cost • Difficult and limited DAS • Limited instrumentation

* Not considered in this text

DAS = data acquisition system
A/C = aircraft

Table 2-2 Examples of Ground Level Test Beds (GL) and Altitude Test Facilities (ATF) Suitable for Transient Testing - Typical Features

Facility	Type & Cell Dia.	Max Flow SL kg/sec	Environmental Control
NRCC Cell 5	GL 4.6 m	140	None
CEPr	GL 10.2 m	1200	None
TUAF Turkey	GL 10 x 7 m	-	None
NASA Lewis Cell PSC 3	ATF 7.3 m	340	1500 to 24400 m 0 to 3.0 Mach No
AEDC Cell T2	ATF 3.75 m	360	0 to 24000 m 0 to 3.0 Mach No
CEPr Cell R6	ATF 5.5 m	400	0 to 25000m 0 to 4.0 Mach No
RAE Cell 5	ATF 6.1 m	636	0 to 30500 m 0 to 3.5 Mach No

Table 2-3 Typical Measurement Requirements for Transient Test - Engine Developer (see also Table 2-4)

STN	DESCRIPTION	PRESSURE				TEMP		FLOW
		STEADY		TRANSIENT		STEADY	TRANS	
(See Fig.2.4-1)		P	PS	P	PS	T	T	
0	Ambient		4		4	4	4	
1	Intake-Airmeter	4	8	2	4			•
2	LP Face							
25	Hp Face	3	6	1	1	3	1	+Rake
13	Fan Outlet	3	6	1	1	3	1	
3	HP Outlet	3	6	1	1	3	1	
-	Bleed	1	1	1	1	1	1	•
4	Combustor Out							
45	HP Turb OUT	6	6	1	1			
5	LP Turb Out	3	6	1	3	6	1	
16	BP Duct Out	3	6	1	3	3	1	
7	Nozzle In							
8	Nozzle Throat							
9	Nozzle Out							
	Cell		4		4	4	4	
ADDITIONAL MEASUREMENTS NOT STATION ORIENTED								
	Fuel-Main		•		•	•	•	•
	Fuel - A/B		•		•	•	•	•
	Structure					•	•	
ADDITIONAL MEASUREMENTS NOT INVOLVING PRESSURE OR TEMPERATURE								
	Thrust	•		Shaft Torque				•
	N_1; N_2	•		Prop Pitch				•
	PLA	•		Power Offtake				•
	NPI	•		Displacement				•
	Vane Angle	•		Video				•

Notes:

- All measurements are recorded as a function of time
- Numbers refer to number of:-
  P, T, rakes (3 or 5 sensors per rake).
  PS, wall tappings
- •; measurement required.

Table 2-4 Examples of Typical Measurand Requirements

Test Objective	User	Typical Significant Transient Parameters[1]
All	All	N_L, N_H, P0, T0, Time, Pamb
Surge Margin Assessment e.g. (HPC by fuel spike) (Section 2.5.1)	Engine Developer	P25, PS3, T25, W_A, W_F, W_{bleed} vane angle, NPI, PLA, P_F
	Test agency	
	Certifier	Pass/Fail - throttle slam PS3, FN, vane angle bleed valve posn, video
	Operator	
Starting and relight (Envelope evaluation) (Section 2.5.2)	Engine Developer	P5, W_A, W_F, vane angle, W_{bleed}, P_F, NPI, PLA, FN, T5, LOD, video
	Test agency	
	Certifier	PLA, video, T5, NPI, P_F
	Operator	
After-burning ignition (Envelope evaluation) (Section 2.5.3)	Engine Developer	P5, W_A, W_F, W_{FAB}, P_F, NPI, PLA, T5, LOD, video
	Test agency	
	Certifier	PLA, NPI, video, LOD, P_F
	Operator	
Control system development (Section 2.5.4)	Engine developer	Dependent on type and problem - P, T, actuator position control system, electrical potentials, etc.
	Test agency	
	Certifier	
	Operator	
Thrust vectoring and reversal, include turboprops (Section 2.5.5)	Engine developer	FN, NPI, prop posn, torque, W_A, W_F, PLA, vane angle, LOD, video, T5
	Test agency	
	Certifier	As specified in operating manual.
	Operator	
Clearance and structural investigations, (Section 2.5.6)	Engine developer	Clearances, vane angles, actuator position, structure temps, X-ray, PLA
	Test agency	
	Certifier	Static and tear down inspection
	Operator	
Overhaul, pass-off, diagnostic, and acceleration tests. (Section 2.5.7)	Engine developer	FN, W_F, W_A, PLA, NPI, accel time, T5, clearance, video, tear down inspection.
	Test agency	
	Certifier	As specified in operating manual.
	Operator	

Notes:
1 Associated initial and final steady-state values also required
2 Sampling rate to be defined
3 Location and arrays of instrumentation see Figure 2-3, Table 2-3
4 PLA = Power lever angle
5 NPI = Nozzle position indicator
6 LOD = Light off detector
7 Video = Camera viewing exhaust nozzle and A/B.

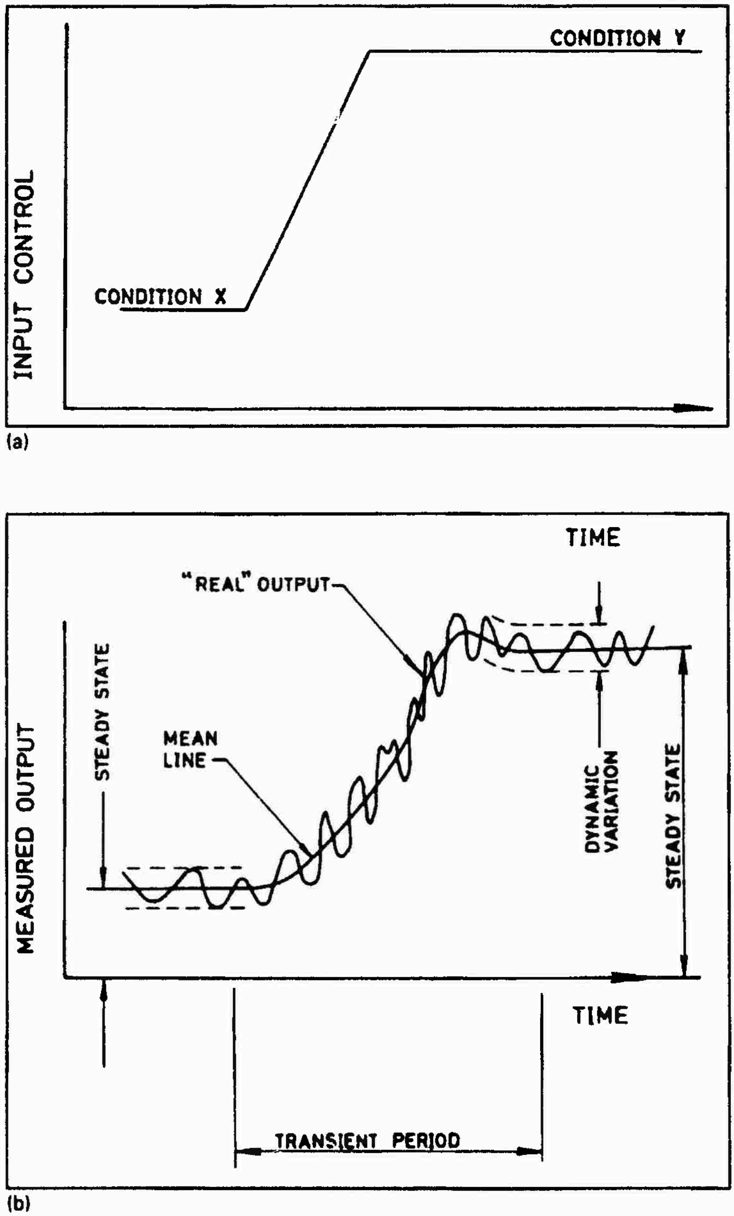


Figure 2.1 Illustration of Steady State, Transient & Dynamic Conditions

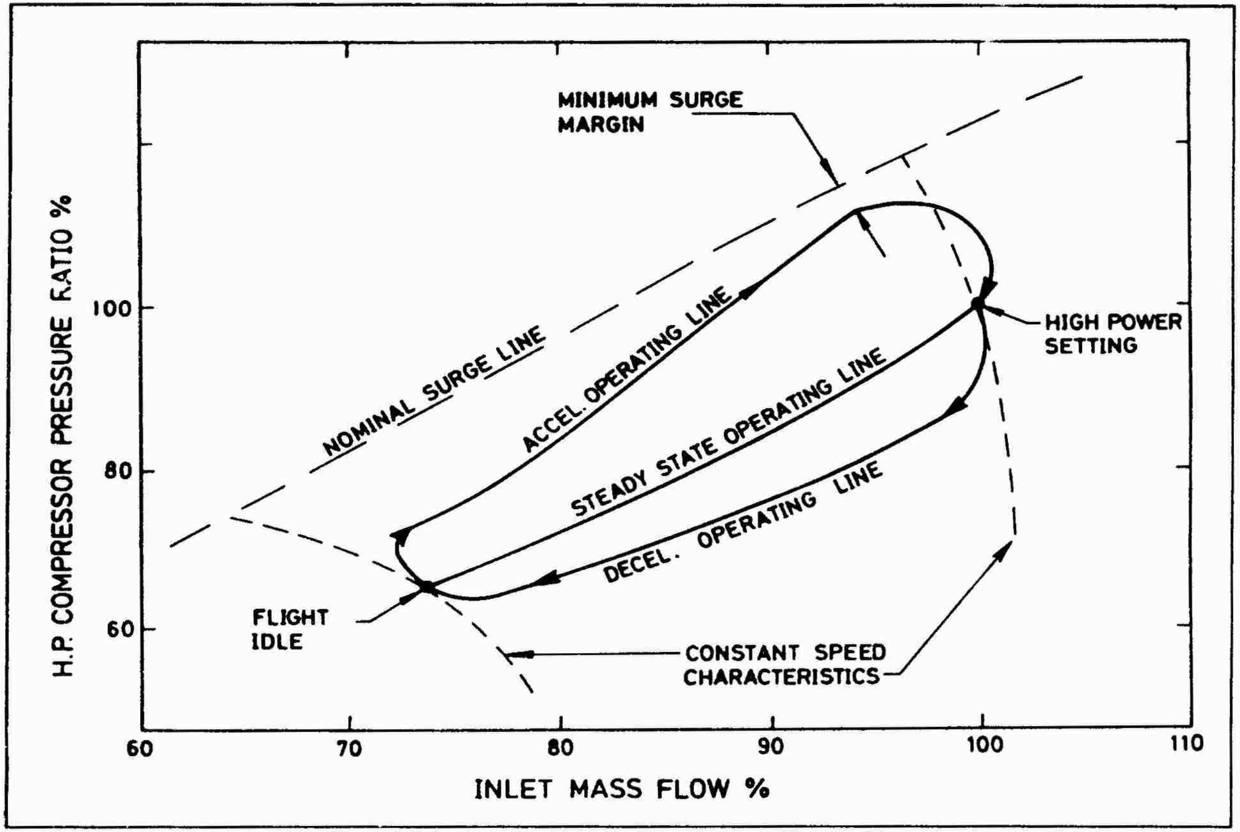


Figure 2-2 Typical Transients for HP Compressor Working Lines

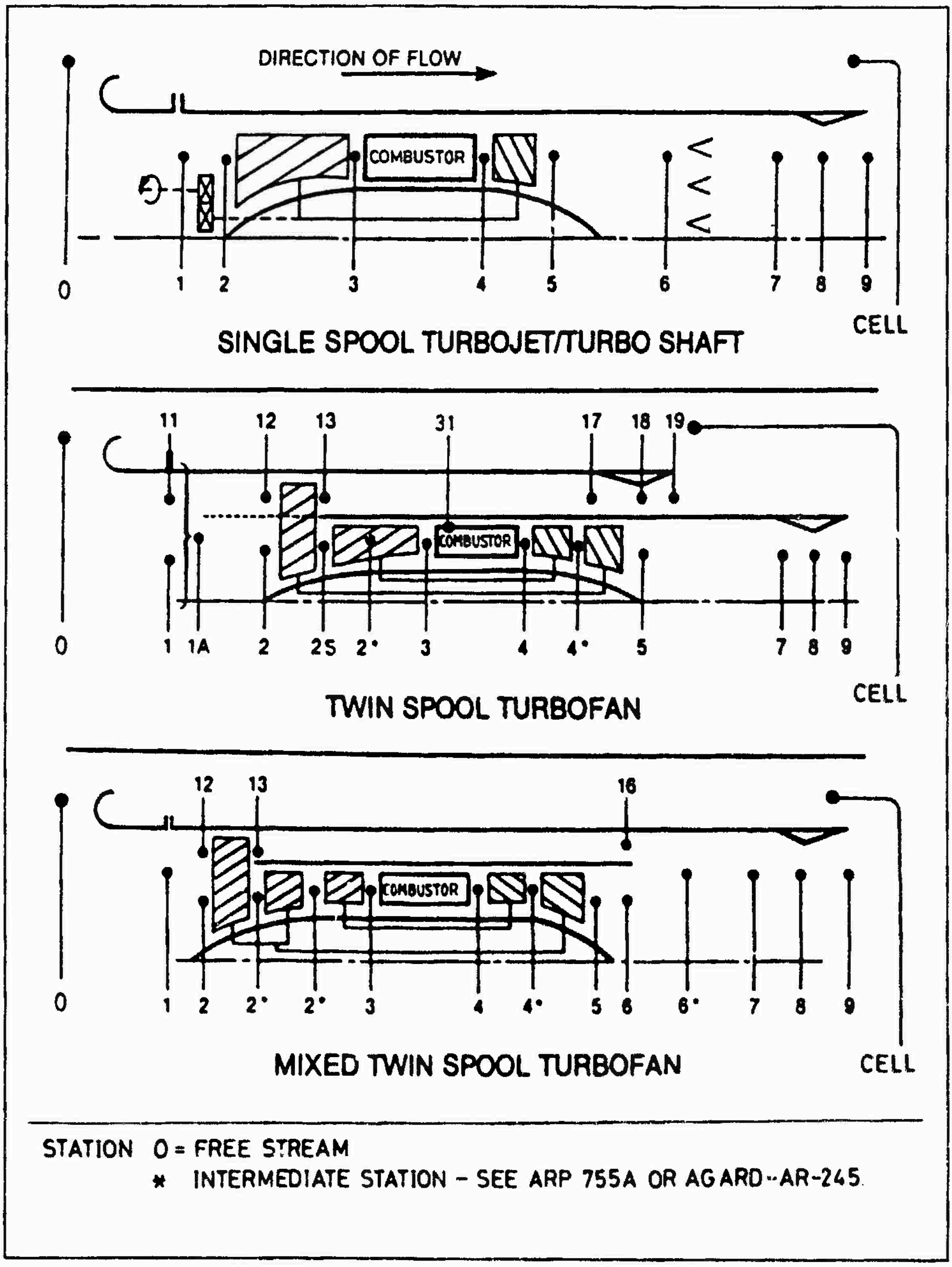
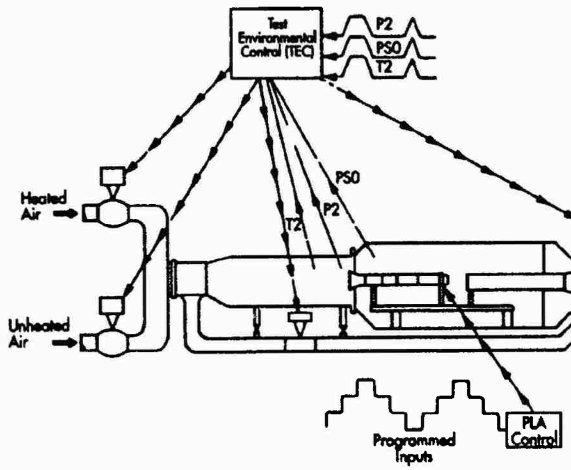


Figure 2-3 Recommended Engine Station Identification for Various Configurations



Features:

- Heated and Unheated Air Supply
- Throttlable Inlet and Exhaust Airflow Control Valves
- Throttlable Bypass Airflow Valve

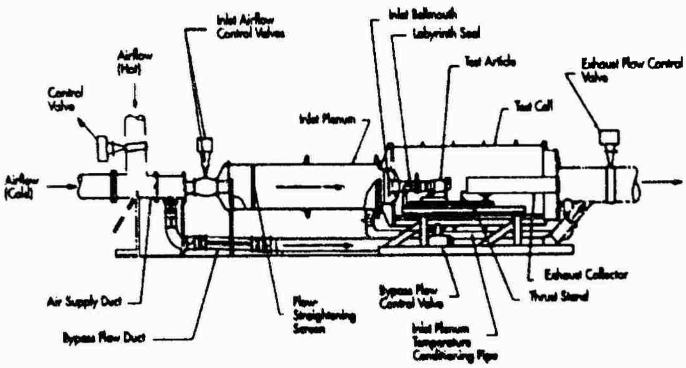


Figure 2-4 Optimal ATF Configuration for Simulation of Flight Transients

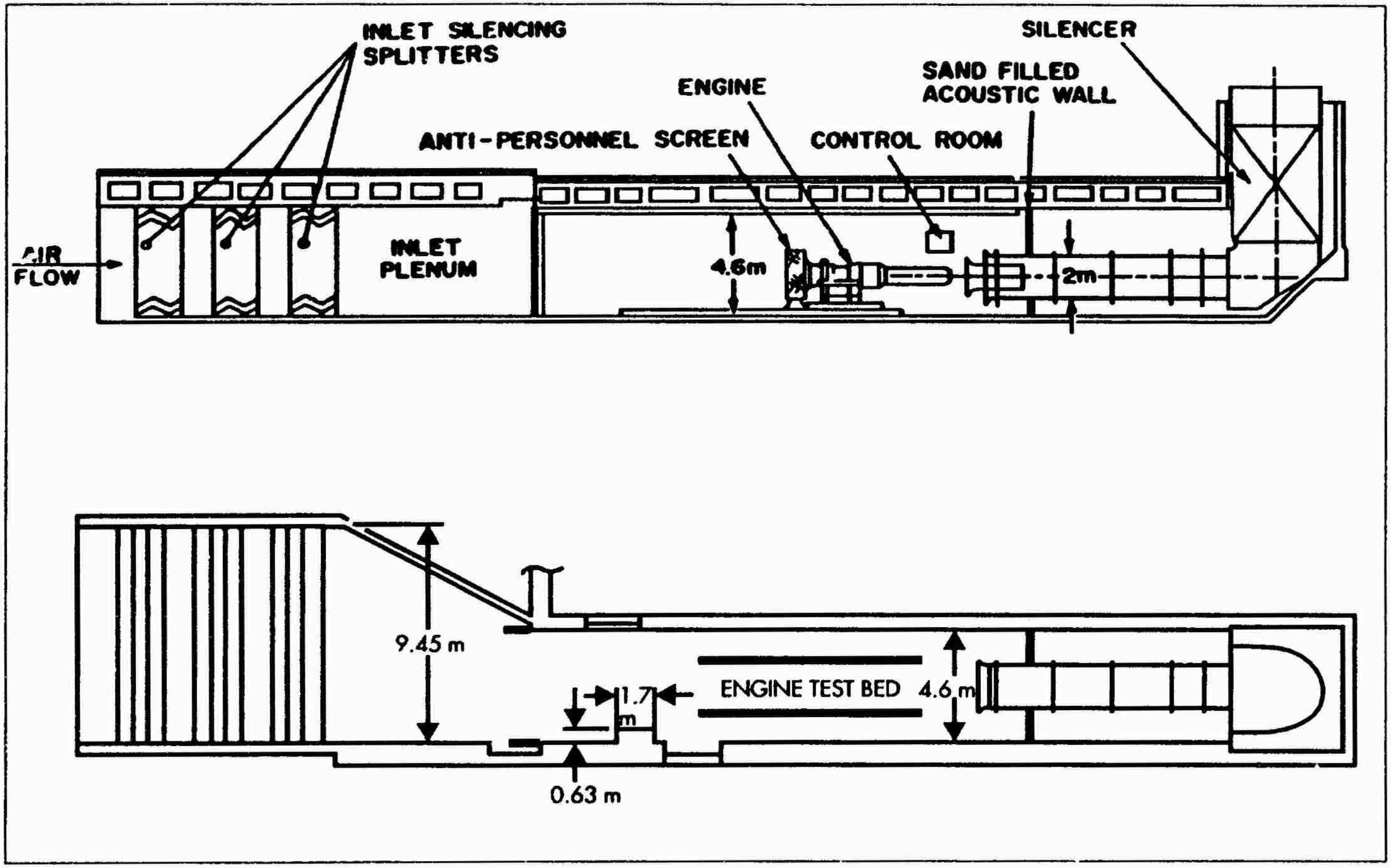


Figure 2-5 Ground Level Test Cell

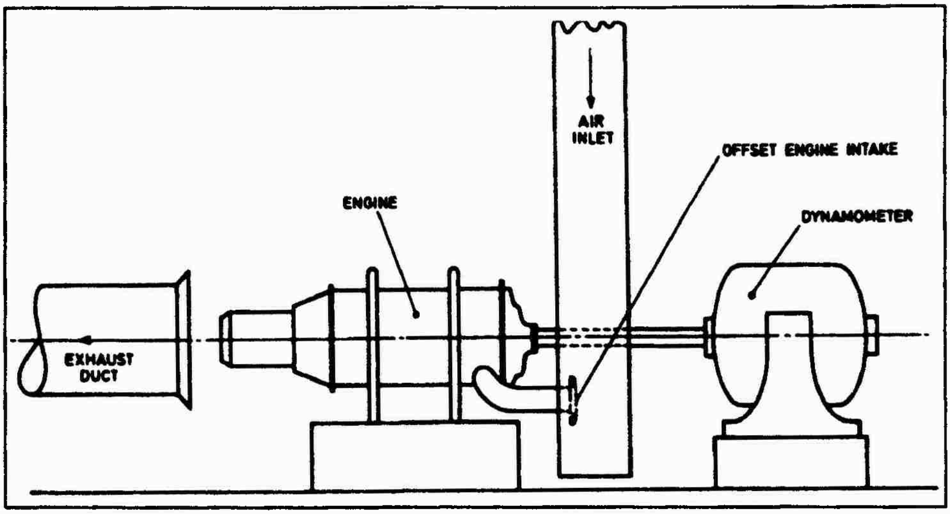


Figure 2-6 Small Turboshaft Engine Test Cell

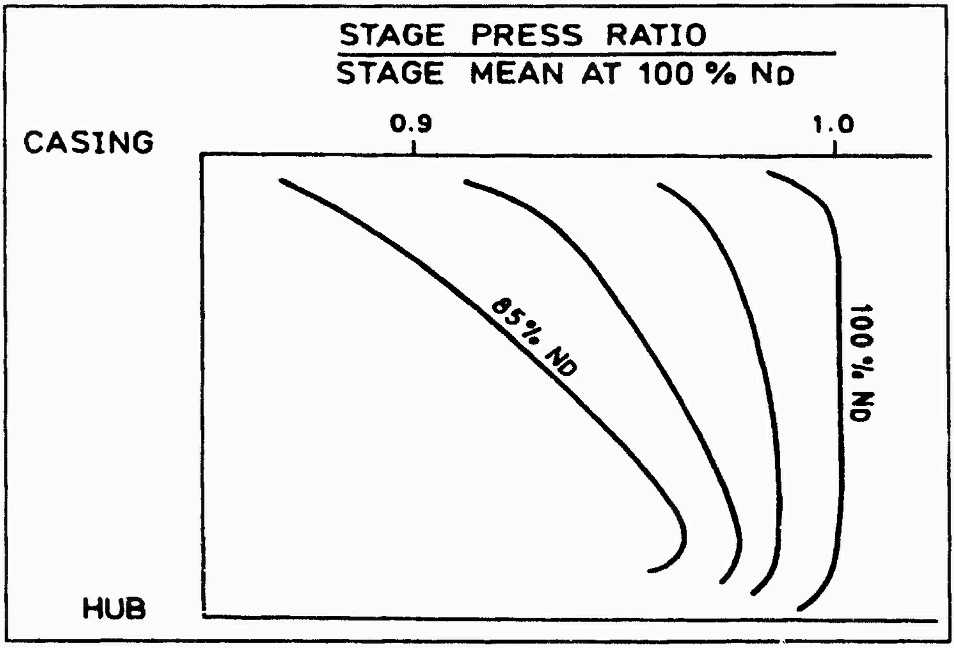


Figure 2-7 Variation of Last Stage Pressure Ratio on Working Line of 3 Stage Fan (Steady State)

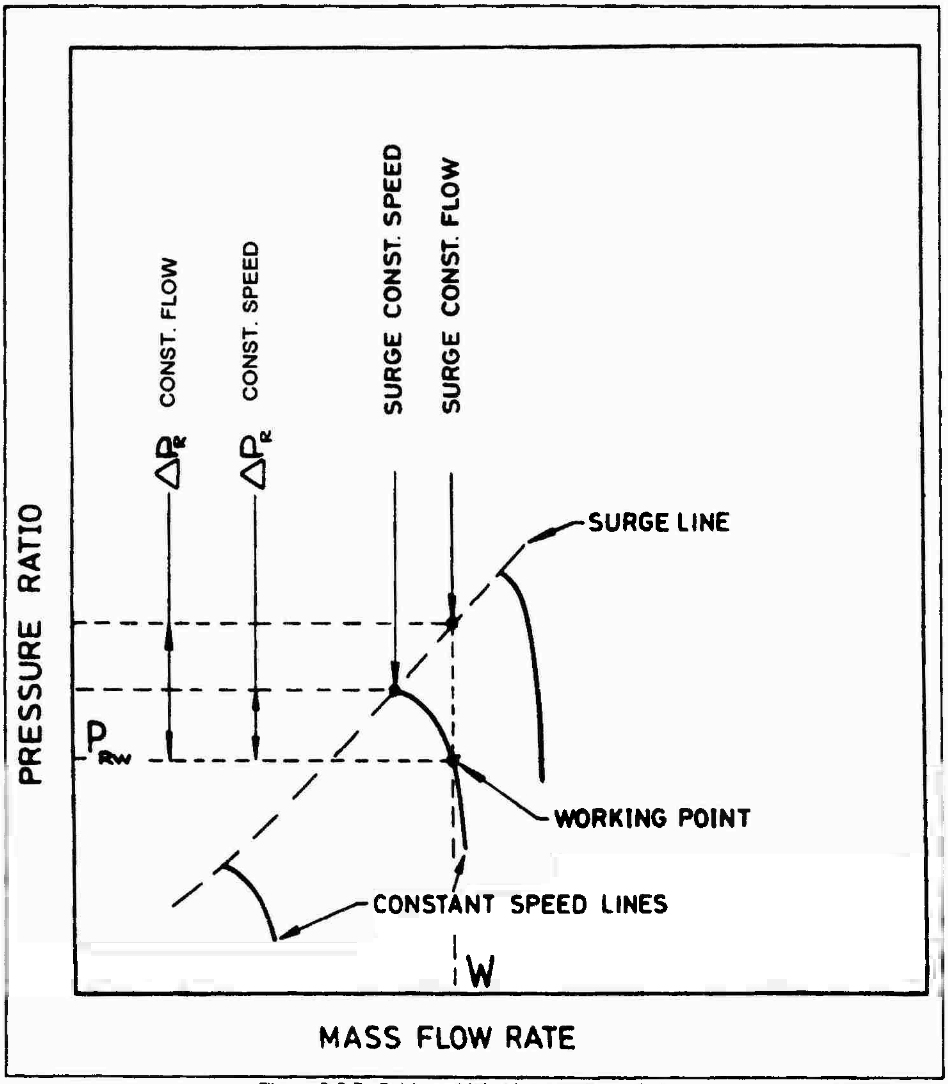


Figure 2-8 Definition of Working and Surge Points

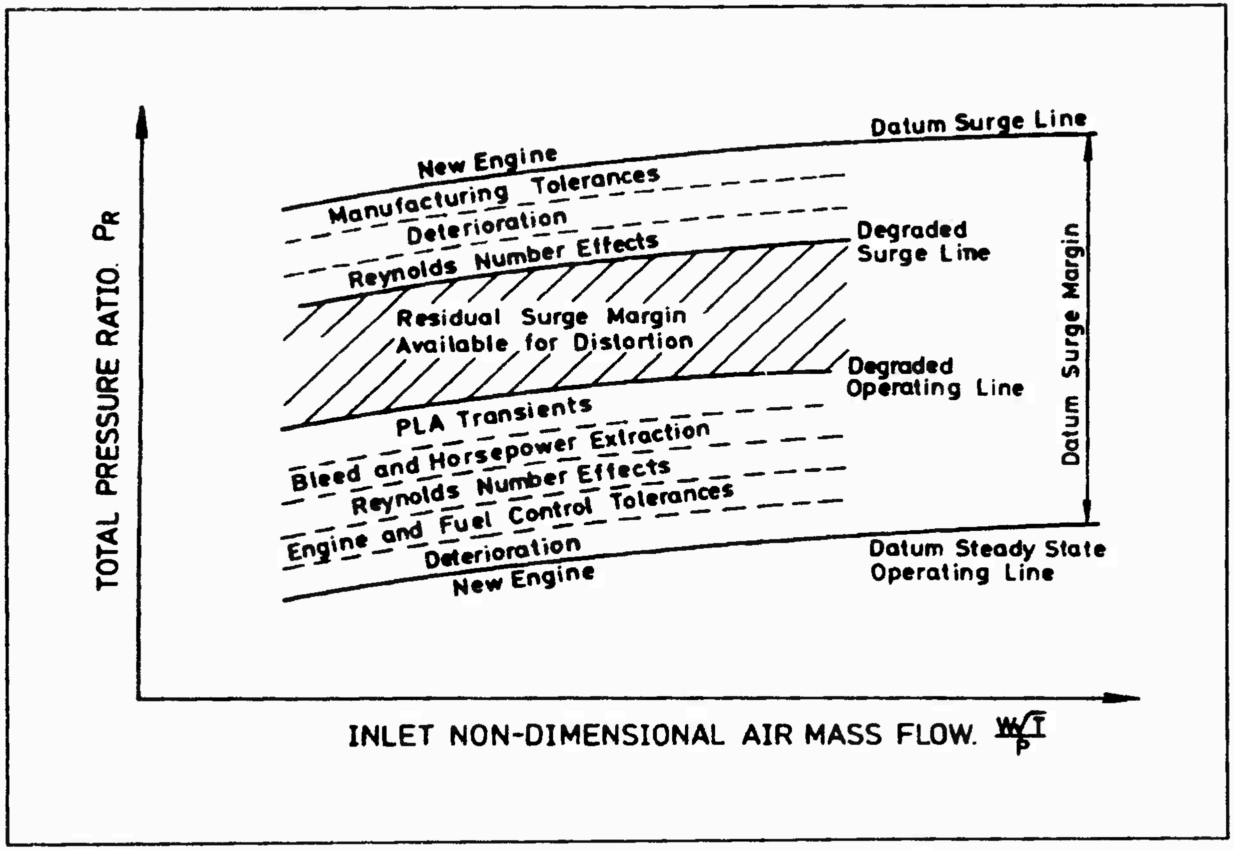


Figure 2-9 Compressor Surge Margin Degradation

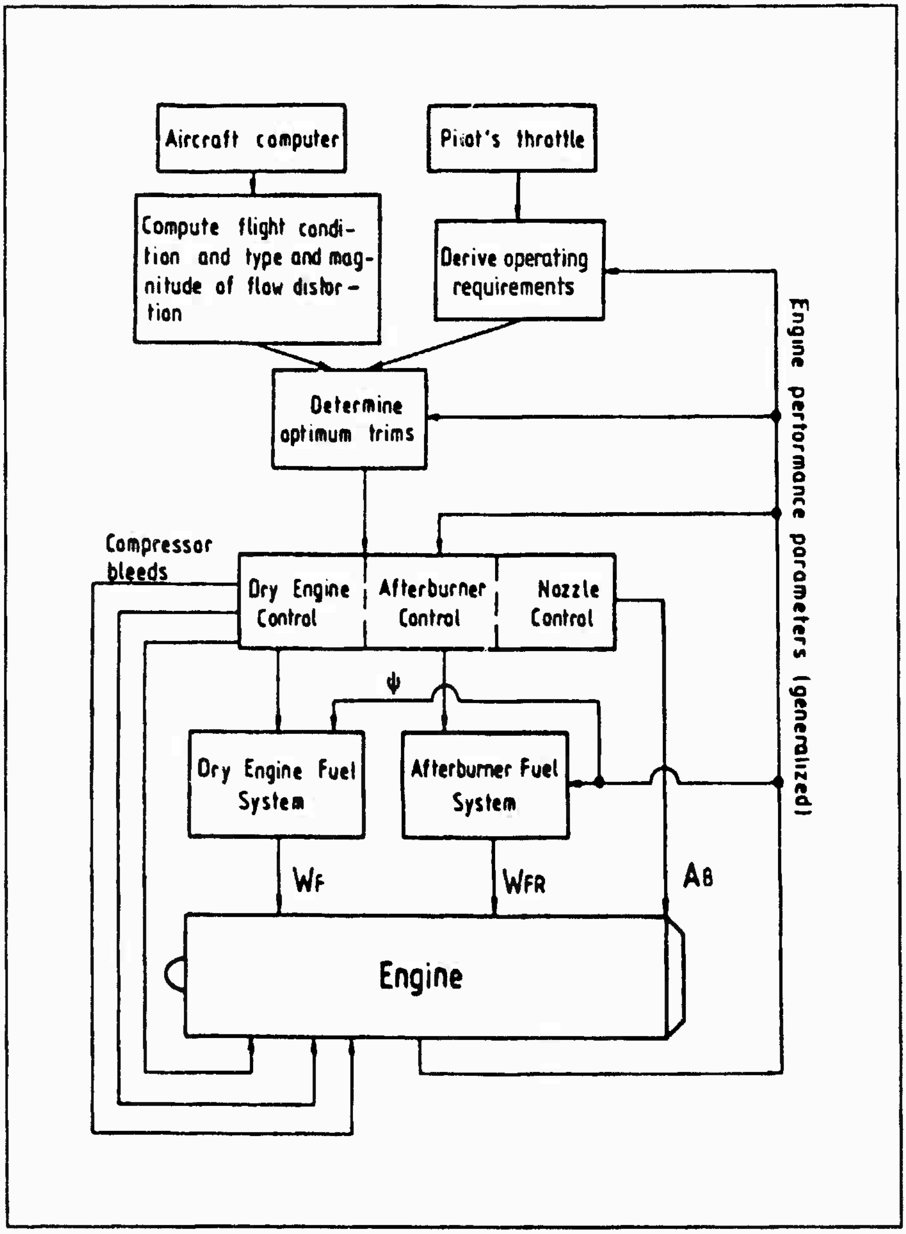


Figure 2-10 Outline of Engine Control System

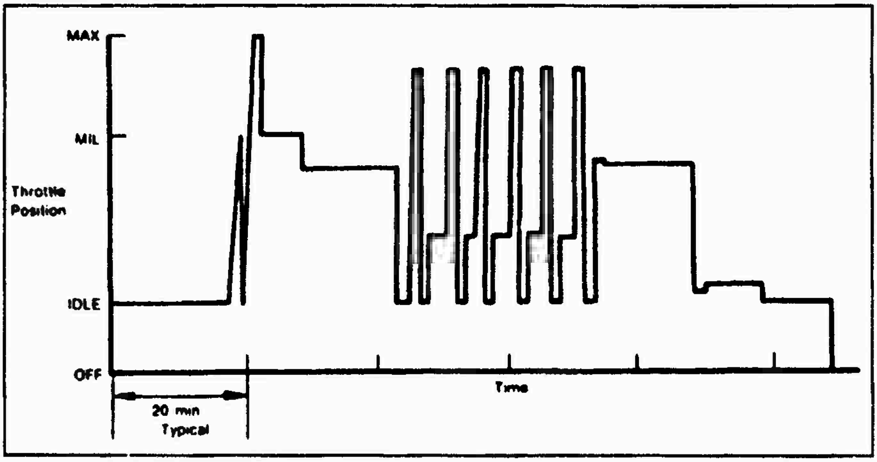


Figure 2-11 Typical Fighter Air Combat Duty Cycle

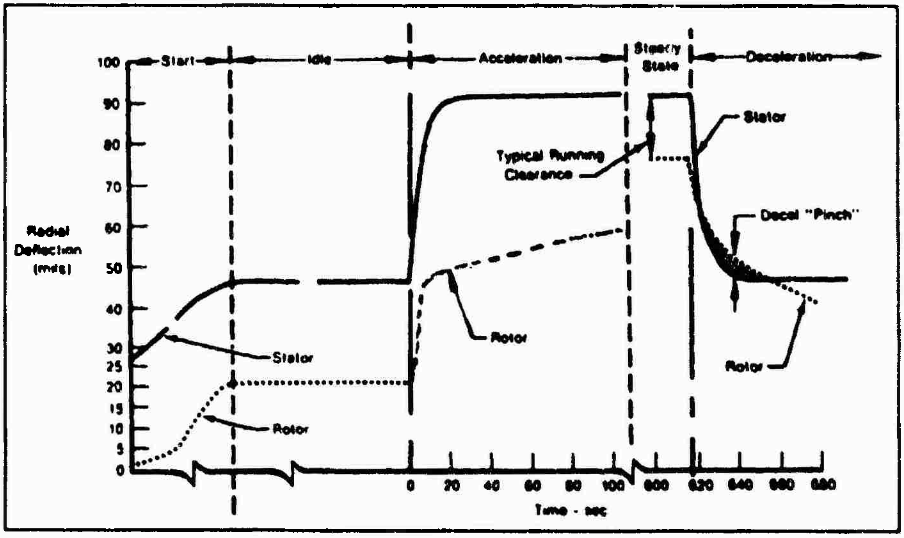


Figure 2-12 Transient Radial Clearances for High Compressor

3. MEASUREMENT UNCERTAINTY[1]

3.1 INTRODUCTION

The estimation of uncertainty is an essential part of all measurements since it guides the interpretation of results and reduces the chance of confusing real results with random error or experimental bias. A pretest estimate of uncertainty is an important step in test planning because it identifies the most significant sources of error in the plann ' measurements and therefore provides a tool for judgi:g whether or not the the required measurement accuracy can be achieved and the test objectives met. When improvements are ne ded, it shows which components of the test system are in most need of improvement and which are adequate as they are. Posttest analysis of uncertainty is used to validate the pretest estimates and plays a key role in maintaining the quality of the test process. In this document we will concentrate on applying uncertainty estimation to transient measurements.

A general method for estimating measurement uncertainty has been developed by Abernethy and Ringhiser in the U.S.A. (Reference 3.1), Ascough in the United Kingdom, and others, which provides a systematic procedure, grounded in statistical principles, for estimating measurement uncertainty. This method has been finding increasing acceptance by professional organizations such as the ISA, ASME, SAE, and ISO and has been applied in standards setting documents (References 3.2, 3.3, 3.4, 3.5). It has also been applied in specific test programs such as the Uniform Engine Testing Program sponsored by the NATO AGARD Working Group 15 (Propulsion and Energetics Panel) (Reference 3.6) and in AGARD Advisory Reports (e.g., Reference 3.7). The method continues to evolve under the sponsorship of national standards laboratories and professional organizations with active committees of both ISO and ANSI/ASME now working on its development (References 3.4 and 3.8).

Two areas in which the method continues to develop are of particular concern in this document. The first deals with the question, presented by many if not most measurement processes, in which the defined measurement result requires one measured quantity to be plotted as a function of another measured quantity both of which are subject to measurement error. Current approaches to combining these errors to get total uncertainty are described below. The second area involves the definition of bias and precision errors and the differentiation of statistically based error estimates from those derived by other means. This also is briefly covered below.

In the past, the method has been applied to "steady state" measurements, that is, to measurements in which the test vehicle is held at a fixed operating point and the measured quantities are time independent or, more precisely, the average values of the measured quantities are time independent.

This document is concerned with transient measurements in gas turbines This includes the measurement of acceleration and deceleration times, transient trajectories on component maps, compressor surge margin, etc. as described in Section 2 above. All of these tests require measurement of quantities which vary in time.

In this discussion, transient measurements are defined as measurements made during transient conditions (as defined in Section 1.3). The measurement objective may be to determine the time dependence of the measured quantity, to determine the peak value of the measured quantity, or to correlate two or more quantities in time as for example when determining the ratio of two pressures at the time of stall.

The time dependence of the measured quantities are functions of the transient behavior of the gas turbine system in response to a dynamic input such as a throttle movement. In addition, the measured results are affected by the time dependent response of the measuring systems. The measuring system must be fast enough to accurately record the transient gas turbine performance parameters of interest to the experimenter but not so fast as to either compromise the rejection of electrical or aerodynamic "noise" or to excessively

[1] Figures begin page 3-18

complicate the data acquisition system and the data reduction process.

Because of the importance of the system time response, the most critical feature in designing and using transient measurement systems is the selection of an appropriate bandwidth, or low-pass or high-pass cutoff frequencies, and the related filter characteristics and sampling rates which are compatible with the test objectives. This requires careful agreement between the experimenter and the user of the test data to ensure that all the useful data has dynamic characteristics which, for example, fall below the low-pass cutoff frequency, and that all information above that frequency can be rejected and that no significant time, amplitude, or phase distortion of the transient signal occurs.

The remainder of this section will describe the application of measurement uncertainty methodology to transient measurements.

3.2 OVERVIEW OF CONCEPTS AND DEFINITIONS

In this section the principles of measurement uncertainty estimation are summarized. The first section describes the general method and includes a review of the application of the method to time-independent (steady state) primary, derived and inferred measurements and also to functionally related measurements. Section 3.3 describes the extension of these methods to measurands that are functions of time.

The "Uncertainty of a Measurement" is defined by the ISO as "an estimate characterizing the range of values within which the true value of a measurand lies" (Reference 3.2). An alternative definition is, "the maximum error which might reasonably be expected for the Defined Measurement Process."

The basic concept underlying uncertainty methodology is illustrated in Figure 3-1. The frequency of occurrence of a given value of a measured quantity in a series of well controlled tests will tend to be normally distributed about some average value. The standard deviation (σ) about that value is approximated, for a finite number of tests, by calculating the precision index (s).

The average value measured does not in general coincide with the true value because of systematic errors that are always present in measuring systems. The aggregate of these systematic errors is termed bias (Figure 3-1). The true value of the measured quantity can never be known unambiguously. At best, a range can be estimated within which the true value would be expected to lie. The uncertainty analysis is carried out by carefully and completely defining the measurement process in such a way that the measurement can be traced back to well defined standards. This traceability path is not always straightforward but it is important that it includes all significant sources of error. For example, there is no general standard for the aerodynamic quantity, total temperature or stagnation temperature. It is generally measured with a thermocouple probe and, while a clear traceability path to international standards can be established for the thermocouple wire calibration, the thermocouple junction cannot be expected to read the stagnation temperature of the high velocity gas stream because of recovery, radiation, and conduction corrections. These corrections are usually obtained by a combination of additional calibrations and analytical corrections which must be included in the uncertainty analysis (see Section 4.3.1).

In the process of uncertainty analysis it is important to maintain the distinction between random (or <u>precision</u>) errors and systematic (or <u>bias</u>) errors. One practical reason for this is that while repetition of the same experiment can reduce the total precision error, it does not reduce the bias. It is useful in addition to distinguish between error source estimates which are based on statistical analysis of experimental data, such as calibration records of thermocouple wire, and estimates which are based on a combination of judgement and analysis such as is most often the case with thermocouple conduction and radiation corrections, and will also be the case with many of the transient uncertainty terms described in this document. Statistically derived error estimates are sometimes called type A errors and other error estimates type B errors (Reference 3.8). Again, as a practical matter, the need for this distinction becomes obvious when setting up an uncertainty analysis because some error sources may be judged to be very important even though little or no experimental data may be either available or obtainable. The appropriate methods for combining A and B type errors are still under development by standards setting organizations (References 3.4 and 3.8). In this document it is assumed that precision and bias estimates of either type can be treated equally in the combining equations, 3-1 and 3-2, described below.

The steps required to carry out an uncertainty analysis must begin early in the test planning and proceed generally as follows:

(a) Study the test objectives and define very specifically the experimental results required to satisfy the test objectives.

(b) Define test procedures and test vehicle requirements.

(c) Define the measurements required and analyze the formulae and data reduction procedures whereby the measurements will be used to obtain the defined test result.

(d) Select and evaluate the measurement systems and for each system make a complete list of error sources including calibration errors, data acquisition errors, data reduction errors and any other errors of method which might affect the measurement. Tabulations of error sources for all the measurements covered in this document are included in the parts of Section 4 dealing with each measurement type.

(e) Estimate each error term and classify them into two categories depending on whether the error would be expected to remain fixed or to vary at random during the Defined Measurement Process. The magnitudes of the estimated errors should, insofar as possible, be based on actual data such as statistical analysis of calibration records or least count of analogue to digital converters (ADCs) (type A errors). Less desirable but also useable are the accuracy specifications of the instrument manufacturer. These may be statistically based but should be treated as type B errors unless the instrument is being used in an environment which is very close to that in which its calibration history was developed. Less desirable also are estimates based on a combination of analysis and judgement as mentioned above, however such estimates must be included if they are judged to be significant. Without their inclusion the uncertainty estimate will lack plausibility and may be quite misleading.

The categories of error used in the current methodology have the following general explanations:

(i) *Calibration Error*

Errors which arise at each step of the calibration hierarchy which establishes the traceability of the working sensor and the data acquisition equipment through working standards and laboratory standards to the national standards institution. The thermocouples (or RTDs) and pressure transducers in aerodynamic probes are traceable in this way.

(ii) *Data Acquisition Error*

Errors which arise from the data acquisition system, that is from voltmeter, signal conditioners, A/D converters, recording devices, etc.

(iii) *Data Reduction Error*

Errors arising from sources such as calibration curve fits, computer resolution, approximations in math models, computational models for obtaining station average values from samples in space and time, etc.

(iv) *Errors of Method*

This category covers error sources which do not fit obviously into the above three categories. The important thing will be to identify all significant sources of error and then to describe how estimates can be made of the magnitude of this error. Some examples of errors of method are errors arising from the use of particular probe and rake designs or from the test vehicle, test facility, or their environment such as described below:

Probe Errors - uncertainty in radiation and conduction corrections, static pressure correction, blockage, streamline distortion, response to unsteadiness, errors due to limited spatial sampling, etc. These errors can not ordinarily be obtained from calibration data but are instead estimated by various means.

Test Vehicle Errors - uncertainty in the operating condition, speed control, blade tip clearance, vane angle settings, manufacturing tolerances for the specific hardware used in the test, etc.

Test Facility Errors - uncertainty in inlet flow profiles, duct area, leakage, bleed flow, etc.

For each error source, a "bias" and "precision" must be assigned which are measures of the uncertainty arising from that source.

The consideration of test vehicle and facility error sources is very important in the testing of gas turbine engines. One must keep in mind that all measurements reflect a reality about a specific, unique test set up. Ordinarily this test set up is intended to represent a generalized system, design or apparatus but, since any given test set up only approximates the generalized system, errors can arise in interpreting the test results. The magnitude of these errors can be determined by including in the defined test process steps such as: repetitions with different hardware built to the same design, repetitions in different facilities and repetitions with similar procedures.

3.2.1 The Uncertainty of Primary Measurements

As explained in Section 4.1.7, measurements can be divided into three classes, (i) primary measurements, (ii) measurements which are derived from two or more primary measurements, and (iii) inferred measurements which are calculated using primary or derived values as inputs. For primary measurements, the magnitude of the individual errors contributing to that measurement are estimated and combined to form an overall uncertainty estimate. At present, the two recommended methods for combining the individual errors are:

$$UADD = \pm\left[B + t_{95}\frac{S}{\sqrt{N}}\right] = \pm\sqrt{\Sigma b_i^2} \pm \frac{t_{95}\sqrt{\Sigma(s_i^2)}}{\sqrt{N}} \qquad 3\text{-}1$$

or

$$URSS = \pm\sqrt{B^2 + \left(\frac{t_{95}S}{\sqrt{N}}\right)^2} = \pm\sqrt{\Sigma(b_i^2) + \left(\frac{t_{95}\sqrt{\Sigma s_i^2}}{\sqrt{N}}\right)^2} \qquad 3\text{-}2$$

where
- b_i = bias, the fixed or systematic error associated with the ith error source.
- B = $(\Sigma(b_i)^2)^{1/2}$ = Total Bias Error.
- s_i = estimate of the standard deviation of the random error associated with the ith error source (also called the precision index).
- S = $(\Sigma(s_i)^2)^{1/2}$ = Total Precision Error
- N = number of repetitions of the defined measurement process. (Note: this is not the number of measurements used to determine s, see t_{95} below and Glossary.)
- t_{95} = parameter defining the 95th percentile point of the Student's "t" distribution. The value of t_{95} depends on the sample sizes used to estimate the S. If all sample sizes were 30 or more, t_{95} can be set = 2.0. If various smaller sample sizes were used to estimate the S, then the Welch-Satterthwaite method (Reference 3.7) must be used to determine t_{95}. For small sample sizes t_{95} is greater than 2.0 and the estimated uncertainty, as calculated from Equations 3-1 and 3-2, is increased.

If b_i or s_i are not statistically based then it is common practice to assume that the degrees of freedom are equal to or greater than 30 and use $t_{95} = 2.0$.

The interpretation of the quantities UADD and URSS has been studied by Abernethy (Reference 3.1) using Monte Carlo methods and is as follows:

UADD = 99 percent of the time the true value is expected to lie within plus or minus UADD of the measured value.

URSS = 95 percent of the time the true value is expected to lie within plus or minus URSS of the measured value.

The ranges, plus or minus UADD or plus or minus URSS, are frequently referred to as confidence intervals at the 99 percent or 95 percent level. They are also said to provide 99 percent or 95 percent "coverage" of the true value. The range of uncertainty to be expected as the result of a measurement process in which there are N repetitions is illustrated in Figure 3-2.

The "true value" resulting from a defined measurement process is expected to be within the total uncertainty interval shown. Note that if the bias is not symmetric it is necessary to estimate the positive bias B+ and negative bias B- separately. Also since the number of repetitions N serve only to reduce the precision error portion of the total uncertainty, and because gas turbine testing is costly, N is usually a small number, often just 1 in transient testing.

3.2.2 The Uncertainty of Derived and Inferred Measurements

Where a final result is derived from two or more individual measurements, the uncertainty of the primary measurements can be combined into an overall uncertainty by the methods of error propagation (Reference 3.7). For example, a pressure ratio might be derived from two pressure measurements or a station average might be derived as the weighted average of an array of point measurements. In an inferred measurement, the result is obtained from complex analytical models using the primary measurements as inputs. The error propagation method in either case is based on use of the first derivative terms in a Taylor's series expansion of the derived quantity and the assumption that the uncertainty of the elemental measurements are mutually independent. Detailed justification of the method is given in Appendix B of Reference 3.7.

Summarizing the result, if Y is derived or inferred from several primary measurands, M_1, M_2 ...M_n, then,

$$Y = Y(M_1, M_2, \ldots M_n) \qquad \text{3-3A}$$

The precision and bias error in Y is estimated from the errors in the primary measurands as follows;

$$S_Y = \sqrt{\sum_{i=1}^{n} \left(S_{Mi} \frac{\partial Y}{\partial M_i}\right)^2} \qquad \text{3-3B}$$

and

$$B_Y = \sqrt{\sum_{i=1}^{n} \left(B_{Mi} \frac{\partial Y}{\partial M_i}\right)^2} \qquad \text{3-3C}$$

where S_{Mi} = Precision error in measurand M_i,
B_{Mi} = Bias error in measurand M_i,
$\partial Y/\partial M_i$ = Influence coefficient of M_i on Y.

In the case in which two or more of the measurands share common, nonindependent error sources, these error sources must be treated separately by direct substitution in the equation for Y, (Equation 3-3A). For example, if a differential pressure is derived from two measured pressures, P_1 and P_2 and there is a common bias error term, B_C, in both due to the fact that the transducers for the two measurements have a common reference, then the measured differential pressure, ΔP is:

$$\Delta P = (P_2 + B_C) - (P_1 + B_C) = P_2 - P_1 \qquad \text{3-3D}$$

and the common bias term contributes nothing to the total error.

In deriving an average pressure from two measured pressures:

$$P = \frac{(P_1+B_C)+(P_2+B_C)}{2} = \frac{P_1+P_2}{2} + B_C \qquad \text{3-3E}$$

and the common bias term contributes a bias equal to B_C to the total error.

For a ratio of two pressures, P_R:

$$P_R = \frac{P_2 + B_C}{P_1 + B_C} \qquad \text{3-3F}$$

and the contribution of the common bias depends on the relative magnitudes of the measured pressures.

In the general case for derived or inferred measurements, identify and determine the effects of the common error terms first by direct substitution as above and then propagate the errors from all the independent error sources using equations 3-3B and 3-3C.

When the error sources are independent, the method can be illustrated by the following example - assume the objective of the measurement process is to measure two pressures P_1 and P_2 and determine their ratio P_R.

$$P_R = P_2/P_1 \qquad \text{3-4}$$

Using Equations 3-3B and 3-3C, the precision index for P_R is then derived from the precision indices for each of the primary measurements as follows;

$$S_{P_R} = \sqrt{\left(\frac{\partial P_R}{\partial P_1} S_{P_1}\right)^2 + \left(\frac{\partial P_R}{\partial P_2} S_{P_2}\right)^2} \qquad \text{3-5}$$

and the bias for P_R is;

$$B_{P_R} = \sqrt{\left(\frac{\partial P_R}{\partial P_1} B_{P_1}\right)^2 + \left(\frac{\partial P_R}{\partial P_2} B_{P_2}\right)^2} \qquad \text{3-6}$$

where

S_{P1} , S_{P2} = total precision index for pressure measurements 1 and 2,

B_{P1} , B_{P2} = total bias for pressure measurements 1 and 2,

$$\frac{\partial P_R}{\partial P_1} = \left(\frac{P_2}{P_1}\right)^2$$ = influence coefficient for P_1

$$\frac{\partial P_R}{\partial P_2} = \frac{1}{P_1}$$ = influence coefficient for P_2

The above process produces a pretest prediction of the uncertainty. Once the test is completed, this should be compared with a post test analysis of uncertainty. The post test analysis evaluates the scatter in a sequence of measured results and compares this with the pretest prediction of precision. If good agreement is obtained one can be reasonably sure that all error sources affecting the precision of the test have been accounted for.

Post test analysis of data does not however yield any information about the pretest bias prediction. Although the bias with respect to the "true" value can never be known, it is possible, once agreement has been obtained between pre-and post-test precision in a given facility, to test bias differences between different facilities (Reference 3.6), between altitude and sea level tests, and between results obtained in individual component tests versus results obtained with the same component in a full engine. Each of these tests for bias would require an uncertainty analysis based on a carefully defined measurement process and mathematical model as outlined above.

In general, systematic error information can be obtained in practice via the following approaches (Reference 3.2):

(a) Interlaboratory or interfacility tests make it possible to obtain the distribution of systematic errors between facilities.

(b) Comparison of independent measurements that depend on different principles can provide systematic error information. For example, in a gas turbine test, airflow can be measured with (1) an orifice, (2) a bellmouth nozzle, (3) compressor speed-flow rig data, (4) turbine flow parameters, and (5) jet nozzle calibrations. As another example, the efficiency of a turbine component can be measured by determining the real versus ideal gas properties at the inlet and exit or by measuring shaft work (torque and speed) and the enthalpy change per unit time of the gas (i.e. mass flow and temperature change).

(c) When it is known that a systematic error results from a particular cause, calibrations may be performed allowing the cause to vary through its complete range to determine the range of systematic error.

(d) When none of the above are available, bias must be estimated by experienced experimenters.

3.2.3 Estimating the Uncertainty of Two Functionally Related Measurements

A very common test objective requires the measurement of two functionally related quantities each of which is subject to measurement error. Two examples which are covered in Section 5 of this document are, nozzle position versus time and stall pressure ratio versus air flow. The defined measurement result is a plot of the measured quantity Y versus the measured quantity X. A "best fit" is then obtained to the data using regression analysis or some similar fitting procedure. The relationship of this plot to the "true" value is shown in Figure 3-3. When there is uncertainty in both X and Y, the problem of estimating total bias in Y, (B_Y $)_{Total}$ becomes more complex. Methods have been developed for using the estimated uncertainties in X and Y as weighting factors in the fitting procedure (Reference 3.10). In these procedures, the total bias in the curve fit at the j_{th} experimental point is defined as:

$$(B_Y)_{Total} = \sqrt{\left[\left(\left|\frac{\partial Y}{\partial X}\right|_j\right) B_X\right]^2 + B_Y^{\,2}} \qquad 3\text{-}7$$

The weighted fitting procedures are designed to minimize this error over the whole curve fit. As can be seen, the total bias error in Y includes the experimental bias in the Y measurement itself but also a term which depends on the bias in X and the local slope of Y vs X. For any curve fit and in general for any defined test result in which one measurement is to be plotted against another, one must take into account the interaction between the uncertainties of the two measured quantities. This additional error, sometimes called "curve slope" error can be estimated using Equation 3-7 for primary measurements which have no common error sources. When the measurements are derived or inferred this expression must be extended as follows (Reference 3-10):

Consider Figure 3-4. To illustrate the effect of bias error, we can construct a rectangle around each point on the curve fit with the dimensions of the bias errors in X and Y. We can see immediately that the magnitude of the effect will depend on the slope of Y vs X and on the magnitudes and signs of B_X and B_Y. If X and Y have no common primary parameters, positive and negative biases are equally likely and the total error can again be found by root sum square (Equation 3-7). If they do have common parameters, the approach developed by Price (Reference 3.10) must be used as follows:

The general expression for the total bias in Y caused by a primary measurand, Mi, is:

$$B_{Y,Mi} = B_{Mi}\left[\frac{\partial Y}{\partial Mi}\right] - B_{Mi}\left[\frac{\partial X}{\partial Mi}\right]\left[\frac{\partial Y}{\partial X}\right] \qquad 3\text{-}8$$

Here X and Y are assumed to be derived or inferred from two or more measured primary parameters which are labelled $_{Mi}$ and the terms of the expression are defined below:

$B_{Y,Mi}$ = Net bias error in the derived or inferred measurement Y due to bias error in the primary measurand, Mi,

B_{Mi} = bias error in primary measurand, Mi,

$\partial Y/\partial X$ = slope of Y versus X, estimated o r calculated from curve fit,

$\partial Y/\partial Mi$ = influence coefficient of primary measurand, Mi, on Y,

$\partial X/\partial Mi$ = influence coefficient of primary measurand, Mi, on X.

When the primary measurements are unique to the Y result, the influence coefficient $(\partial X/\partial Mi) = 0$ and Equation 3-8 becomes

$$B_{Y,Mi} = B_{Mi}\left[\frac{\partial Y}{\partial Mi}\right] \qquad 3\text{-}9$$

The bias in Y which is contributed by primary parameters Mi which are unique to X is obtained from Equation 3-8 by setting $(\partial Y/\partial Mi) = 0$ yielding

$$B_{Y,Mi} = -B_{Mi}\left[\frac{\partial X}{\partial Mi}\right]\left[\frac{\partial Y}{\partial X}\right] \qquad 3\text{-}10$$

For primary parameters which are common to both X and Y, neither of the influence coefficients $(\partial X/\partial Mi)$ or $(\partial Y/\partial Mi)$ are zero and the full expression in Equation 3-8 must be used to calculate $B_{Y,Mi}$. Finally the total bias in Y is obtained as the root sum square of the biases from all the i primary measurements.

$$(B_Y)_{Total} = \sqrt{\Sigma(B_{Y,Mi})^2} \qquad 3\text{-}11$$

Now consider Figure 3-3. The precision error in the test manifests itself in the scatter about the curve fit to the data points. The estimated precision error of the measurement can be compared with the standard error of the estimate, SEE, of the curve fit which is defined (References 3-11 and 3-12) as

$$SEE = \sqrt{\frac{\sum_{j=1}^{nm}(Y_j - Y_{cj})^2}{nm - K}} \qquad 3\text{-}12$$

where nm = Total number of measured pairs X_j, Y_j,

K = the order of the curve fit,

Y_{Cj} = Value of Y obtained from the curve fit at X_j.

The precision index for the curve fit at Xj, Scj, can be expressed as

$$S_{cj} = (SEE) \times \sqrt{\frac{1}{nm} + \frac{(X_j - \bar{X})^2}{\Sigma(X_j - \bar{X})^2}} \qquad 3\text{-}13$$

Near the middle of the curve fit, Xj ~ $\bar{X}$ and

$$S_{cj} \approx \frac{SEE}{\sqrt{nm}} \qquad 3\text{-}14$$

If we were to repeat the defined measurement process N times at a fixed X_j, the precision error of the resulting average would be

$$\frac{S_Y}{\sqrt{N}} \qquad 3\text{-}15$$

This shows that S_Y, which we recall is the pretest estimate of precision error, plays a role similar to the SEE which is calculated post test from a curve fit to the data and, provided N is significantly larger than K, the order of the curve fit, the pretest estimate Sy should be comparable in magnitude to the post test SEE. If it is not, it is likely that some important random error sources were not accounted for in the pretest estimate.

3.2.4 Outliers

All test set ups and measurement systems occasionally yield "wild" data points, that is, data points which differ by an unexpectedly large amount from the mean of the complete data set. These may be due to intermittent malfunctions, gross errors in reading a gauge or similar events which cause that particular data point to be not within the same control as the remainder of the data set. Such points are called outliers. All data should be inspected with the objective of eliminating outliers wherever possible. A variety of schemes have been developed for the detection of outliers all of which depend on having a good estimate of the standard deviation of the data set available. Where extensive records have been kept of prior test histories for a given measurement it is usually possible to define the standard deviation of the population of those measurements with good confidence and to set up quality control procedures which flag outliers. One such scheme is described in appendix D of The Measurement Uncertainty Handbook (Reference 3-13). This method, called the AEDC Outlier Detection Method, applies to steady state measurements only. Each data point in a set of N points is tested against the following criterion:

Data points outside the following interval are outliers: $\bar{X} \pm CS$

where $\bar{X}$ is the mean of the data set, S is its standard deviation and C is a constant which depends on the size N of the data set. If $N \geq 65$, $C=3.0$. For smaller data sets, $C < 3.0$ and can be computed from the following expression given in the reference.

$$C = \frac{-1.6819236 + 1.6386898N - 0.00721312N^2}{1.0 + 0.59286772N - 0.00355709N^2}$$

3.3 THE UNCERTAINTY OF TRANSIENT MEASUREMENTS

3.3.1 The Transient Uncertainty Model

The estimation of measurement uncertainty is particularly important when carrying out transient measurements since the dynamic characteristics of the measurement systems themselves can have a profound impact on the measured results. Pressure measurements can be greatly modified by the dynamic characteristics of the tubing connecting the probe to the transducer, peak temperature measurements in gases can be drastically in error due to thermocouple response time and the use of improper noise reduction or anti-aliasing filters in the data acquisition system can degrade the performance of even the fastest transducers. The uncertainty analysis allows the most important error sources to be identified and corrected if necessary and also allows a judgement to be made as to whether the test planned is capable of yielding results of adequate accuracy.

The uncertainty method described in Section 3.2 above is a systematic procedure for estimating the precision and bias of any measurement. The treatment of transient measurement uncertainty expands on the definition of the usual uncertainty terms by proposing that the effects of the dynamic response of the measuring system be treated as additional known and unknown bias and precision errors. These errors are estimated by a combination of calibration and analysis but in this case,unlike the steady state case, the corrections and their uncertainty depend on both the dynamic response characteristics of the measurement system and also on the time behavior of the measurand itself. This dependence can be deduced from Equations 3-7 and 3-8 in the last section by equating the measurand X_j with time. The known bias due to dynamic effects can be removed by the method to be described below; the unknown bias from this source is the residual error remaining due to the uncertainty in this correction.

The transient uncertainty model compares the measured value in time with the true value in time. The model is illustrated in Figure 3-5. For purposes of illustration, the measured values are shown as discrete samples in time at a uniform sampling rate such as would typically be obtained from a digital data acquisition system. A similar argument holds however for analog data acquisition systems as well since such systems are all characterized by some finite integration time. The quantities t_n and Δt represent the system clock time and the system sampling time interval respectively. The "true" value shown is purely hypothetical since, as in the steady state, the true value can never be unambiguously known. The objective of the transient data analysis is to correct, if necessary, the measured value so as to remove the known bias of the measuring system and the transient uncertainty analysis estimates the residual unknown bias in this correction. In addition, the transient uncertainty analysis must estimate the precision of the measurement where this is defined by analogy with the steady state case and represents the standard deviation of the measured values that one would expect to obtain in repeated trials of the same transient test. If at all possible the measurement systems should be designed to be fast enough so that the anticipated transient corrections are small; the transient correction procedures are at best approximate and therefore large corrections lead also to large transient uncertainty estimates. Small corrections on the other hand can be estimated and incorporated directly as bias terms in the uncertainty analysis.

The result of a transient measurement consists of a sequence of two pieces of information: the value measured and the time of that measurement. Each data unit of a transient measurement is a combination of the value measured and the associated time.

True time can in principle be defined as the universal time kept by national standards organizations and measurable with very high accuracy but, in practice, the time of interest here is the system clock time of the data acquisition system. For most transient measurements, time is measured from an arbitrary zero, perhaps defined by an initiating event, by the system clock which can be calibrated against national standards. It is essential that all measurement systems in a transient test be referable to a common system clock. The output of any transient measurement system is the magnitude of measured quantity at a sequence of times, that is, $Q_o(t_n)$.

Figure 3-6 illustrates the results one might expect to get at one particular clock time, t_n, from repeated trials of the same transient event. For purposes of defining the uncertainty which is due to the measurement system, assume that the repeated transients are indeed identical. The frequency distribution of measured magnitudes at time t_n is then a measure of the precision and bias of the measuring system. The figure shows the average of the measured values and the bias between the "true value" at t_n and the measured average. The distribution of measured values of system clock time t_n, reflects both the uncertainty in the measurement system's ability to measure the magnitude of the measurand and the uncertainty in system clock time. In the hypothetical experiment described here the precision and bias in time cannot be separately determined since only the system clock's time and the magnitude of the measurand are recorded. The precision error and bias in time illustrated in the figure must be determined in a separate evaluation of the data acquisition system. The effect of this uncertainty in time on the uncertainty in magnitude is an example of the case where two related quantities are measured each with some uncertainty as discussed in the last section. The magnitude of the time uncertainty effect is summarized in Section 3.7 below.

In order to form a conceptual framework suitable for the problem of transient uncertainty analysis it is helpful to assume that the measurement system can be modelled, at least approximately, by linear time-invariant differential equations (Reference 3-14). The measuring system can then be described by operational transfer functions in the form of impulse response functions (Reference 3-15) or sinusoidal transfer functions (Reference 3-14). The latter will be used for purposes of illustration in this section. Under the above assumptions the uncertainty analysis depends on the following:

1. The uncertainty of the steady state performance of the measuring system where steady state can be interpreted as "at frequencies approaching or equal to zero".
2. The dynamic characteristics of the measurement system and the uncertainty in these dynamic characteristics.
3. The time behavior of the measurand.

The effect of the time response of the measurement system is a known bias and can, in principle at least, be corrected out. The uncertainty of these corrections is an unknown bias and must be included in the uncertainty analysis.

3.3.2 Time Dependent Effects of the Measuring System

Using the sinusoidal transfer function model $T(i\omega)$, each component of the measuring system can be represented by its transfer function. Here $T(i\omega)$ is a complex number which determines the amplitude response and phase effect of each system component at each frequency ω. The form of typical transfer functions is as follows (Reference 3.14):

For a first order instrument describable by a single time constant, the transfer function is:

$$T_1(i\omega) = \frac{K_1}{(i\omega\tau + 1)} \qquad 3\text{-}16$$

where ω = angular frequency
τ = time constant
K_1 = steady state calibration constant

The dynamic behavior is entirely dependent on τ. A thermocouple probe is an example of a system component which is approximately first order. The calibration constant, K, has units like "degrees Kelvin per millivolt" and is determined by steady state calibration. The magnitude of $T(i\omega)$ approaches K as the frequency, ω, approaches zero.

For a second order instrument the dynamic behavior is entirely described by a natural frequency ω_n and a damping constant ξ, Equation 3-17 :

$$T_2(i\omega) = \frac{K_2}{\left[\frac{i\omega}{\omega_n}\right]^2 + \left[\frac{2\xi i\omega}{\omega_n}\right] + 1} \qquad 3\text{-}17$$

A pressure probe and a short length of tubing is approximately second order. Here K_2 is the steady state calibration constant usually expressed in millivolts per KPa per volt of excitation.

Another very useful transfer function is the one that represents a simple time delay or dead time. In a pressure system, the time required for the pressure signal to propagate from the probe through the tubing to the transducer is an example of such a delay. Pressure systems can be modelled approximately as the product of a first or second order transfer function as described above and a delay time. The transfer function for the delay, $T_3(i\omega)$, is (Reference 3.14):

$$T_3(i\omega) = K_3 e^{-i\omega\tau_d} \qquad 3\text{-}18$$

Here the dead time (τ_d) is the tube length divided by the sound velocity in the tube. (For a more extensive discussion of tubing response, see References 3.16, 3.17, 3.18 and 3.19 . For thermocouple reponse see References 3.20 and 3.21)

The model which might apply to a pressure measurement system is shown in Figure 3-7. This figure illustrates that the input $Q_I(t)$ is modified by each of the system components ultimately producing the sampled output $Q_0(t_n)$. The overall system response is the product of the transfer functions of the individual components. To determine the output given the input, the following steps would be carried out:

(i) Calculate the Fourier transform components of the input:

$$q_I(i\omega) = \lim_{t_1 \to \infty} \int_{-t_1}^{+t_1} Q_I(t) e^{-i\omega t} dt \qquad 3\text{-}19$$

where $Q_I(t)$ = input as a function of time,
$q_I(i\omega)$ = Fourier component of $Q_I(t)$ at ω.

(ii) Determine the Fourier components of the output by multiplying by the system transfer function (Equation 3-20):

$$q_0(i\omega) = q_I(i\omega)\ T(i\omega) \qquad 3\text{-}20$$

For the pressure system shown in Figure 3-7:

$$T(i\omega) = \frac{K_p e^{-i\omega\tau_d}}{\left[\left[\frac{i\omega}{\omega_p}\right]^2 + \left[\frac{2\xi i\omega}{\omega_p}\right] + 1\right]} \times \frac{K_T}{\left[\left[\frac{i\omega}{\omega_T}\right]^2 + \left[\frac{2\xi i\omega}{\omega_T}\right] + 1\right]} \times \frac{K_A}{(i\omega\tau + 1)} \qquad 3\text{-}21$$

where the subscripts refer to:

P = probe,
T = transducer,
A = amplifier/filter.

(iii) Calculate the output as a function of time by inverse transform:

$$Q_o(t) = \lim_{\omega\to\infty} \int_{-\omega}^{+\omega} q_o(i\omega)e^{+i\omega t}d\omega \qquad 3\text{-}22$$

The magnitude of the sampled output at time t_n, is then $Q_o(t_n)$.

The results of a measurement are of course the output of the measurement system, $Q_o(t)$. The input, i.e. the true value $Q_i(t)$, is unknown. The first step in the transient uncertainty analysis is to estimate the known bias due to the dynamic response of the measuring system. Two outcomes are possible, either the bias is negligibly small compared to the desired accuracy in which case the transient uncertainty terms will consist of small unknown bias terms and precision terms, or the bias will be large and must be corrected out. Whenever possible, measurement systems should be designed so that no corrections are necessary. To do this one must know how to estimate the magnitude of the corrections.

3.3.3 Determining the Magnitude of the Corrections for Dynamic Response of the Measuring System

In general the method for correcting for dynamic response is the reverse of the process used to calculate the output from the input. Now, however, one starts with a finite discrete record of the output vs time. This process is called deconvolution and can be carried out in either the frequency or the time domain(Reference 3.22). In the frequency domain, the discrete Fourier components of the output can be computed up to a maximum frequency which is dependent on the sampling rate, that is, up to the Nyquist frequency, $f_N = 1/(2\ \Delta t)$, where Δt is the interval between samples (Reference 3.23). In order to insure that the data is not contaminated by higher frequency information, an appropriate anti-aliasing filter must be included in the data system (See Section 4.9.4). Now the steps in the process are as follows:

1. determine the discrete Fourier components of the output,
2. divide by the system transfer function at each ω,
3. compute the input by inverse transform.

This yields the corrected magnitude of the measurand and is illustrated in Figure 3-8. If the magnitude of the correction is significant then it is necessary to estimate the contribution to transient uncertainty from the computational method itself and from the uncertainty in the ω_n, ξ, and τ used in the computation. The latter can be done using the same computational method and varying the dynamic parameters over the range of their uncertainty. Again it is desirable to design the measurement systems to be fast enough so that transient corrections are small.

If the magnitude of the correction is small then it can be used directly as an estimate of the bias due to the transient response of the system.

3.3.4 Estimating the Correction for Simple Cases

The general method for correcting transient data is relatively complex. Fortunately, for relatively simple transients, it is possible to obtain analytical solutions which allow the magnitude of the correction and its uncertainty to be estimated. If the transient can be represented by a ramp which terminates at time T, the analytical solution for the error of a first order system (Reference 3.14) is:

$$[Q_i(t) - Q_o(t)] = \frac{\partial Q_i}{\partial t}\tau(1 - e^{-\frac{t}{\tau}}) \qquad 3\text{-}23$$

If τ is significantly less than T, then the maximum error is the steady-state component:

$$[Q_i(t) - Q_o(t)] = \frac{\partial Q_i}{\partial t}\tau = \frac{\Delta Q_i}{T}\tau \qquad 3\text{-}24$$

The response and maximum errors for a second order system under similar ramp input signal conditions are also shown in Figure 3-9.

Analytical solutions are also available for steps, sawtooths and truncated sinusoids and, where these approximate the measurand's expected time behavior, they can be used to estimate corrections. These corrections can also be used to estimate the uncertainty by calculating how much the correction varies over the expected range of uncertainty of the dynamic constants, ω_n, ξ and τ.

For example, assume the total time T, for the input of a linear ramp of amplitude ΔQ, is one second and a total uncertainty of 1% or less is required. Then, for a first order measuring system:

$$\text{max error} = \frac{\Delta Q_i}{T}\tau \leq 0.01\Delta Q_i$$

Therefore

$$\tau = \leq 0.01T = 0.01 \text{ sec} = 10 \text{ msec}$$

Corrections will have to be made for any first order components of the measuring system which have time constants of the order of 10 msec. or greater. In addition, any uncertainty in time constants that approach 10 msec will be significant in the uncertainty analysis and, since there are likely to be many other error sources present, it would be prudent to ensure that time constants are selected to be about 1/10 of this maximum (or one msec) to keep the overall uncertainty within the desired limit.

3.3.5 Dividing the uncertainty analysis into a steady state and transient part

The K's in Equations 3-16, 3-17, and 3-18 are the steady state calibration constants of each component of the measurement system. The uncertainties in the K's are determinable using the historical approach to uncertainty analysis. The extension of this methodology to transient measurements then depends on estimating the additional uncertainty that accrues as a consequence of the uncertainty in the time dependent characteristics of the measurement systems. As has been shown above, for most systems these characteristics include things like time constants, resonant frequencies and damping constants as well as dead time effects.

Within the framework of the measurement system model described in Section 3.3.2, the uncertainty analysis can be divided into two parts; a steady state part which depends on the K's, and a transient part which depends on the frequency dependent terms shown in brackets in Equations 3-16, 3-17 and 3-18.

In general, the following guidelines are recommended for the separation of error sources into steady state and transient bias and precision terms;

1. Steady state error sources are any error sources which are independent of the time response characteristics of the measuring system.
2. Transient error sources are any error sources which depend on the time response characteristics of the measuring system.
3. Bias errors are those errors which would be expected to remain fixed during the defined measurement process.
4. Precision errors are errors which are expected to vary at random during the defined measurement process.

Some examples: If a working pressure transducer is calibrated against a local standard prior to each of a series of transient measurements, the uncertainty in the local standard is a steady state bias error, the uncertainty in the working transducer calibration is a steady state precision error, the uncertainty due to the dynamic response of the transducer and tubing is a transient bias error.

Transient precision errors are principally due to noise which is superimposed on the measurand of interest from aerodynamic, mechanical and thermal sources and also from electrical sources influencing the measurement system. In this document, our system model as exemplified in Figure 3.7, contains a filter in the signal conditioning system which is designed to cut off frequencies above the highest frequency of interest in the signal. All noise below this cut off frequency contributes to the transient precision error and would manifest itself as random fluctuations in the output of the measurement system when exposed to identical inputs. The magnitude of this error can be obtained by measuring the noise level in the steady state signal prior to initiating the transient provided it is judged that the noise levels during the transient will be similar. Under the assumption that the time varying signal has stationary random noise superimposed on it, the standard deviation of the measurand prior to initiation of the transient can be used to estimate the noise getting through the filter during the transient. Alternatively, repetitions of the same transient can be carried out and the noise or precision error estimated from the standard deviation of the individual samples from the ensemble average at any given time during the transient. There is further discussion of this question in chapter 10 of Reference 3.24 where several approaches to filtering out noise are described. In all cases there is a trade off, since, as the cut off frequency of the filter is lowered, the noise is reduced at the expense of increased bias in the measured average value of the signal.

3.4 SOURCES OF STEADY-STATE MEASUREMENT UNCERTAINTY DATA

The estimation of measurement uncertainty under steady-state conditions is extensively described in the literature. For example, the recommended practices document published by AGARD Working Group 19 (Reference 3.7) covers pressure and temperature measurement. These and other steady-state measurands are covered in References 3.2, 3.3, 3.6, and 3.25. In a transient measurement system the uncertainty analysis begins with an assessment of steady-state error sources. Each component of a measurement system will have calibration, data acquisition, etc., errors as described above in Section 3.2, which are determined by the systems steady-state response and are a lower limit to the total uncertainty when measuring a transient.

Examples are:

- o Pressure transducer calibrations are normally done steady-state and checked against fixed standards before and after a transient measurement.
- o Thermocouple wire is calibrated steady-state
- o Fuel flow meters are calibrated steady-state
- o Voltmeters and A/D converters are calibrated steady-state

The above error sources contribute to the total uncertainty of the transient measurement but do not take care of the additional time dependent error sources which arise when measuring transients.

3.5 SOURCES OF TRANSIENT MEASUREMENT UNCERTAINTY DATA

The total uncertainty of a measurement system can be drastically affected by its dynamic response as previously discussed. Pressure measurements are greatly affected by the complex dynamic behavior of connecting tubing. The dynamic response of the transducer can be obtained from the manufacturer's specification sheets. The response of the tubing must be either calculated as described in Section 4.2 or, for complex systems, directly measured. The time response of temperature probes is a function of their size, geometry, and heat transfer coefficient as described in Section 4.3. Fuel flow meters differ widely in their dynamic response depending on their mechanical and electrical design. Section 4.4 gives examples and references. In general, the dynamic response of systems for various specific types of measurements are described in the sections of this report covering that measurement and these sections should be consulted for details and references on error sources. Here the point is made that for each measurement system to be used for transient measurements the dynamic response must be determined and used to estimate the transient contributions to uncertainty. Since the operations required to estimate the transient part of the uncertainty are usually quite different than those for the steady state, we have chosen in this document to treat them separately. However, the general measurement uncertainty methodology holds for all the transient error sources just as it does for the steady state. That is, each error source must be categorized as bias or precision and have a well defined process by which it is determined: such as dynamic calibration, analytical computations, signal to noise measurements or, if all else fails, "engineering judgement".

3.6 COMBINING STEADY-STATE AND MEASUREMENT TRANSIENT UNCERTAINTY

Using pressure as an example, the system model given in Figure 3-7 lists the steady state and transient error sources for this system. Figure 3-10 is an error source diagram which lists in separate columns the steady state and the transient errors. This diagram is intended as an example only and is not expected to adequately represent all systems. In order to carry out the uncertainty analysis, it is necessary to estimate the bias b_i and the precision s_i contributed by each error source. In general the steady state terms are those associated with the steady state or zero frequency calibration constants of the system. The transient terms are calculated from the uncertainty in the dynamic constants of the system, the corrected time behavior of the measurand , and the system noise. As previously described, the transient bias errors can be estimated by the discrete Fourier transform method or by other appropriate means. In many cases the transient uncertainty will be dominated by one component of the measuring system such as the pneumatic tubing in a pressure system , the thermocouple in a temperature system, or the rotor inertia in a turbine flow meter.

For both the steady state and the transient terms, bias errors are those which are expected to stay fixed during the test and precision errors are those expected to vary at random. The transient errors will include the unknown bias resulting as a residual error from the correction process and the precision terms are obtained from noise level determinations or by examining the repeatability of the measuring system components to repeated trials of the same transient.

To obtain the total uncertainty it is recommended that the steady-state and the transient uncertainty be combined as follows:

Referring to Figure 3-10,

Let b_i^{ss} = bias error for the ith steady state error source,

s_i^{ss} = precision index for the ith steady-state error source,

b_i^T = bias error for the ith transient error source,

s_i^T = precision index for the ith trans-ient error source.

Total Bias error is;

$$B = \sqrt{(B^{SS})^2 + (B^T)^2} \qquad 3\text{-}25$$

where

$$B^{SS} = \sqrt{\sum (b_i^{SS})^2}, \qquad B^T = \sqrt{\sum (b_i^T)^2} \qquad 3\text{-}26$$

Total Precision error is;

$$S = \sqrt{(S^{SS})^2 + (S^T)^2} \qquad 3\text{-}27$$

where

$$S^{SS} = \sqrt{\sum (s_i^{SS})^2}, \qquad S^T = \sqrt{\sum (s_i^T)^2} \qquad 3\text{-}28$$

The total uncertainty for one repetition of the defined measurement (i.e. setting N=1 in Equations 3-1 and 3-2) is then

$$UADD = \pm(B + t_{95}S)$$

with 99% confidence, or

$$URSS = \pm\sqrt{B^2 + (t_{95}S)^2}$$

with 95% confidence.

3.7 THE UNCERTAINTY IN TIME

All of the above discussion refers to the uncertainty in magnitude of the measurand and would be present even if the uncertainty in the time of the measurement were zero. One must next add the effect of the uncertainty in time.

The precision and bias in the system clock time, illustrated on the time axis in Figure 3-6, can be determined by first carefully analyzing the defined measurement process to identify the critical timing factors and then reviewing the characteristics of the data acquisition system components which multiplex, digitize and record the signal amplitudes and the associated time of occurrence of those amplitudes. A simple example of the effect of the uncertainty in time can be illustrated by reference to a pass-off test in which the time to accelerate from idle to takeoff thrust is measured. If the defined measurement process requires the measurement to be made by an operator observing a thrust meter and using a stop watch then, even if the uncertainties due to the thrust meter and the stopwatch are negligible, there will be an uncertainty due to the response of the human operator who is the data acquisition system in this case.

The uncertainty in time could be determined using a known calibrated transient signal and a setup which simulates the actual test situation and recording the results of many trials. This would yield the precision and bias for the individual operator and the differences between operators. Typically uncertainties in time of several tenths of a second would be expected. The timing errors for automated systems are discussed more fully in Section 4.9 below titled "Data Acquisition and Processing Systems". In that section the principal parameters which effect the uncertainty in time are described. They are:

1. "Burst Sampling Rate" of the data acquisition system (see Section 4.9),
2. Sampling rate in each data channel,
3. Time lag between channels,
4. Sampling time (aperture time and digitization time) of the analog to digital convertor.

All of this information should be available as part of the design specifications of the data system. Should any doubt exist about the true uncertainty in time, the data system should be tested using precise synthesized transient signals as inputs to the data acquisition system multiplexor and the bias and precision in its timing would then be determined in repeated trials of simulated transient events.

The data system should be designed so that the uncertainty in time has a negligible effect on the measurement process. The effect of an error in time is illustrated in Figure 3-11. Using the approach described in Section 3.2 for two related measurements that have no common primary measurands (see Equation 3-7), the effect of the uncertainty in time, U_t, on the measurement of the time dependent quantity Q can be estimated. Then, requiring that this error be small compared to the total uncertainty limit for the measurement yields the following criterion for the tolerable uncertainty in time:

$$U_t \left.\frac{\partial Q}{\partial t}\right|_{t_n} \ll U \qquad 3\text{-}29$$

where U = UADD or URSS = total uncertainty in the measured magnitude of Q due to the steady-state and transient uncertainties of the measurement systems. i.e. the total uncertainty in $Q(t_n)$, and U_t = Total uncertainty in the time t_n, and

$$\left.\frac{\partial Q}{\partial t}\right|_{t_n} = \text{Rate of change of } Q(t_n) \text{ at } t_n.$$

3.8 CONCLUSION

This report shows that measurement uncertainty methodology can be applied to the estimation of the uncertainty of transient or time dependent measurements. The method proposed depends on carefully separating the error sources into a steady state category and a transient category. The transient category includes all error sources which depend on the dynamic response of the measurement system and therefore also on the time behavior of the quantity being measured. The dynamic characteristics of the measurement system and the uncertainty in these dynamic characteristics must be determined as a prerequisite to the uncertainty analysis. The steady state or zero frequency uncertainty and the transient uncertainty terms are separately estimated, then combined to yield the total uncertainty.

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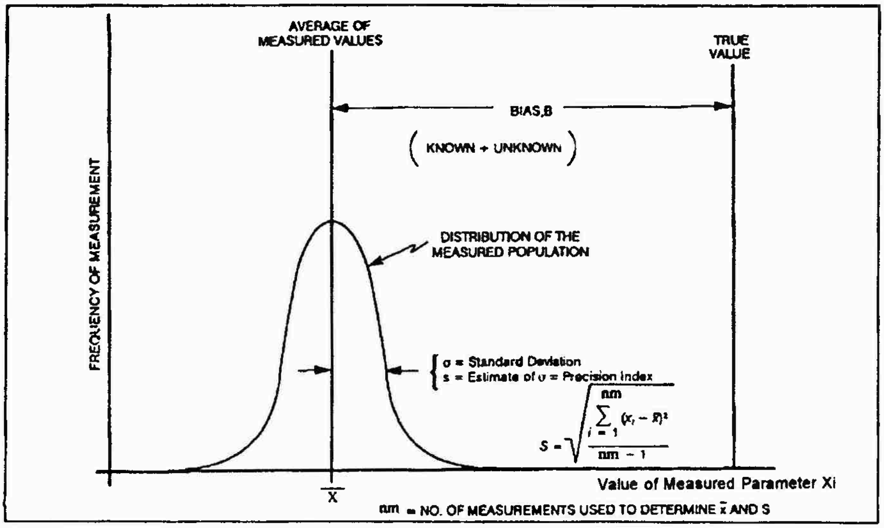


$$S = \sqrt{\frac{\sum_{i=1}^{nm} (x_i - \bar{x})^2}{nm - 1}}$$

Figure 3-1 The Steady State Uncertainty Model

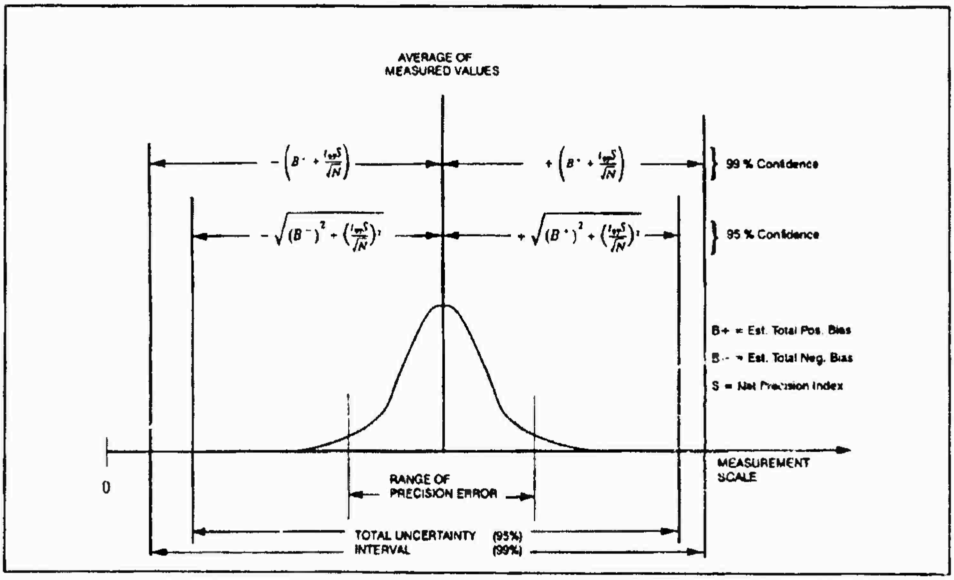


Figure 3-2 The Total Uncertainty Interval for a Defined Measurement Process

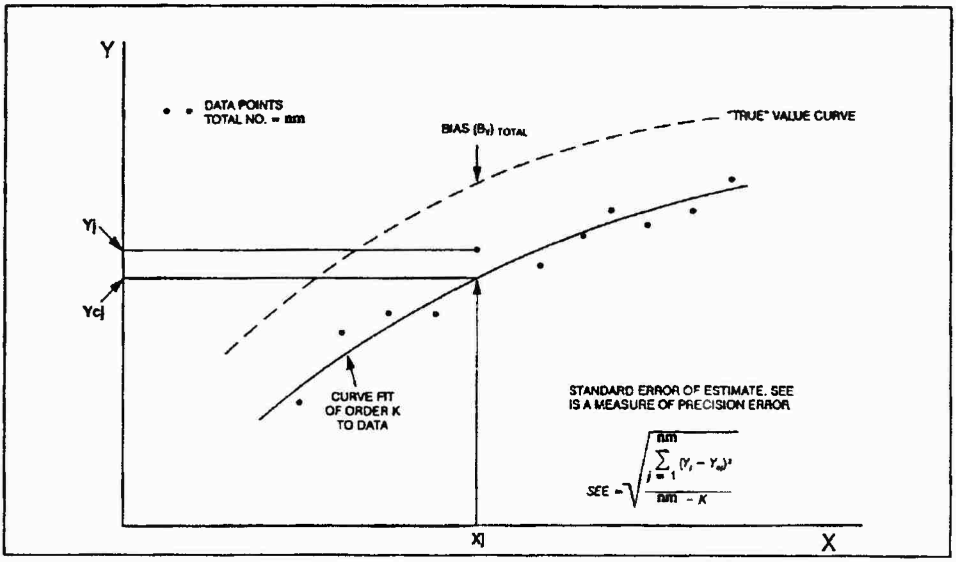


Figure 3-3 Bias Error in an X-Y Plot

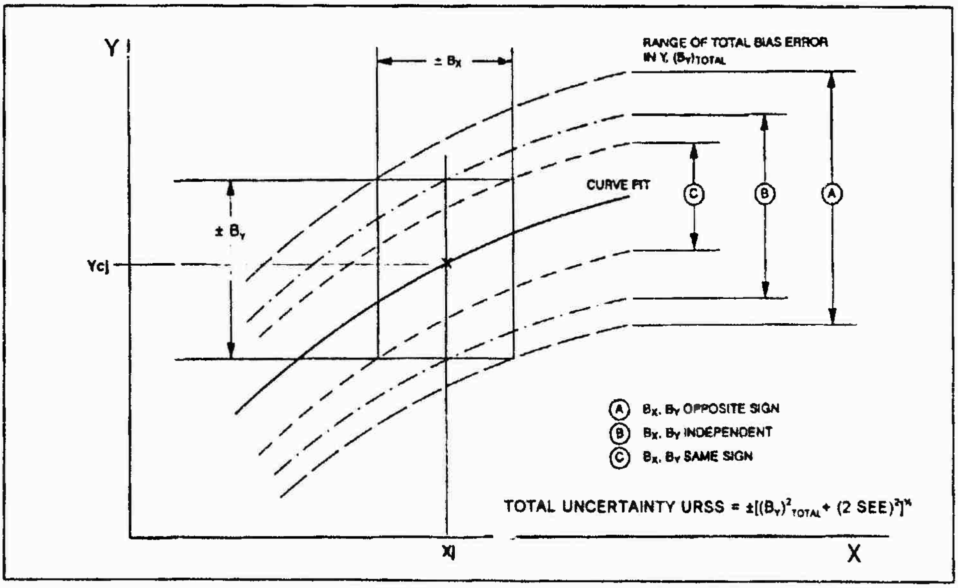


Figure 3-4 Range of Bias Error in an X-Y Plot with Error in Both X and Y

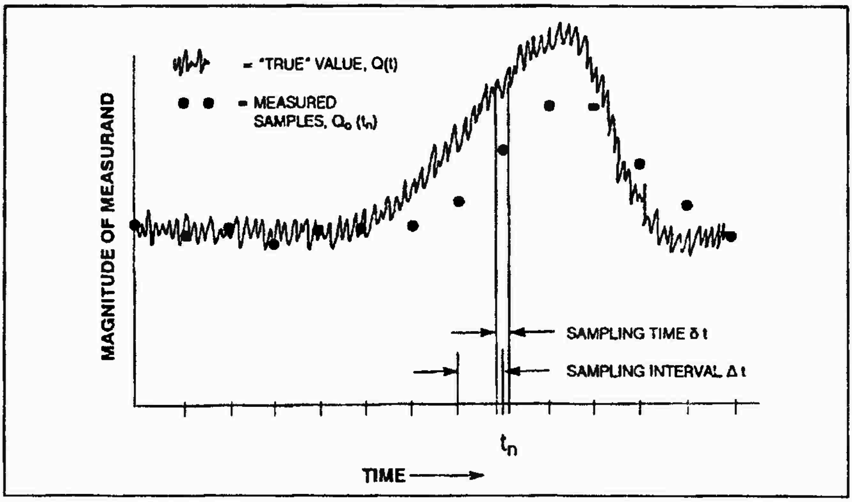


Figure 3-5 The Transient Uncertainty Model

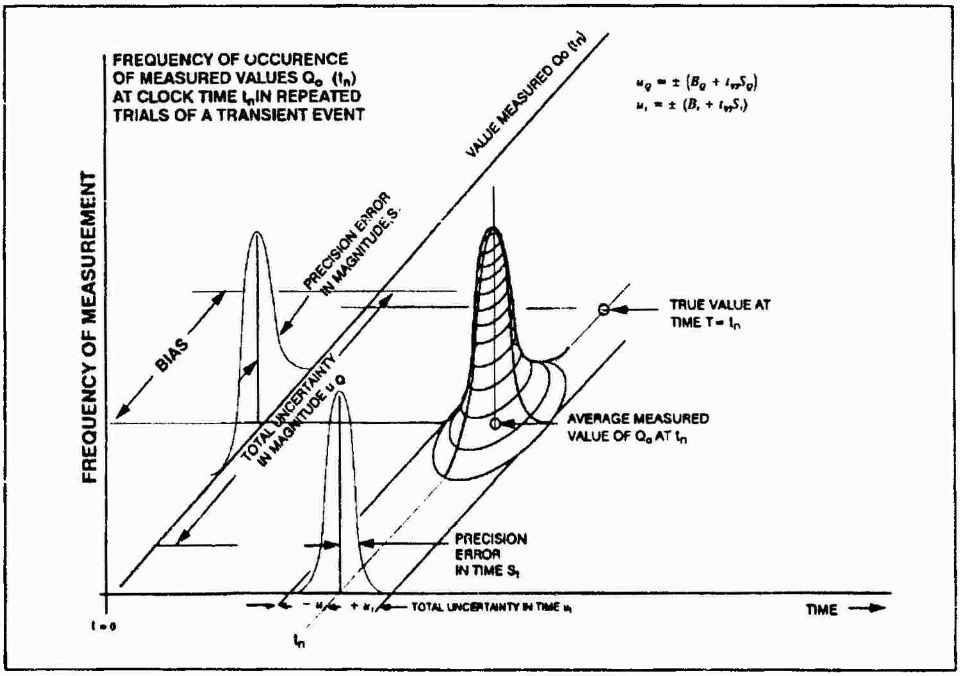


Figure 3-6 Frequency of Occurence of Measured Values $Q_o(t_n)$ at Clock Time t_n in Repeated Trials of a Transient Event

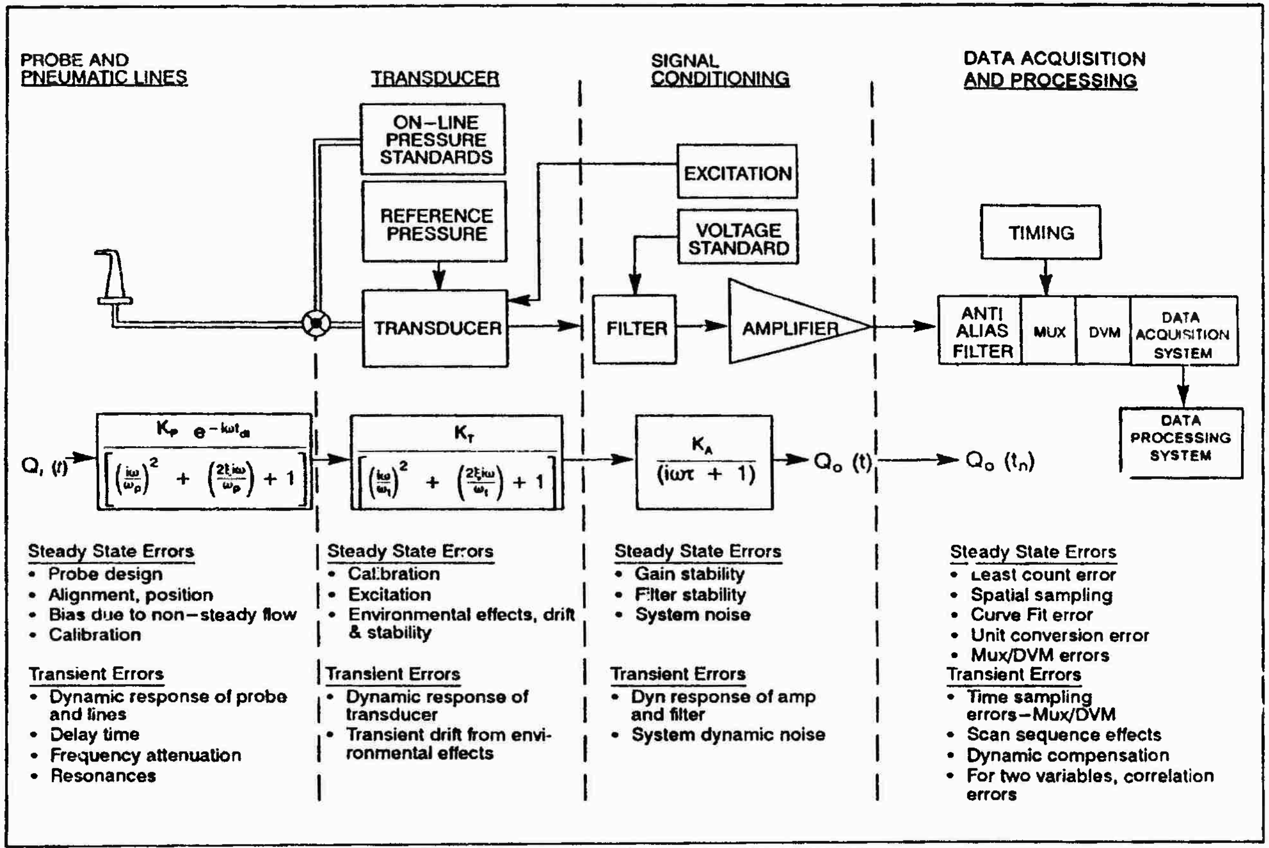


Figure 3-7 A Pressure Measurement System Model

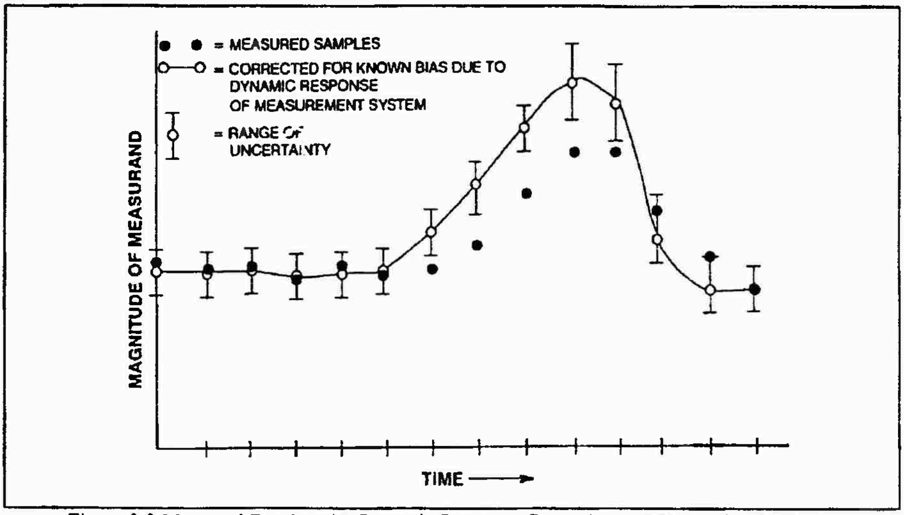
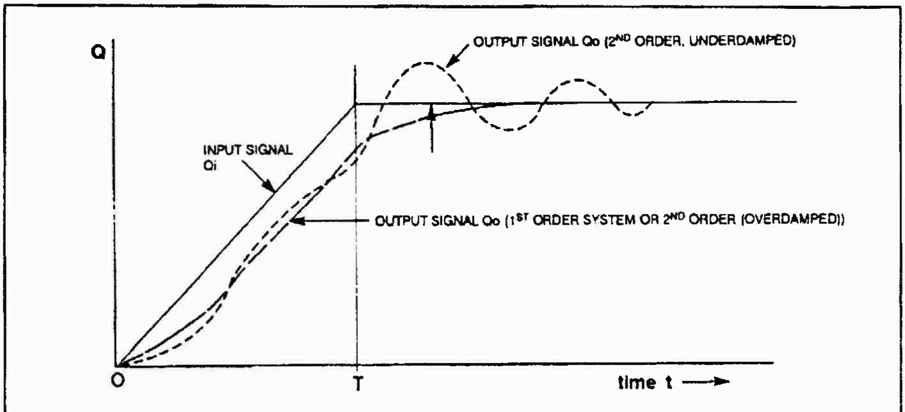


Figure 3-8 Measured Results with Dynamic Response Correction and Uncertainty Estimate



1st Order System: Max Error = $\frac{\delta Q}{\delta t} \cdot \tau$

2nd Order System (Overdamped): Max Error
Ideally Damped or Over Damped = $\frac{\delta Q}{\delta t} \cdot \frac{2\xi}{\omega_n}$

(Underdamped): Max Overshoot = $\frac{\delta Q}{\delta t} \cdot \frac{1}{\omega_n \sqrt{1 - \xi^2}}$

Figure 3-9 Response to a Simple Transient - The Terminated Ramp

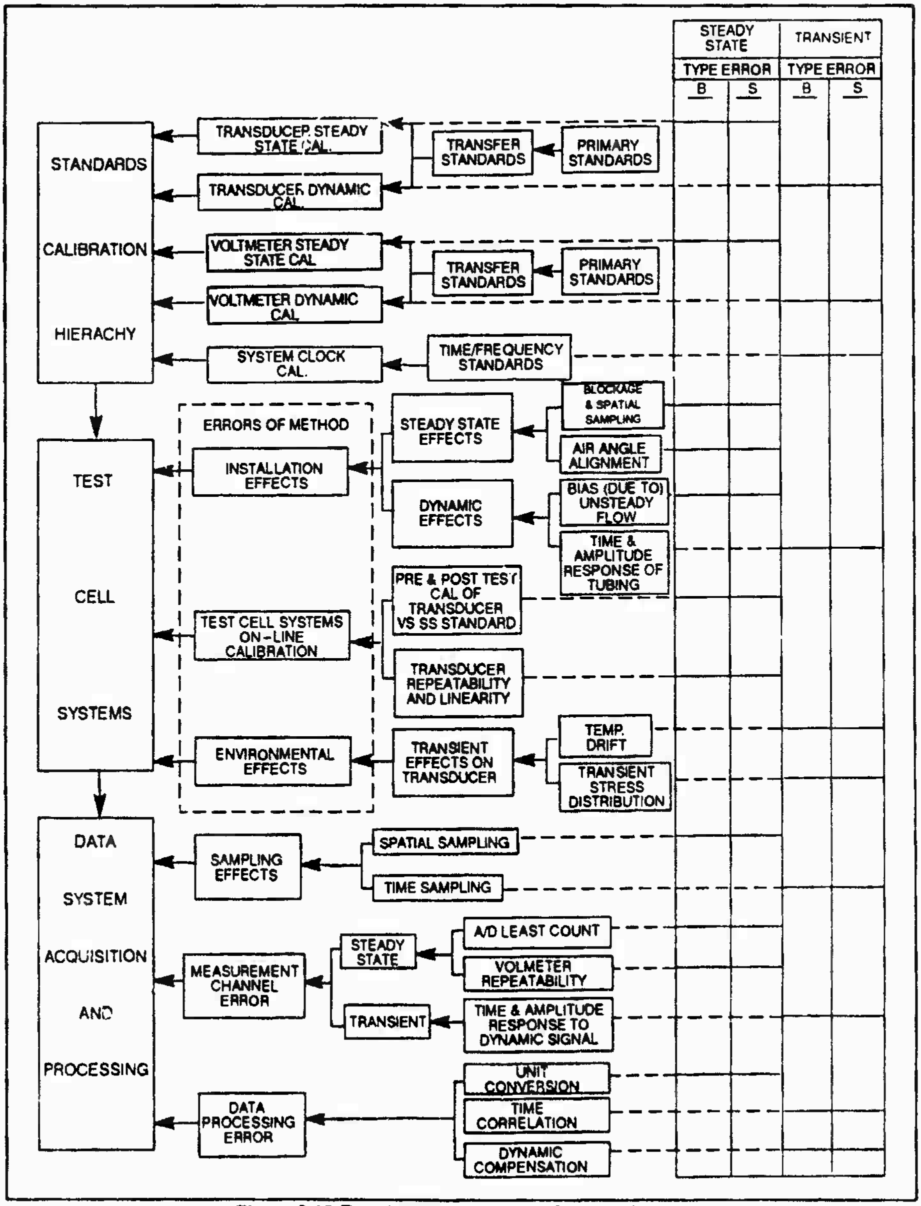


Figure 3-10 Transient Pressure Error Source Diagram

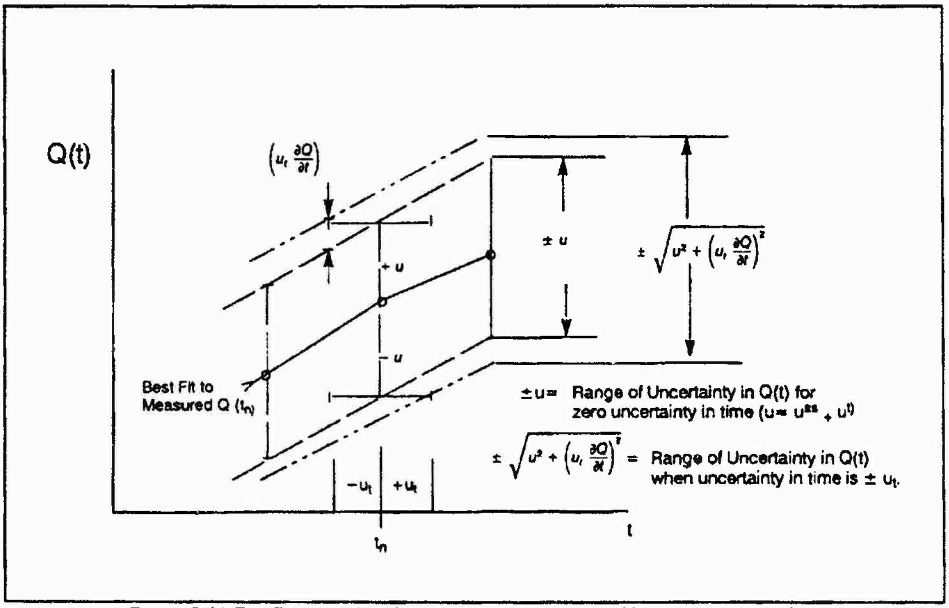


Figure 3-11 The Effect of the Uncertainty in Time on the Net Uncertainty in Q(t)

4. TRANSIENT MEASUREMENT SYSTEMS

The design of optimum transient measurement systems is a complex combination of science and art. A compendium of requirement-driven design and operationally-recommended practices did not exist at the time this study was initiated. In this extensive section, the general definitions of transient measurement systems for gas turbine engines are developed first (Section 4.1). Then the current state-of-the-art recommended practices for the instrument portion of measurement systems, i.e. the sensor, transducer, power supply, signal conditioning and calibration, are given in Sections 4.2 through 4.8 for a number of basic measurement parameters. These measurement parameters include all the measurements normally made during transient testing of gas turbines. In addition, the more promising opportunities for advancing the state-of-the-art of transient instrumentation are discussed for each type of measurement.

As would be expected, the data acquisition and processing portions of the measurement systems for all parameters are essentially the same. Therefore, current recommended practices for transient data acquisition and data processing are grouped in Section 4.9. Finally, one or more specific relevant design examples are presented in each of the sections to provide technical demonstrations of the methodologies.

4.1 GENERAL DEFINITIONS OF MEASUREMENT SYSTEMS

4.1.1 Introduction

The objective of a proposed investigation will determine the variables to be recorded and the required accuracy of the measurement. In the parts of Section 4 that follow, various techniques and instrumentation set ups are described with sufficient detail to guide the reader as how to make the desired measurements. The applications for different measurement systems range from time-variant pressure (liquid and gas) (Section 4.2), time-variant temperature (gas, liquid, and metal) (Section 4.3), time-variant flow (gas and liquid) (Section 4.4), geometry (rotational speeds, displacement - linear and angular) (Section 4.5), to time-variant thrust and torque (Section 4.6). In addition, the utilization of engine control system parameters is discussed in Section 4.7, and a number of special, miscellaneous, (e.g. flame detector) measurement applications are described in Section 4.8. As noted above, the data acquisition and data processing portions of the measurement systems are addressed in Section 4.9 for all parameters. Before proceeding to those sections, for instructions on how to make a measurement, some definitions and basic issues on measurement systems will be discussed. Although each user will have a different set of requirements, and each measurement system is different, there are common concerns and problems. The goal of Section 4 is to provide definitions and guidelines which can be used to set objectively the measurement system performance requirements and to develop specifications.

A measurement system is configured to produce information to make a decision. A basic system configuration has a number of functional components that comprise the major modules within the overall measurement chain. The three major modules of a complete measurement system are the *instrumentation system*, *the data acquisition system*, and *the data processing system*.

The first step in defining a measurement system is the requirement for stating the test objective. A clear and written definition of the objective starts the planning. The planning is the foundation for the development of the system specifications. The specifications define the end users' needs as well as the constraints of the transient phenomena to be measured. The test objective guides the process for planning the design, and also facilitates the selection of measurement systems best suited to the requirements. Careful pretest planning saves time and ensures data quality. Issues to be examined during the planning phase are:

- o What is to be measured?
- o What accuracy is required for each measurement?

The identification of what is to be measured and the stated accuracy requirement initiate the activity for definition of the measurement systems. The subsequent parts of Section 4.1 develop the definitions and discuss issues for the design process to identify and specify measurement system configurations. The focus is on the design for specific requirements addressing system response and accuracy. The process begins by defining the performance requirements for the various links which join and chain the measurement system modules. The measurement system extends from the instrumentation system (discussed generally in Section 4.1.3 and, more specifically, in Sections 4.2 through 4.8) to the data acquisition and data processing systems (discussed particularly in Section 4.9) which acquire, record, and process data.

The required measurement systems process measurands that are varying with time. To control the system complexity and the potential costs, the system adequacy must be evaluated by examining system requirements for response ann accuracy. The evaluation requires repeated analysis by examining the system properties (discussed in Section 4.1.3) and comparing them to the required measurement uncertainty (discussed in 4.1.5). The properties have both physical and mathematical interpretations. Examining them by analysis during the design phase, and by test and analysis during the application of the measurement system, we develop insights (estimates) and mathematical representations for the accuracy of the system. The system operational transfer function relates the system response as a function of inputs and outputs, and system uncertainty is quantified by the mathematical analyses discussed in Section 3.

The control of the accuracy cannot be any better than the imposed control over the system. The issues of calibration and accountability, which control the measurement system performance, are discussed in Section 4.1.4. Calibration envelopes the performance requirements of the measurement system, and establishes the control over the system accuracy. The subject of calibration is key to the maintenance of system fidelity.

Measurement systems for transient testing can be divided into two general categories: (1) measurement systems to evaluate component/rig/engine performance, and (2) measurement systems that are unique to facility control and safety. The two categories are described in reports issued by AGARD PEP Working Groups 19 (AR-248) and 15 (AR-245) (References 4.1.1, 4.1.2). Each category of measurement system will have a different level of acceptable measurement errors. This report is concerned primarily with the first category, i.e. measurement systems to evaluate engine or component performance, but the principles and techniques described can have general application.

In summary, the objective of Section 4.1 is to identify issues to be considered in the planning for the main elements of the measurement system. The definitions are flexible and the reader should consider the importance of the performance requirements in relation to the overall test objective. The section includes a discussion on the issue of the integration of data in space and time, and it concludes with definitions of primary, derived and inferred parameters.

4.1.2 Measurand

4.1.2.1 *Definition*

A measurand is the elemental physical quantity which is the objective of a specific measurement. To the measurement system it is known as an input. The measurand has a measurable amplitude, and phase(time) characteristic. In a transient event it is a continuous time signal which has an allocation of real value for every value of real time.

The time variant measurands considered in this document are listed in Section 2.6.1 and include pressure, temperature, flow, geometry, and thrust and torque. It is very important to define the transient characteristics of the measurand so that the appropriate measurement system can be specified. A close examination of the requirements may indicate that the desired data set may be obtained from any of several different measurement system configurations. Each possible measurement system should be examined to determine whether it satisfies the requirements that have been established prior to making a choice.

4.1.2.2 *Time Behavior (Amplitude and Phase)*

The measurands discussed in this document are explicitly time dependent. A transient time function is one that exists over a finite time interval and is zero (or at least time invariant) at all other times. The transient properties of the measurand exhibit complex phase (time) behaviors, and these properties need to be measured with defined amplitude and phase(time) resolution.

The term transient implies a relatively slow variation in engine operation or a time dependent change in rotor speeds and flow regimes. The time-variant characteristics are the time dependent variations of continuous flow systems due to an engine operational mode change, to reactions to changes through an interaction process in the engine core, or to transient influences at the engine inlet or exit. The relevant measurands of the time-variant phenomena are the magnitude of change, the time of occurrence, and the distribution through the (axial, radial, and circumferential) measuring stations. In addition, measurement stations and probes are required for the engine fuel and control systems. The command and response characteristics of the engine can be very important to the investigation. During transient events there are significant time lags within the systems due to the inertia characteristics of the engine rotor systems. Measurements of the command and response characteristics are keys to facilitate interpretation.

The measurement objective is to determine the amplitude and its time dependence and to correlate two or more measurands in time and space. The amplitude of the measurands during non-steady events is important, but, in addition, the variation of the amplitude with time is required to characterize the transient event. The amplitudes of the measurands are used in calculations while interpretation of the transient event is assisted by preserving the time variant (transient) character of the signal.

The spectrum of a transient time function contains all frequency components, and not just a harmonically related set of discrete frequencies as in the case of a periodic waveform. The spectral components of a transient time function can be determined mathematically by employing the *Fourier integral transform* method. A major reason (Reference 4.1.3) for converting functions from the time domain to the frequency domain is to perform certain desired operations which are more revealing in the frequency domain than in the time domain. The method is used to resolve any transient function into an infinite number of individual sinusoidal components each having a discrete amplitude and phase. For example, the spectral components are required (analysis of uncertainty, Section 3) to correct for dynamic response of the measuring system. The correcting process requires the discrete Fourier components of the output. A detailed discussion of the *Fourier integral transform* is beyond the scope of this chapter. However, due the importance of the concept, which is fundamental to signal conditioning, data acquisition, and processing, the reader is directed to References 4.1.4 to 4.1.7 for additional information.

The measurement capability for studying transient phenomena must include adequate frequency response, and the desired frequency response range must be considered during the design phase. A paper titled *Techniques for Determining Engine Stall Recovery Characteristics*, from *Engine Handling*. AGARD Conference Proceedings No.324 (Reference 4.1.8), suggests frequency ranges of relevance for different types of transient phenomena. It states that the transient phenomena to be characterized may consist of planar axial perturbations of low fundamental frequency (2-20 Hz) such as surge, and high fundamental frequency phenomena (50-100 Hz) such as rotating stall. However, to characterize surge dynamics the instrumentation must be capable of measuring phenomena with frequency content of 1000 Hz or greater.

Pressure and flow disturbances such as wake transport phenomena through rotating blades or pressure and temperature variations in combustors are high frequency dynamic events and require special instrumentation. Although they affect component efficiency the measurement of their behavior will not be considered in this document.

4.1.2.3 *Spatial Distribution*

Based on stated objectives, in some cases it may be adequate to sample local behavior only. Other cases, such as the determination of the mean (average) properties at an entrance or exit station, may require an array of measurements. Obviously, to facilitate the analysis and to assist in the interpretive processes, the spatial distribution of the sampling stations is important. If a comparative (component to component build) or sequential timing of events is all that is required, single sensors may be adequate. However, if absolute values are required, a detailed spatial array, or carefully selected sensor positions, may be very important. The design considerations for the sampling stations have to be catalogued, based on various degrees of priority and on the desired results. It may be necessary not only to measure the response with accuracy and phase coherence, but to include capability to define the spatial boundaries of the transient event. An extensive background of work exists covering the measuring stations and their identification codes. The reader is referred to Section 2.4.2 for the recommended station identification and nomenclature.

It is not possible to recommend an array of spatial measurement stations to be adequate for all test cases. Even the testing of complete engines may require a minimum array of derived spatial stations while a component or rig test may demand a generous array of instrumentation aimed at achieving maximum information. It will be desirable to conserve correlation by using common instrumentation between the rig and full engine testing.

4.1.2.4 *Acceptable Uncertainty*

Each class of user will have a different set of requirements for uncertainty based on the test objectives. The uncertainty requirements are defined by the intended use of the measurements. Therefore, the uncertainty is an issue of confidence for the significance of the observed differences between a set of measurements. The consequences for the required accuracy and associated uncertainty requirements are two fold. The magnitude of the stated uncertainty can not only enhance the probability for a well informed decision, but, also, it affects the technical requirements for the measurement system with the associated impacts on costs and schedules. The systematic procedure for uncertainty analysis is grounded in statistical principles and in engineering judgements. The steady state methodology has been described in standard documents (References 4.1.2, 4.1.9, 4.1.10).

The methodology for the analysis of uncertainty for measurement systems measuring explicit time dependent phenomena is presented in Section 3 of this document. The uncertainty of the measurement system is affected by the dynamic response characteristics of the measurement system attempting to replicate the true value of the measurand and its time dependence. In addition, bias errors introduce a further level of uncertainty. In the proposed methodology, the bias errors are estimated by a combination of calibration and analysis methods. However, for the purpose of definition of acceptable uncertainty, bias errors rooted in experience and engineering judgement are used to quantify sources of error associated with a proposed measurement system. Therefore, a familiarity with sources of error, and how they interact, enables the measurement system designer to quantify and state an acceptable overall system uncertainty. The stated overall uncertainty value for the measurements not only should be realistic to the requirements of the test objective but also practical.

AGARDograph No. 307 (Reference 4.1.11) addresses test facility steady state measurement uncertainties as defined by the Propulsion and Energetics Panel Working Group 15 report on "The Uniform Engine Testing Programme" (Reference 4.1.1). It is a highly recommended document for definition of a single methodology for the assessment of data quality and for comparison of achievable uncertainty for steady state measurements. The expected uncertainty for a transient measurement will normally be larger than that for a steady state measurement because of the time dependent factors involved in a transient measurement. Those factors that tend to increase the uncertainty in a transient test are indicated in principle in Figure 3-10 and typical values are provided in the examples related to the individual measurements described later in Section 4.

4.1.3 Measurement Systems

The generalized measurement system is quite simple. The role of the measurement system is to provide the means to convert the measurands into usable information that can be analyzed and evaluated. But difficulties are encountered when the system characteristics are matched for compatibility to the properties of the measurand. The signal conditioning module has the assigned responsibility to modify and convert the measurands into usable signals for further processing. In Figure 4.1-1 (see page 4-13), the major components of a generalized measurement system are illustrated (see also Figure 3-7). There are variations in the arrangement of components within a given system, but the main elements are the sensor, transducer and the signal conditioning, leading to the data acquisition and processing. (The data acquisition which stores the variable being measured, can be either digital or analog or both. For clarity both systems are shown in Figure 4.1-1. The characteristics of data acquisition systems of importance in transient testing are discussed in Section 4.9.)

The main theme of this document is how to make the desired measurements of time variant events to satisfy the test objective. The theme places importance on techniques and applications for the measurement of transient pressure, temperature, flow, geometry, thrust and torque, and control system parameters. This section (4.1.3) introduces the generalized measurement system, and reflects on issues which may influence system performance and accuracy. It will commence with the introduction of the further parts of Section 4 which will inform and guide the reader with the required details as how to make the specific measurements. The intent of this introduction is to contribute a general overview for the sections that follow rather than to give details as how to make the measurements.

Pressure, Section 4.2

There are limited options for the selection of suitable sensors, transducers, and signal conditioning systems for the measurement of time variant pressure. This section provides the required details for the selection of sensors and the design of measurement systems for gas and liquid pressures for events that occur during transient operations in gas turbine engines. It illustrates some of the problems encountered in the application of pressure measurement systems for proper functioning during normal monitoring and during transient events. The section delineates not only the issues of design and application, but also discusses calibration and system accuracy, and concludes with specific design examples.

Temperature, Section 4.3

This section reviews the complex requirements and specifications for the measurement of transient temperatures for gases, solid surfaces and liquids. Techniques for the measurement of transient temperatures by thermocouples are discussed in some detail. Error sources in high velocity and high temperature environments and their effects on the dynamic response characteristics are reviewed. Resistance Temperature Devices (RTDs), hot-wire systems and a number of advanced techniques are outlined. The section concludes with design examples.

Flow, Section 4.4

The objectives of this section are to provide system design and application guidelines for flow measurement in gases and liquids. Of all physical measurements, transient flow probably offers the greatest challenges, mainly due to the complexity of the measurement systems that are required. There are numerous systems available; the five most common types are discussed in this section. Major concerns for derived measurement systems (see Section 4.1.7 below), such as inferential flow processing, primary measurement phase relationships, and flow uncertainty, are addressed. The section is structured to discuss each of the instruments and application techniques from basic theory to the required signal conditioning. The importance of system calibration is stressed in association with uncertainty considerations, and the section concludes with a specific design example.

Geometry, Section 4.5

The primary interest of this section is motion and dimensional measurements. Measurement devices to derive rotational speeds, degrees of angular rotation, and linear position are explained for components regulated by engine controls, e.g., variable inlet guide vanes. A variety of methods are described for the measurement of structural deformations introduced during transient testing. Examples and typical accuracies of various techniques are presented.

Thrust and Torque, Section 4.6

Transient engine thrust and torque are diagnostic measurements which can indicate events such as augmenter lightoff or can be used to characterize operational problems. To make the fundamental measurements even at a stabilized steady-state condition is a very difficult task. In recognition of the importance of these measurements during transient engine events, the section presents measurement techniques for the assessment of engine thrust and methods to quantify the variations with time. The section addresses the application techniques including the basic theory of the measurement, signal conditioning, calibration, and error assessment, and concludes with specific design examples.

Control System Parameters, Section 4.7

Section 4.7 discusses the possible use of accessible control system parameters to provide information on engine performance during transient operation. The control system is often a convenient, and sometimes the only, source of certain transient data. Typical control parameters and the advantages and disadvantages associated with their use are identified.

Miscellaneous, Section 4.8

Other performance parameters that may be of interest during transient testing include flameout, accessory power extraction, and flow offtake or injection. The measurement of each of these parameters under transient operation is discussed in this section.

Data Acquisition and Processing, Section 4.9

The data acquisition and processing systems provide the interface between the instrumentation systems and the users of the data. These elements acquire the outputs from the signal conditioning units and process these electrical signals to produce output information in prescribed digital and/or analogue formats.

The measurement system should have the capability to accommodate a variety of inputs including both low level and high level signals. Typical low level signals include thermocouples, transducers, and RTDs, while devices such as Linear Variable Displacement Transformers (LVDTs) produce high level signals. An understanding of the physical, mechanical, and electrical characteristics of the instrumentation in the measurement chain is advantageous when considering component compatibility. Such an understanding also affords an opportunity to objectively compare the performance of the various components and, using manufacturers' specifications and stated errors, allows a reasonable estimate to be made of system accuracy.

The main elements of a measurement system are the sensor, transducer, signal conditioning, signal transmission/distribution network, and the data acquisition and processing systems. The following definitions form the basis of the generalized measurement system. Summary definitions are included in the Glossary of this report.

4.1.3.1 *Sensor*

The sensor is the element that acquires energy from the physical phenomenon to be measured. In the hierarchy of a measurement system the sensor is the primary element which receives the energy from the physical phenomenon, and transmits it for either a mechanical or electrical transformation to convert the energy into a useable form. For example, in aerodynamic and flow measurements, pressure sensors are common items. The sensor can be an open-ended tube facing into the gas path or a wall pressure tap, and, by means of tubes, the pressure is transmitted to a transducer for processing into a useable signal.

4.1.3.2 *Transducer*

The transducer is the fundamental link in the measurement system chain and converts the amplitude and phase of the measurand received from the sensor into an electrical quantity that can be amplified and conditioned. The transducer performance characteristic which is most significant is the transducer response as an input and output relationship (i.e. transfer function). Some other issues related to accuracy are, for example, the requirements to have adequate range to operate satisfactorily from minimum to maximum operational conditions, the linearity, response, and the ease and repeatability of calibration.

In transient measurements the measurands are time variant. The required transducers and sensors respond as first-order or second-order systems (see Section 3.3.2). The response of first or second-order systems is defined by time, frequency, and damping constants. The selection process should examine the properties of the measurand for compatibility with the natural frequency and damping characteristics of the transducer.

Transducer devices are categorized as either active (commonly called "self-generating") or passive. Active transducers are measurement devices that generate an electrical output signal due to a physical phenomenon without requiring an excitation voltage source. Typical active devices are piezoelectric transducers and thermocouples. The active system is simply an input-output device without the need of external electrical excitation. Passive devices require that an external excitation be applied in order to produce an electrical output due to a physical input.

4.1.3.3 *Signal Conditioning*

Signal conditioning is required to convert a transducer output to a signal suitable for an input to a data acquisition system. In a modern measurement system the analog signal conditioners are available as modular units; they offer a number of features and the selection depends on the needs of the transducer being conditioned. Some of those features are:

- o Provide electrical excitation for a passive transducer. It is generally in the form of a constant voltage or current and can be either AC or DC. Constant voltage excitation from a DC source is the most popular and provides acceptable excitation accuracy. The power supply is critical because it has the potential to directly affect the accuracy of the measurement. Voltage regulation and noise both directly affect the accuracy of the measurement.
- o Provide completion networks for bridge or potentiometric devices. The basic bridge circuits are used for the measurement of resistance, inductance, and capacitance. The completion networks provide the user with the flexibility in selecting different type of transducers.
- o Provide for voltage amplification to normalized inputs to a multiplex system or analog tape recorder. The output of most transducers is in the millivolt range; therefore, some form of amplification is required to raise the amplitude to a level suitable for further processing. The

amplifier provides voltage gain and impedance matching between the transducer and the other parts of the recording system. Voltage inputs to data acquisition systems are configured to be either single-ended or differential. For large signals the single-ended is sufficient while for small signals and noisy environments the differential is recommended. An error source of significance is the common mode voltage which represents a voltage that is referenced to a zero potential point and is common to both input leads. The common mode error calculations are treated in detail in References 4.1.3 and 4.1.12.

- In signal conditioning, filters are used to remove undesirable frequency components or to enhance other frequency components of the signal. Signal conditioning analogue filters, often called wave filters, are frequency selective networks designed to 'pass' or transmit sinusoidal waves in one or more continuous frequency bands, and to 'stop' or reject sinusoidal waves in other bands. Analogue filters with single passbands are typically classified as high-pass, low-pass, and band-pass or band-reject (see, for example, Reference 4.1.13). In Section 4.9.4 methods and techniques of filtering are discussed, including applications in both real-time digital data acquisition and off-line data processing to prevent data contamination such as aliasing of the digitized signal.
- Provide for fault isolation.
- Provide for interchangeability to allow a given system channel to process a number of different type of transducers.

4.1.3.4 *Signal Transmission/Distribution*

The transmission of signals is a necessary part of any measurement system. Transmission simply indicates that the measurement system needs to make a measurement at one physical location and transmit the signal to another place for additional processing either for signal conditioning or data acquisition and processing. The primary requirement is to carry faithfully the required information without allowing external influences to degrade the validity of the acquired information. In a typical real-time system the signal transmission is by cables for distribution to the various components within the system. In an analog system the properties of cable resistance and capacitance need to be considered; in addition, signal contamination is possible by the pickup of noise voltages from a number of sources. The success or failure of measurement systems can be illustrated by one expression - the signal-to-noise ratio. It is a good design practice to focus on potential major noise sources such as signal cables and associated shielding, instrumentation grounding, and power supplies. Successful techniques for noise reduction are not well defined. However, noise is defined as an unwanted signal that interferes with the validity of the acquired signal and noise in transmission lines can be described as having its origin as a spurious resistance change or induced voltage. Induced voltage is an issue of grounding and shielding and successful methods are well described (Reference 4.1.14). The issue of spurious resistance changes is complex. It may occur within the bridge circuit, in lead wires, in connectors, due to effect of temperature, and in sophisticated mechanical and electromechanical switching and scanning devices. It is vitally important to minimize any noise present within the measurement system, and ideally this should be investigated during the checkout phase prior to the test. It is important to minimize noise sources in the early stages of the measurement system before the amplifier and recording elements. Filters can be of help, but filters will affect the response of the system and should be used with caution in transient measurements when signals with fast rise time are being measured.

Types of cables used to transmit analogue signals are normally shielded, twisted-pair, coaxial, or multi-conductor shielded. Cables are susceptible to noise pickup and capacitive coupling within the cable; therefore, the designer must select the best type for the application. In low-level signal environments, with the potential for ground loops and disturbances, the shielded (screened) cable with a differential amplifier is recommended.

4.1.3.5 *Data Acquisition and Processing*

The data acquisition and processing systems (discussed in Section 4.9) provide the interface between the instrumentation systems and the user of the data. They support the instrumentation systems by acquiring and processing the signals to produce an output that is in a format that the user can use. The outputs from the various signal conditioning systems are generally in the form of analogue electrical signals which allow for convenient processing with both analogue and digital systems. An analogue recording system can be used to preserve the real time-variant history of the transient event as characterized by the measured physical phenomena.

In view that the measurement system for most transient engine tests is designed to support a low bandwidth application (< 200Hz), a digital data acquisition system is the preferred method. Digital data acquisition systems convert analogue voltages into corresponding digital values by extracting relevant statistical properties of the real-time measurements. The incorporation of a sample-and-hold circuit is recommended based on the stated measurement objective to correlate two or more measurands in time (Section 4.9.3.2).

4.1.4 Calibration

The importance of calibration cannot be over-emphasized. It is the calibration procedures and methods that firmly establish control over the accuracy of the system components and, indeed, the whole system. In the hierarchy of calibration procedures it starts with the off-line calibrations of instruments against primary standards. Traceability is the key issue. ISO 9000 standards setting documents are required reading, and metrology laboratories which are ISO accredited should be preferred providers of calibration services. Primary calibration services are also available from standards organizations in the various NATO countries.

The accuracy of the instruments which quantify the measurands' properties is derived from standards. Periodically the instruments are calibrated in a metrology laboratory which is guided by the requirements delineated in standard documentation (e.g., Reference 4.1.15). The calibration procedure involves a comparison of the particular transducer or instrument with either a primary standard or a secondary standard with higher accuracy than the instrument to be calibrated. The user is also faced with the need to calibrate the overall system.

The measurement system, from the transducer/sensor output to the data processing, must meet the total measurement uncertainty. The calibration and analysis of a measurement system is a complex one because the system response is highly dependent on the system time constant and damping characteristics. The system calibration method establishes the corrections to be considered in the uncertainty analysis. Since the system dynamic behavior is dependent on time, frequency, and damping properties, an appropriate calibration method is required to describe the operational transfer functions of the system.

Ideally, complex and multi-component systems should be calibrated by exposing the sensor and transducer to a known input signal. The recorded output is then compared with the known input, and the interactions of all the system components are fully accounted for. This results in a calibration of the entire system from the sensor input to the data processing. Frequently, for example with transient pressure systems, the sensor cannot be exposed to a suitable input (pressure) signal. With such systems an electrical substitution method can be applied to audit the degree of accuracy of the system. In the electrical substitution method a transient signal is applied in place of the transducer, allowing overall system accountability to include system response to a sinusoidal transfer function which determines amplitude attenuation and phase shift for each of the input frequencies. In addition, the system's sensitivity from input to output, time correlation, and signal-to-noise ratio is evaluated. The definition of signal-to-noise ratio for any waveform is the ratio between the rms signal level within a specified frequency band to the rms value of the electrical noise.

4.1.5 Accuracy of the Measuring System

Calibration requirements and system performances specifications enable the user to make an objective evaluation for accuracy on a specific measurement system. Errors arise from many sources, with the errors having their origins in any part of the measuring system from the environment to the data acquisition system. The effect of some errors can be reduced or eliminated by proper calibration. However, errors arising from component and system response deficiencies or from transmission losses must be treated with analysis and dynamic calibration techniques. A calibration with known standards can determine the predictable inherent errors of the individual instruments and systems. The links within the measurement chain can be approximated generally as linear outputs of a first order or second order system where the output can be approximated by assuming time, frequency, and damping constants to define the measurement systems response (see Section 3.3.2). The output is then evaluated in terms of a transfer function modified by the appropriate time, frequency or damping constant (Figure 3-7). It is essential to be able to identify the errors and have methods to analyze them to establish uncertainty.

4.1.5.1 *Measurement Uncertainty*

The issue of measurement uncertainty is extensively covered in Section 3. The ideal approach in determining measurement system uncertainty is to test in place the entire measurement system from the measurand input to the final output. To test a measurement system's dynamic characteristics for the time variant behavior of the measurands presents a degree of difficulty. The system response can be described in terms of an impulse response function or sinusoidal transfer function, provided that the system response is linear. In estimating uncertainty, a linear approximation to the system transfer function can be employed. The significant dynamic errors are evaluated either from first order dynamic behavior which is dependent on a time constant, or from second order behavior that is dependent on frequency and damping constants (Section 3.3.2).

A complete accounting of the potential elemental errors in a measurement system is essential. The process of identifying elemental errors (References 4.1.10, 4.1.16, 4.1.17) has a few steps; 1) define the system, 2) consider the possible errors, 3) note the plausible errors for further analysis, and 4) classify as either bias (systematic) or precision (random). The following information is required for completeness:

Description of the measurement system,
Equipment manufacturer's specifications,
Operating environment,
Calibration methods,
Data sampling scheme.

4.1.5.2 *Data Validation*

The test data obtained should be subject to data validation analysis. In gas turbine transient testing the issue of data validation is a complex one; therefore, criteria are identified to provide guidance for the establishment of specific data validation functions to be used during the fundamental development of the measuring systems. In a typical test cycle the data validation issue is considered during the pre-test, test, and post-test phases of the test program. Basic improvements in the measurement system's uncertainty are possible by the examination of various concerns in each of the phases of the test program. The system designer should give careful thought to the design of the test program by asking some key questions. Some questions may seem rather elementary, but they should be asked frequently and throughout the progress of the test program. As a minimum, it is recommended that the following issues be examined by the system designer:

Pretest
Is the measurement system appropriate for the test objective?
Is the measurement system calibration current?
Is the measurement system performance adequate for the requirements?
During Test
On site calibrations
Comparison of predicted to measured responses
Redundant parameter correlation
Comparison of steady to non-steady measurements
Continuity and Polarity Checks
Post Test
Verify System Calibrations
Measurement usefulness to analytical needs
Uncertainty of the result

4.1.6 Integration of Data in Space and Time

Transient data gathered from various transducers throughout the engine can be categorized broadly as periodic and non-periodic. Periodic behavior implies potential characterization by frequency domain techniques, i.e., by frequency, amplitude and phase relationships. An example of a periodic behavior noted in turbine engines is that of rotor vibration occurring synchronously with rotation of one of the rotor systems. Vibration at one location in the system can be related through amplitude and phase to vibration at other locations.

Non-periodic behavior can be represented and interpreted in the time domain only, i.e., characterized by amplitude and time. Periodic events as well as non-periodic events in a turbine engine can be related in the time domain through mathematical expressions. Furthermore, in many instances an event occurring at one location in the engine can be interpreted and used to predict resultant time-based behavior at another location or of the entire system. An example of this would be the effect of an engine flame-out. The detection of flame-out by an appropriate sensor or sensors is a precursor to a series of time-related events throughout the propulsion unit: dropping of rotor speed, modulation of fuel flow, trimming of exhaust nozzles and resetting of variable vanes typify engine reaction to the flame-out. These time related phenomena throughout the engine are functions of many variables, yet can be characterized in the time domain in development testing.

To characterize either periodic or non-periodic behavior in a gas turbine engine requires accurate time based data from a strategically located array of sensors. Development and rig test programs which are typically more amenable to extensive instrumentation than production engines should be used to minimize this array. This minimization requires that relationships inboth time and space be fully characterized and understood.

Having signals of interest, either periodic or non-periodic, related to a common time base allows characterization of a system's transient behavior. Consider a periodic phenomena such as rotating stall which may exist in the part speed, transient operating range of a multistage compressor. During rig or development testing a multitude of high response pressure transducers located throughout the compression system would typically be used to accurately define any stall behavior. The detailed knowledge of the relationships existing between the pressures measured by each of the transducers would be used to determine locations where rotating stall could best be detected in the compressor. Using a minimal number of high response pressure transducers in the production engine, the signals obtained could be used to detect rotating stall, and a definition of the pressures throughout the compressor could be made using the inferred relationships obtained during the rig and development periods. This technique of inferring time-based behavior of engine components using experimentally derived relationships forms the basis of engine health monitoring systems.

4.1.6.1 *Adjustment of Non-Simultaneous Samples to a Common Time*

The analysis of time-based signals requires that an accurate amplitude versus time characterization be made. Positioning and skewing of heads in magnetic tape recorders, switching times required by analog to digital converters, lags and attenuation in amplifiers and filters and other phenomena create contaminated signals relative to an accurate amplitude versus time characteristic. In Section 4.1.4, calibration was discussed. In this section, particular attention will be focussed on techniques which adjust or correct time-based data to a common time base.

Time based errors can cause apparent phase shifts relating the harmonics of the periodic signals. Consider first the errors created by head locations in a magnetic tape recorder. These errors appear as a fixed time error independent of frequency. Two techniques can be used to align signals to a consistent time. The first is to use an input sinusoidal voltage at the frequencies of interest through all channels of the tape recorder and obtain phase shifts as functions of frequency for each of the channels to be analyzed. The phase relationships between the various signals can be obtained accurately by using electronic techniques to obtain the apparent phase angles and correcting by the phase shifts obtained in the calibration phase. The second technique involves relating time directly to phase shift as a function of frequency. Since the frequency can be defined with a characteristic time and the error created by head spacing can be defined in terms of a time interval through using phase shifts at a known frequency, this time interval divided by the characteristic time of any frequency yields the apparent phase shift between two signals. Either technique allows signals to be examined at a common point in time.

A particular problem in referring periodic signals to a common time occurs when a sequential analog-to-digital conversion is made of the signals. For this discussion, a sequential analog-to-digital conversion will be defined as one in which signals are sampled sequentially and at a fixed digitizing rate, consequently creating a small time differential to exist between the digitized data. This differential time will appear as apparent phase shift errors unless correction for the digitizing technique is made. AGARD Monograph No. 298 (Reference 4.1.18) presents a more detailed discussion of this method of signal analysis.

To relate non-periodic signals requires a definition of the time errors or times of acquisition between the signals. Phase cannot be used to relate them. The problem in correcting to a common time is more complex for non-periodic signals. Errors induced by head spacing in tape recorders and from analog to digital converters can be determined as for periodic signals. However, the time shifts arising from the electronic data reduction system which are a function of frequency are difficult to obtain. The use of square wave inputs delivered simultaneously into the measuring systems can be used to obtain time relationships between the signals and thus to correct to a common point in time.

4.1.6.2 *Determination of Station Average from Discrete Number of Measurements*

At several places within the engine there may be variations across the flow measurement plane in the value of the parameter (temperature, pressure or flow) of importance. To accurately determine the total (or mean) flow through the flow area (or the temperature and pressure distributions) a number of sensors or probes must be placed across the measurement plane. The recommended designs for such sensor rakes, and the principles for effective averaging of the measurements obtained, are described in Section 4 of Reference 4.1.3.

4.1.7 Primary and Derived Parameters

The described measurement systems with their accompanying capabilities and properties are used to provide primary measurements of specific states or quantities. The definitions presented here seek to clarify the difference between measured states and the gas turbine related parameters used to analyze engine thermodynamic, aerodynamic and mechanical performance. The following three types of parameters or measurements are defined:

A **primary** parameter is the physical state actually measured. The physical state is captured by the sensor, and the transducer transforms the physical state to a voltage and supplies the electrical representation to the data acquisition system. Primary measurement systems have a single measurand as an input and deliver a single time-varying output which is interpretable using a single calibration factor to convert to engineering units. Pressure is an example of a primary parameter.

Derived parameters are performance parameters calculated from two or more primary parameters. In the analysis of transient performance, derived parameters are typically used as inputs to transient computer models or as comparison values. Some examples are pressure ratio and station average.

Inferred parameters have either primary or derived parameters as inputs and are obtained as a result of calculations involving modelling and/or analytical fitting of experimental data. Examples of inferred parameters include airflow and component efficiency.

4.1.8 References

4.1.1 *The Uniform Engine Test Programme*, AGARD Advisory Report No. 248, February, 1990.

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4.1.3 Doebelin, E.O., *Measurement Systems*, McGraw-Hill, 1975.

4.1.4 Oppenheim, Willsky, and Young, *Signals and Systems*, Prentice-Hall, 1983.

4.1.5 Lim and Oppenheim, *Advanced Topics in Signal Processing*, Prentice-Hall, 1988.

4.1.6 Schwartz & Shaw, *Signal Processing*, McGraw-Hill, 1975.

4.1.7 Weaver, *Applications of Discrete and Continuous Fourier Analysis*, John Wiley & Sons, 1983.

4.1.8 *Techniques for Determining Engine Stall Recovery Characteristics* in *Engine Handling* AGARD Conference Proceedings No. 324, 1983.

4.1.9 *Measurement Uncertainty*, ANSI/ASME Power Test Code 19.1-1985(R1990), ASME, 1991

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4.1.11 *Measurement Uncertainty Within the Uniform Engine Test Programme*, AGARDograph No.307, May, 1989.

4.1.12 Taylor, J.L., *Computer Based Data Acquisition Systems - Design Techniques*, Instrument Society of America, 1986

4.1.13 Veatch, D.W., Bogue, R.K. *Analogue Signal Conditioning for Flight Test Instrumentation*, AGARD-AG-160-Vol. 17, 1986.

4.1.14 Morrison, R., *Grounding and Shielding Techniques in Instrumentation*, John Wiley & Son, Third Edition, 1986

4.1.15 ANSI/ASQC Standard MI-1987, America Society for Quality Control, 1987.

4.1.16 Coleman H.W. and Steele W.G.Jr., *Experimentation and Uncertainty Analysis for Engineers*, John Wiley and Sons, 1989.

4.1.17 Taylor, J.W., *Fundamentals of Measurement Error*, Neff Instrument Corporation, 1988.

4.1.18 Platzer, M.F. and Carta, F.O., *AGARD Manual on Aeroelasticity in Axial-Flow Turbomachines, Volume 1, Unsteady Turbomachinery Aerodynamics*, AGARD Monograph No. 298, March 1987.

See also:

Handbook on Experimental Mechanics, Society for Experimental Mechanics, 1987.

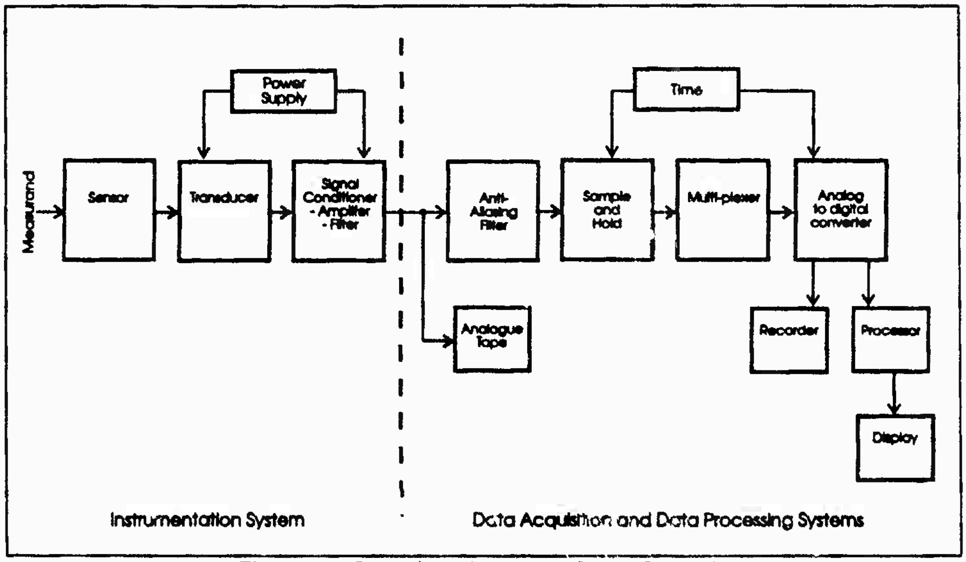

Figure 4.1-1 Generalized Measurement System Schematic

4.2 PRESSURE[1]

4.2.0 Introduction

The measurement of gas and liquid pressures is extremely important for monitoring or evaluating the transient operation of gas turbine engines. The types of engine tests discussed in Section 2.2 cause transients in internal gas path pressures, inlet/exhaust pressures, and control system liquid (fuel, lubricant, hydraulic) pressures. Transient pressure data can provide insight to the behavior of control and engine components, correlate with overall performance parameters such as airflow and thrust, and indicate engine instabilities.

Pressure measurements for steady-state component performance evaluation are described in Reference 4.2.1. The guidelines for steady-state pressure sensor selection apply as well for transient measurements with special consideration given to sensor location. Variations in mean flow direction and pressure gradients (discussed in Reference 4.2.1) can be significantly more severe during transients due to increased component operating ranges and effects of thermal transients, control system responses, and off-design or unbalanced cycle operating conditions.

Accuracy requirements and the amount and type of transient instrumentation will vary greatly depending upon the specific test objectives and resources available. Pressure data of a quantity and quality sufficient for the determination of actual component performance during transients are extremely difficult to obtain. Transient pressure data are more often used to qualitatively evaluate component or engine operation, to monitor for specific identifiable events like light-off/flameout, stall, or instability, and to diagnose operational problems by establishing a sequence of events and identifying cause and effect relationships.

In the following paragraphs, the fundamental considerations for transient pressure measurements will be discussed with regard to test objectives, available instrumentation options, and the advantages-disadvantages of each. The engineer should remember that the measurement system in the engine test environment is typically exposed to vibrations, fuel, oil and hydraulic fluids, heat and/or cold, and large amounts of electro-magnetic noise. Unnecessarily sensitive or delicate equipment is likely to fail, making the best solution the system that just meets the user's requirements with the highest reliability and lowest cost.

4.2.1 Transient Pressure Measurement Systems

It is important to clearly identify the objectives of the testing so that appropriate instrumentation requirements can be defined. Objectives include the planned data reduction and analysis procedures, amplitude and frequency ranges of the fluctuating pressures of interest, required accuracy in amplitude and phase (time), and method of data acquisition or recording. Non-steady pressures of interest for the types of tests described in Section 2.2 may be very periodic such as result from rotating stall or combustor and augmentor instabilities. For these conditions the user must anticipate the frequency and nature (spectral content) of the waveform to determine the frequency response of the instrumentation necessary to meet the test objectives. The more common case is for the non-steady pressures to be transient in nature without significant periodicity. Frequency response requirements are then associated with the minimum rise (or decay) time of the pressure signal.

The pressure sensor is defined in Reference 4.2.1 as an open-ended tube or port facing into the gas stream for total-pressure measurement or flush with a wall for static-pressure measurement. The tube transmits the pressure to a transducer which converts pressure into a readable signal. The difference between steady-state and transient pressure measurement systems is in the required response characteristic (transfer function) of the recorded signal to a time variant pressure at the sensing end of the tube. The tube length and cross-sectional area, and other cavities/volumes between the sensor end and the transducer must be sized considering the resulting amplitude attenuation, phase shift, and resonances of the system. The transducer must have acceptable response capability for the pressure amplitude and frequency range of interest and generate a signal which is suitable for display or recording as a function of time. These requirements

[1] Table and Figures for Section 4.2 begin on page 4-36

generally lead to the use of transducers producing electrical signals and located close to the sensing end of the tube. A schematic showing the instrumentation portion of the transient pressure measuring system is shown in Figure 4.2-1 (See also Figure 3-7).

The transient pressure instrumentation system shown in Figure 4.2-1 consists of 3 major functional elements: 1) the sensor and transmission tube capture and deliver the pressure signal to the transducer, 2) the transducer converts the pressure to an electrical signal, and 3) the signal conditioning components alter the characteristics of the electrical signal to match the input requirements of the data acquisition and processing device(s) (which are discussed generally in Section 4.9).

This section (Section 4.2.1) covers the sensor/transmission tube and transducer including the transducer reference pressure. Signal conditioning is discussed in Section 4.2.4.

4.2.1.2 *Pressure Transducer*

Many types of pressure transducers are available including strain gauge, capacitive, variable inductance, potentiometric, and piezo-electric. Descriptions and general characteristics of these devices are contained in Reference 4.2.2. Most pressure transducers currently used for transient measurements are based on either piezo-electric or semiconductor (strain gauge type) components. Piezo-electric transducers produce small electric charges when a quartz crystal is deformed due to pressure fluctuations. A primary drawback to these devices is that they respond to the dynamic portion of the pressure signal only and provide no information about the steady or slowly changing pressure levels. Another limitation is that piezo-electric transducers have relatively large frontal areas and cannot be used where a miniature sensor or probe is required.

Semiconductor transducers are the most widely used today and will be discussed exclusively in the remainder of this section. Semiconductor pressure transducers produce electrical signals proportional to the surface strains in a mechanical member which deflects due to a differential between the pressure signal and a reference pressure (see Section 4.2.2.3). A schematic of the pressure transducer is included as Figure 4.2-2. The electrical output of the transducer is generated by excitation (see Section 4.2.4.1) of two opposite corners of a four-arm strain gauge bridge attached to the deflecting mechanical member. The electrical potential or output voltage across the remaining two corners of the bridge will vary as the resistances of the bridge arms change with strain level.

The transducer output is affected by installation or mounting-induced loads and thermal stresses which affect the loading and strain on the mechanical member. Most transducers contain circuitry to reduce the impact of thermal stress (temperature compensation). Careful signal conditioning and calibrations (see Sections 4.2.4 and 4.2.5) can reduce measurement uncertainties resulting from the installation. Requirements for high frequency response, small transducer size, and low cost often result in compromised accuracy, stability, and ruggedness. It is important to understand the trade-offs and to select a transducer consistent with overall measurement system characteristics to best meet the user's needs.

A representative variety of transducers is shown in Figure 4.2-3. Table 4.2-1 is a typical transducer specification sheet provided by the manufacturer. The parameters in Table 4.2-1 are explained further in Section 4.2.2.2. Transient measurements generally require the use of a separate transducer for each sensor since mechanical scanning devices (scanning valves) are too slow for the sampling rates necessary. Compact systems are available containing multiple transducers which are scanned electronically. Very high sampling rates can be achieved and these devices are well suited for use with a digital data acquisition system. An example is shown in Figure 4.2-4.

4.2.1.3 *Flush Mounted System*

When the transducer is "flush mounted", the tube in Figure 4.2-1 is eliminated. The transducer diaphragm (deflecting mechanical member, see Section 4.2.1.2) is directly exposed to the pressure to be sensed, that is, flush with the wall for static-pressure measurement or forward facing (impact probe) in the total-pressure probe as shown in Figure 4.2-5. This configuration eliminates the transmission tube effects, discussed in Section 4.2.2.1, which result from tubing length and volumes between the sensor and the transducer. Drawbacks to flush mounting are presented in Section 4.2.3 and result primarily from space/accessibility restrictions for installation and operating environment effects on the transducer. High temperatures, contamination, or damage from the fluid or from fluid borne particles and vibrations can be problems. Directional sensitivity for a total-pressure probe must also be considered and should be experimentally determined.

Flush mounting eliminates distortion of the pressure signal seen by the transducer. It can be a desirable configuration when the installation problems are not prohibitive. The example shown in Figure 4.2-6 is typical of this type of installation. A high-response transducer (see Section 4.2.1.2) is flush mounted on the outer flowpath wall of the bypass duct of an augmented turbofan engine. The transient static-pressure data can be used to evaluate duct pressure variations resulting from rotor speed, nozzle, or augmentor transients. The high-response transducer output recorded on analogue tape provides significant detail of the duct pressure during an engine surge.

The frequency response potential of a flush-mounted system is limited only by the transducer. The pressure range and temperature capability of the transducer (typically less than about 500K (450°F)) are selected based on operating conditions of the sensed fluid and surrounding environment to avoid transducer damage or large uncertainties caused by operation beyond the rated limits of the transducer. Other major considerations are the space available for installation checkout and repair, the effects of vibration, and possible exposure to engine fuel, lubricant, and hydraulic fluids.

Flush mounted systems are ideal when signal distortion cannot be tolerated, for example, when multiple pressure measurements are to be time correlated. Flush mounted systems are most often used in the inlet or forward compression stages of the engine where temperatures are relatively low and the flowpath is generally more accessible. Small or miniature transducers may be necessary due to space and mounting considei ıtions.

A special ι ase of the flush mounted system is the surface mounted ıransducer shown in Figure 4.2-3. This is a low-profile, miniaturized transducer which is bonded directly to or imbedded in the flowpath or airfoil surface. The electrical leads are also either secured to or imbedded in the surface until they can be routed externally. This arrangement is especially useful on static parts such as frame struts or stator vanes where there is insufficient depth for a conventional installation or when hardware modification required to install a conventional transducer is not possible.

4.2.1.4 *Resonant System*

A resonant system uses a pneumatic or hydraulic tube to transmit the pressure signal from the sensor to the transducer. The length and diameter of the tube will vary significantly depending on the installation constraints and user's data objectives. The advantage of the resonant system is in the installation flexibility gained by removing the transducer from direct exposure to the fluid at the sensor. Figure 4.2-7 shows a typical (static pressure) resonant system.

Many of the problems associated with flush mounted systems can be eliminated with the resonant configuration. Most internal parts of the engine can be instrumented during buildup or with partial disassembly. A tube is attached to the static or total-pressure sensor and routed out to an accessible location where the transducer is mounted. This permits the use of larger, more stable transducers and liquid or gas cooling can be used, if necessary, to enhance transducer survivability and data accuracy. The transducer may also be accessible for calibration, trouble shooting, or replacement.

A second example of a resonant system is shown in Figure 4.2-8. The transducer is connected by a short flexible hose to a fitting on the engine control sensor line for compressor discharge pressure. The engine control sensor line is a 6 mm (1/4 inch) tube, more than a metre (several feet) in length, connecting a static-pressure tap in the combustor to the hydromechanical control unit. The transient pressure measurement records control-sensed compressor-discharge pressure for monitoring engine operation as well as for evaluating control system response. Figure 4.2-8 shows transient pressure data recorded on a pen plotter versus engine speed during accel and decel transients.

The primary consideration when designing resonant systems is distortion of the pressure signal by the transmission tube. For transients such as surge/stall, combustor or augmentor instabilities, or control system responses, a frequency response up to a hundred hertz or more may be achieved with short (about 10 cm (4 inch)) tube lengths.

Response requirements on the order of 10 Hz for engine speed and augmentor fueling transients permit the use of longer tubing. Amplitude attenuation, phase shift, and acoustic resonances must be evaluated to assure that limitations are understood and the user's data requirements are met. Analytic and experimental techniques for determining system characteristics are presented in Sections 4.2.2.1 and 4.2.5.

4.2.1.5 *Non-Resonant System*

When the minimum length of tubing required for installation results in acoustic resonances in the frequency range of interest, a non-resonant system may be necessary. A non-resonant system places the transducer as close as possible to the sensor but the transmission tube extends beyond the transducer a length sufficient to eliminate reflected signals (length/diameter greater than about 5000). Resonances are eliminated due to the damping effect of the long tube. A non-resonant system is shown schematically in Figure 4.2-9. The transducer is flush mounted to the side of the transmission tube which extends several metres in additional length. The tube may be capped, connected to the steady-state data system, or to the reference side of the transducer (see Section 4.2.2.3).

Precise response characteristics of a non-resonant system are difficult to predict when the tubing length between the sensor and transducer is longer than several centimetres. Experimental evaluation as described in Section 4.2.5 is recommended. The length between the sensor end and the transducer should be kept as short as possible and equal lengths used when phase relationships between multiple measurements are important. Resonances can result from discontinuities in the tube cross-sectional area, sharp bends, and defects which present reflection surfaces to the pressure waves. Attention to detail during fabrication and bench testing can reduce the chances of this becoming a problem.

Two examples of non-resonant systems are included to show their application over a range of data requirements. Figure 4.2-10 shows a radial rake containing total-pressure sensors. A high-response transducer is flush mounted to the side of the tube extending from each sensor and continuing out of the rake to the steady-state data system. The tube connecting the sensor to the steady-state system acts as the "infinite" length for the non-resonant transient system. In this example, accurate amplitude and phase response are maintained up to about 500 Hz as a result of the short length between the sensor and the transducer. Notice also that the transducer is protected from direct exposure to impact damage and can be made replaceable without removing the rake. This installation does require a miniature, high-response transducer which is subjected to the temperature environment within the rake body and flow path air on the diaphragm.

A second example is shown in Figure 4.2-11. In this case the user's requirement is to monitor for the presence of augmentor instability with a known characteristic frequency on the order of a few hundred hertz. The precise amplitude of the instability is of secondary importance so long as safe operation can be maintained based on previously established limits for this type of measurement. The use of a non-resonant system greatly simplifies installation and allows the transducer to be located in a suitable (cooled) operating environment. The remotely mounted non-resonant system works well in this example where uncertainty in phase is not important and the amplitude attenuation is within the established test limits.

4.2.1.6 *Differential Pressure System*

The data of interest may be a differential pressure rather than an absolute pressure level. Examples are the difference between total and static pressure or the pressure drop across an orifice. When the differential pressure is only a fraction of the absolute pressure level, the uncertainty resulting from comparing individual measurements may be unacceptably large. Direct measurement of the differential pressure of interest allows the instrumentation system to be designed for the lower range measurement resulting in significantly improved accuracy. This approach is analogous to treating one of the pressures as the transducer reference (see Section 4.2.2.3) and the other as the sensed pressure.

An example of the transient measurement of a differential pressure is shown in Figure 4.2-12. The measurement of interest is the drop in fuel pressure across the compressor inlet temperature sensor of a hydromechanical control system. The pressure drop is proportional to the temperature of the air surrounding the sensor and represents the compressor inlet temperature input signal to the hydromechanical control unit.

A differential pressure transducer is close coupled to the fuel lines connecting the temperature sensor with the control unit. The measured pressure data are then converted to temperature units using the sensor manufacturer's calibration data. Control sensor response during engine operation can be evaluated if independent transient measurements of compressor inlet temperature are available. Also, control system response to sensed temperature (input) transients can be compared to the predicted behaviour based on the known temperature input signal.

There are transducers designed specifically for measuring differential pressures. An example is included in Figure 4.2-3. It is important to check with the manufacturer before selecting a transducer when both pressures are anticipated to be changing rapidly with time. The response characteristics of a transducer to fluctuating pressures on the reference and sensing sides can be quite different from the steady state calibrations.

4.2.1.7 *Engine Control Sensors*

Internal engine pressures are used in controlling most engines. These control pressures can often be tapped as a convenient source of transient data. This is especially important for the user with limited ability to modify or rework engine hardware to add instrumentation.

Hydromechanical controls use the actual pressure signals as input with tubes transmitting the pressures to the control unit. The response characteristics of these control sensor systems are generally well understood and well matched to engine transient operation. As discussed in the example in Section 4.2.1.4, transient pressure data can be acquired by installing an instrumentation fitting or by temporarily replacing the engine control tube with an instrumented "slave" tube. Care must be taken not to disrupt the normal operation of the control system. A flush mounted or close-coupled resonant system, which does not add significant volume to the sensor tube, is a good choice.

Engines with electrical or electronic controls have transducers which convert pressures to electrical signals for use within the control unit. For these engines it may be possible to record either the analog electrical output of the transducer or the digitized signal in the case of a digital control. Again, care must be taken to properly isolate the engine control from being influenced by the presence of the data acquisition system. The user should be aware of the characteristics of the digital control data such as update rate and phase relationships with other control sensed parameters which may also be recorded.

Figure 4.2-13 shows an example of transient data recorded at the data buss interface with a digital engine control. Compressor discharge pressure (PS3) is used by the control in limiting maximum and minimum fuel flow rates. A two-pulse compressor surge can be seen clearly during the initial accel from idle in the example of engine test data shown in the figure. The speed and fuel flow signals in the figure were also acquired from the engine control.

Control system parameters and their use in transient engine testing are discussed further in Section 4.7.

4.2.2 Basic Theory of Transient Pressure Measurement

4.2.2.1 *Transmission Tube*

The transmission tube must transmit the pressure signal, without unacceptable amplitude attenuation/amplification or phase shift, from the sensor to a transducer. Distortions of the pressure signal result from the tubing length and volumes which connect the sensor port to the transducer. For the transients described in Section 2.2, the required maximum frequencies are typically less than 1/rev of the rotor speed but the amplitudes can be quite large, especially at the lower frequencies.

4.2.2.1.1 *Amplitude Attenuation and Phase Shift*

Flush-mounted systems described in Section 4.2.1.3 completely eliminate the transmission tube. The transducer and data acquisition system become the limiting elements providing the highest frequency response potential with the minimum amplitude or phase distortion. In practice this arrangement is not always practical due to the limitations discussed in Sections 4.2.1.3 and 4.2.3. The addition of a tube and/or volume between the sensor port and transducer can result in amplitude and phase shifts in the pressure signal at the transducer relative to the true signal at the sensor port.

For resonant and non-resonant systems, the time-variant pressure travels as a compression or rarefaction wave through the tube, and the tube volume fills or empties with large pressure changes at the sensor. A schematic showing system elements and effects to be considered is given in Figure 4.2-14. The behavior of all but the simplest systems is difficult to predict analytically with certainty. Bench testing is useful but often the installed operational environment cannot be duplicated. Therefore, analytical and experimental techniques typically cannot provide information suitable to completely "correct" the measured data. Analysis and bench test results establish a confidence level which can be quantified for inclusion in the uncertainty analysis described in Section 3.

A variety of analytical models have been developed to predict response, at the termination or intermediate points of fluid systems made up of tubing and cavities, to a changing pressure at the entrance. The following references are included to aid the user in selecting a suitable analytical approach for his specific application. All methods are based on fundamental fluids equations (Navier-Stokes, continuity, energy, and state equations) and/or analogies to other physical systems (electrical, mechanical). Simplifying assumptions are made in all cases so that practical solutions may be obtained. Many of the references include examples and comparisons with experimental results. The user is encouraged to carefully review the derivations, assumptions, and limits of applicability included in the references. Keep in mind that the response of a system will vary with tube geometry, fluid properties, and the specific nature of the pressure signal such as frequency, amplitude, and shape of the pressure waveform. Whenever doubt exists as to the suitability of the measurement system for the specific user requirement, the experimental techniques discussed in Section 4.2.5 should be employed.

Reference 4.2.3:
- o Based on equations for unsteady, compressible, laminar flow in circular tubes of a constant volume system. See Figure 4.2-15 for sketch of system and output format.
- o Analog computer used to solve equation.
- o Experimental verification presented.
- o Specific application in the reference is pressure measurement in intermittent wind tunnels.

Reference 4.2.4:
- o Based on one-dimensional equations with nonlinear terms in continuity and momentum equations, viscous effects handled in a quasi-steady manner.
- o Equations reduced to ordinary nonlinear differential difference equations.
- o Experimental verification presented. Effects of line length and diameter, chamber volume, and pressure step magnitude and direction are given. See Figure 4.2-16 for sketch of system and output format.
- o Specific application in the reference is for long line lengths (greater than 30 metres (100 ft)).

Reference 4.2.5 :
- o Pressure propagation through thin circular tubes with connected volumes. Based on fundamental flow equations. Explicit formulae are developed for a single tube-volume and for a tube-volume-tube-volume system with sinusoidal input. See Figure 4.2-17 for sketch of system and output format.
- o Experimental verifications presented.
- o Specific application in the reference is the measurement of pressure distributions on oscillating windtunnel models.

Reference 4.2.6:
- o Single tube and cavity systems filled with a liquid. Based on energy methods. See Figure 4.2-18 for sketch of system.
- o Estimation of damping ratios and natural frequencies for a first order system.

Reference 4.2.7:
- o Application of Reference 4.2.5 equations to short (2.54 cm (1 in)) probes. See Figure 4.2-19 for sketch of system and output format.
- o Experimental verification presented.
- o Effects of probe configurations for particle impingement protection and variations in entrance flow area.
- o Includes computer program listing for solutions to equations.

Reference 4.2.8:
- o Steady-state equations developed based on empirical observations describing flow through a tube and then extended into a quasi-steady analysis of the transient flows when the system is closed on one end.
- o Comparisons with experimental results for impulse, continuous, and shock-type inlet pressure transients. See Figure 4.2-20 for sketch of system and output format. Specific application in the reference is for missile pressure sensing systems.

Reference 4.2.9:
- o Method for predicting amplitude-frequency response of blocked pneumatic lines for signal frequencies higher than the characteristic frequency of the system. See Figure 4.2-21 for output format.
- o Based on electrical analogy.
- o Experimental verification presented.
- o Nomograph method is presented for first order approximation.

Reference 4.2.10:
- o Application of methods from various referenced sources to some specific problems. Solutions to time responses of a capillary connected to a relatively large volume and for a system of tubing only filled with gas or liquid. See Figure 4.2-22 for output format.
- o Worked out examples.

4.2.2.1.2 *System Resonances*

The natural or resonant frequency of the probe and transmission tube must be kept well above the range of interest to the user so that false indications and amplification of the actual pressure signal are avoided. A first approximation of the fundamental frequency of a resonant system with no cavity (volume) at the end can be obtained using the expression for a standing wave in an open-closed pipe.

$$f_R = \frac{a}{4L} \qquad 4.2\text{-}1$$

where: f_R = resonant frequency
a = speed of sound
L = length of tube

Some sensor/probe configurations include a blockage in the tube ahead of the transducer to prevent particle impingement damage. The acoustic resonance due to communication of the cavity created between the transducer and the blockage with the external air, is analogous to a spring-mass system and is called a Helmholtz resonance. The resonant frequency for such a configuration is given in Reference 4.2.11 by

$$f_a = \frac{a}{2\pi}\sqrt{\frac{A}{LV}} \qquad 4.2\text{-}2$$

with the configuration as shown in Figure 4.2-23.

To assure a flat response, the predicted resonant frequency of the system should be kept at least five times above the highest frequency of interest to the user. Filtering techniques should be employed as discussed in Section 4.2.4.3 to remove data which are outside the flat response range of the instrumentation system.

Unexpected resonances in non-resonant systems can result from discontinuities in cross-sectional area, sharp bends, or defects in the tubing which act as reflection surfaces. These should be avoided through care in the design and manufacture of the system. The example shown in Figure 4.2-24 is the measured response of two non-resonant systems of the type discussed in Section 4.2.1.5. Note the expected rolloff (amplitude attenuation) above 500 Hz due to the damping effect of the tube. The system made with tubing which was not deburred shows significant resonances in the range below 500 Hz. This example points out the importance of experimentally verifying the performance of the system to avoid misinterpretation of the data obtained.

4.2.2.2 *Transducer Characteristics*

The transducer specification sheet shown in Table 4.2-1 is typical of what is available from manufacturer's literature. Reference 4.2.1 gives good explanations for many of the characteristics which are important in the selection of a transducer for transient pressure measurements. A portion of the text taken directly from Section 5.3.4 of Reference 4.2.1 is included below.

RANGE: Most manufacturers recommend a maximum pressure based on a specified departure from linear response. Ordinarily, a transducer should be selected which will operate for the given test at 50 to 90 percent of its full scale range.

OVERRANGE: This is usually the maximum pressure the transducer can sustain without damage. Overrange operation can result in calibration shifts in some transducers. Where overrange operation is necessary, some transducers provide positive stops to avoid distressing the diaphragm, or other mechanical member.

REFERENCE PRESSURE: Arrangements available include: gauge - referenced to ambient through an open tube, absolute - referenced to zero in a sealed internal cavity, differential - referenced to a second pressure source. Some transducers are provided with sealed internal gauge references.

SENSITIVITY: Electric output per unit pressure input such as millivolts per kPa (mv/psi). [Normally defined for a specified excitation voltage.] Usually refers to the average value over the operating range.

RESONANCE FREQUENCY: In a diaphragm transducer, the resonant frequency of the diaphragm. For non-steady measurements, the resonant frequency should be typically five times the maximum frequency to be measured. In steady-state measurements, it is only necessary to ensure that excitation of the transducer resonant frequency is avoided.

OUTPUT IMPEDANCE: Important for the design of the data acquisition system. Affects input filter characteristics.

NON-LINEARITY: A variety of specific definitions are used but typically refers to the maximum deviation of any calibration points from a best straight line fit. Where detailed calibration curves are used linearity may not be as important as stability of the calibration.

HYSTERESIS: This is the tendency of the transducer to produce a different output when a give pressure is approached from a higher value or a lower value. It can have a number of specific definitions but is typically quoted as the maximum difference to be expected in percent of full scale.

TEMPERATURE RANGE: This can mean either the temperature range over which the stated transducer specifications are valid or alternatively the range over which the transducer can operate without damage. In transducers having built-in temperature compensation, the former is frequently called the compensated temperature range and the latter the operating temperature range. The upper and lower temperature limits are used to specify the range; and, where the exact meaning is not clear, one should check with the manufacturer.

THERMAL SENSITIVITY SHIFT: All pressure transducers exhibit more or less temperature dependence and most include some built in means of compensation. The remaining effects are specified as percent change in sensitivity over the given temperature range.

THERMAL ZERO SHIFT: In addition to the sensitivity shift, most transducers exhibit a temperature dependent zero shift which requires internal compensation. The residual effect is again typically specified as max. zero shift over the operating temperature range.

ACCELERATION SENSITIVITY: Most transducers are more or less sensitive to shock and mechanical strains. One of several indicators of such sensitivity is this specification given as percent full scale per acceleration.

MEDIA COMPATIBILITY: Since some portion of the sensitive part of the transducer must come in contact with the medium in which the pressure is to be measured, restrictions are frequently placed on the nature of this medium. In gas turbine applications, the transducer must be tolerant of water and combustion gases. Transducers designed for use with liquid water, fuel, or oil are sometimes referred to as "wet" transducers.

ACCURACY: The meaning of the term "accuracy" sometimes specified by the transducer supplier should be obtained from that supplier. It frequently is defined as the root sum square of linearity, hysteresis, and repeatability as obtained under some prescribed conditions in the supplier laboratory tests. The user should consider it as a guide only and, in any given measurement system, the "uncertainty" attributable to the transducer should be obtained via the defined measurement process and calibration hierarchy as described elsewhere in this document.

PRECISION/REPEATABILITY: Again, the transducer supplier should be queried for the specific definition when these terms are included in the transducer specification. Within the measurement uncertainty protocol used in this document, this normally should be the "precision error" obtained by the supplier in his own evaluations and should be used as a guide only.

The transducer characteristics listed above are important considerations in the selection of a transducer but are not sufficient in themselves to allow the accuracy of a transducer to be deduced. The transducer sensitivity and null output are affected by temperature, vibration and mechanical loading so that calibrations should be evaluated in the environment of actual use. In-place calibrations are discussed in Section 4.2.5 but are usually not practical under actual test conditions (engine running). The data provided in the manufacturer's specifications plus experimentally derived characteristics (see Section 4.2.5) must be considered for the anticipated test environment to determine the sources and magnitudes of calibration errors for the uncertainty analysis described in Section 3.

The selection of a transducer for the transient pressure measurement system should be made considering the user's data objectives and consistent with the overall characteristics of the measurement system. The transducer generally will not be the limiting element for frequency response since those available (as indicated in Table 4.2-1) have resonant frequencies far above that required for the types of transient tests described in Section 2.2. Pressure range, installation considerations, and operating environment will usually dictate the selection. It should be remembered that the smaller and higher-response transducers are typically more expensive, less accurate, and less rugged than larger units. Miniature transducers should be used only when required by installation constraints.

Over-specification of transducer requirements can actually compromise data quality. An example is the case where the stated frequency response requirement is unnecessarily high. The stated requirement might lead to a design using flush mounted, miniature transducers exposed to severe temperature excursions during the transient tests. This instrumentation would probably result in data with a relatively large uncertainty due to the unpredictable impact of temperature on the pressure measurement. The complexity and cost of the instrumentation could also be higher than what it takes to meet the actual frequency requirement. A realistic requirement could possibly be met with a resonant or non-resonant system using more accurate and lower cost transducers in an accessible location where temperature can be controlled.

Selection of a transducer should be made as part of the system design process with full knowledge of the data requirements and the impact of the transducer characteristics on the system's ability to meet those requirements.

4.2.2.3 *Reference Systems*

The transducer output is proportional to the pressure differential across a deflecting mechanical member (diaphragm). Thus far in Section 4.2, discussion has focused on the pressure on the sensing side of the transducer diaphragm. The pressure on the reference side is also a key consideration in transient pressure measurement and several options are described in the following paragraphs.

4.2.2.3.1 *Absolute Pressure Transducer*

Many transducers are manufactured with an evacuated cavity (pressure < 0.1 kPa) on the reference side of the diaphragm. This type is referred to as an absolute transducer with the output proportional to the absolute level of the sensed pressure. The absolute transducer has the advantage that the reference condition is always known and does not change. The disadvantage is that the transducer range must be sufficient to cover all pressure levels for the testing of interest to the user. This can result in relatively lower output signal levels when the sensed pressure is low or when the amplitude fluctuations in the sensed pressure are small. These conditions should be identified in the user's requirements (see Section 4.2.3) and considered when selecting the transducer. Amplifier gain settings can be adjusted to match the transducer output and operating pressure level to the recorder range for specific portions of the testing. However, this may disrupt testing and should be considered only when necessary. The maximum operating pressure anticipated must also be considered to avoid damaging the transducer. A shutoff valve in the sensing tube can be used to protect a low range transducer during operation at high pressure levels. Also, when required, transducers are available with mechanical overrange protection features. These steps are not required for all applications and adequate quality data can often be obtained using absolute transducers.

4.2.2.3.2 *Floating Reference Pressure*

The maximum differential pressure across the transducer diaphragm can be reduced by treating the reference pressure as a variable in the instrumentation design process. A transducer with this capability has a tube or fitting connected to the reference pressure side. The reference side can be connected to whatever source provides the desired characteristic. The transducer reference is often vented to the ambient (test cell) environment which changes with operating condition so that the differential pressure across the transducer is less than the absolute pressure level. This works well in altitude facilities when the testing includes significant variations in ambient pressure. The disadvantage is that the reference pressure must also be monitored. If absolute pressure is the desired measurement, it can be calculated by adding the sensed (differential) pressure to the independently measured reference pressure. This becomes more of a problem when the reference is vented to an area where pressure is not constant during test transients. A separate transient pressure measurement system may now be required to record the reference pressure. For multiple differential pressure measurements, the reference sides may be manifolded together. This configuration assures that all measurements are referenced to the same pressure and minimizes the number of measurements required to monitor the reference pressure.

When a very small pressure differential must be maintained across the transducer, the reference side may be connected to the same pressure source as the sensing side. A delay in the reference side response to a changing pressure at the sensor results in a differential pressure across the transducer. The delay is achieved by use of long tubing lengths or a volume and orifice between the sensed pressure and the reference side pressure. This configuration is in effect a pneumatic high-pass filter. The response characteristics of this configuration must be evaluated experimentally and understood to avoid misinterpretation of the data. The advantage is that a low range transducer can be used to sense small pressure fluctuations at elevated pressure levels. An example of this configuration is the non-resonant system with the end of the tube downstream of the coils attached to the reference side of the transducer. This is shown schematically in Figure 4.2-25.

4.2.2.3.3 *Controlled Reference Pressure*

Another advantage of the transducer with a reference tube is the potential to apply a pressure to the reference side with the system installed on the engine. This is beneficial during checkout and troubleshooting and can be used for calibration (see Section 4.2.5). An extension of this idea is to connect the reference tube to a source which can be remotely adjusted to best meet the requirements of specific test conditions. One approach to this is the "zero-operate-calibrate" (ZOC) system shown in Figure 4.2-26.

This system has three remotely selectable operating modes. The "operate" mode provides an adjustable reference pressure which is set to meet the particular test requirements. This would normally be the mode used during testing/data acquisition. The "zero" mode connects the sensed pressure to the reference side as discussed in Section 4.2.2.3.2. This mode can be used when pneumatic AC coupling is desired or during calibration to check or adjust the null output of the transducer at a condition of zero pressure differential. The "calibrate" mode is a second reference pressure level which can be used in conjunction with the "operate" and "zero" modes to establish the overall system sensitivity. This can be done installed and with the engine operating at test conditions so that all elements of the instrumentation system are included.

Much simpler systems can be used when the complexity of a ZOC system is not warranted. The simplest may be a tank or manifold which is charged with a known pressure and to which the reference tube is connected. A potential problem with reference pressure systems is leakage. When the reference pressure is not equal to the ambient environment of the transducer, leakage in the reference tube can cause the actual pressure on the reference side of the transducer to be different from that measured in the reference tank or manifold. This problem may go unnoticed and care should be taken to leak-check the system before and after testing.

4.2.3 Advantages and Disadvantages

The advantages and disadvantages of the different types of transient pressure instrumentation systems are summarized in Table 4.2-2 as an aid in selecting the system which best meets a specific user's objectives. A flush-mounted transducer offers the advantage of the highest potential frequency response capability. Signal distortions associated with transmission tubing and volumes are eliminated. The disadvantages stem from the need to mount the transducer directly to the sensor. Space and accessibility are typically constraints which may be prohibitive or at least necessitate the use of miniature transducers. The smaller transducers generally are more expensive, more fragile, and less accurate. Direct exposure to the fluid being measured can present problems of contamination, corrosion, or particle impingement damage to the transducer. Temperature variations of the fluid contacting the transducer can also impact measurement accuracy.

Most of the disadvantages of flush mounting can be reduced with a resonant system employing a transmission tube which allows the transducer to be located in a more convenient place. Larger, more rugged, and more accurate transducers can often be used enhancing system performance and reliability. Techniques for controlling the transducer operating environment (temperature) are more readily applied. External mounting locations also allow access to the transducer for checkout, calibration, or replacement. The disadvantage with these systems is the signal distortion resulting from the transmission tube and volumes. Acoustic resonances limit the useful frequency range of systems with relatively short tubes where viscous damping effects are not large. These resonant frequencies must be determined by the techni discussed in Sections 4.2.2.1 and 4.2.5.3 to problems with interpretation of the data. Systems with long tubing lengths or very small (capillary) tubes and volumes at the transducer can have significant viscous damping effects. The response will be like a first order system with the disadvantages of signal amplitude attenuation and phase shift. These effects must also be carefully evaluated as discussed in Sections 4.2.2.1 and 4.2.5.3.

Sometimes the required tubing length is too long to avoid resonances in the frequency range of interest and additional damping from a longer tube would result in unacceptable amplitude attenuation and phase shift. A non-resonant system can be employed with the advantage of eliminating the acoustic resonances associated with the length of tubing between the sensor and transducer. The response characteristics of this configuration can be evaluated using the experimental techniques of Section 4.2.5.3.

A differential transducer should be used when the measurement of interest is a relatively small difference between two pressures. A disadvantage for higher frequency data requirements is that the response characteristics of the two sides of the transducer may not be the same. The manufacturer should be consulted if this is a concern. Also, a second measurement is required if the absolute pressure is of interest.

The major advantages to using control signals as transient pressure measurement sources are that they are in place, often relatively easy to access, and their response characteristics should be well understood. On the other hand, the response characteristics cannot be changed and might not meet the user's requirements. Care must be taken not to alter the normal operation of the engine and control as a result of instrumentation application.

The advantages and disadvantages of the various types of transient pressure measurement systems must really be viewed with respect to the specific requirements identified by the user. The user must specify the requirements in such a manner that they can be used in the process of selecting a measurement system. The following guidelines are suggested for specification of requirements.

DESCRIPTION OF CONDITIONS AT THE SENSOR:

1. Identify where in the engine and what type of pressure is to be sensed. Engine station or axial location, flowpath, wall or immersion, and static or total pressure must be specified. If there is an existing probe/sensor or potential access through a borescope plug, instrumentation fitting, bleed port cap, etc., include this information. A verbal or written description of the pressure or physical phenomena of interest is often helpful to the instrumentation designer.

2. Describe the type of testing planned and the engine responses anticipated. Provide a copy of the test plan or matrix and test procedures to be used. Are the events of interest planned or is the intent to monitor for unplanned events?

3. Define the anticipated range of pressures, temperatures, and local Mach numbers at the sensor location. The ranges should cover all conditions anticipated at the sensor location. Consider inlet temperature and pressure conditions to be tested, operating speed range including shutdown and overspeed if appropriate, and off-design operation anticipated such as surge, stall, flameout, fuel steps, or other severe transients.

4. Define the frequency and amplitude of pressure transients which will result from the testing defined in 3 above. Generally each type of test or procedure to be performed will have its own representative transient pressure characteristics. Provide as much detail as possible, examples of previous test results may be helpful.

DATA REQUIREMENTS:

1. Specify how the data are to be displayed/recorded. Indicate whether analog or digital data are required and what the intended display and/or recording systems will be. Specify whether the data must include the DC (low frequency) component or if it is sufficient to obtain high-pass filtered results.

2. Specify the pressure range(s) of interest. The range may be less than what is described in 3 above when there are anticipated engine operating conditions or transients which are not of interest to the user. The data requirements may need to be broken down into more than one pressure range such as for starting and low speed versus high speed or high altitude/low Mach versus low altitude/high Mach inlet conditions. It can be useful to specify data ranges for the type of testing included in the test plan mentioned in 2 above.

3. Specify the frequency response requirements and associated fluctuating amplitudes. Provide realistic amplitude, phase shift and frequency requirements consistent with the conditions described in 4 above and the intended use of the data. Specify the desired accuracy and also the maximum uncertainty that may be acceptable. Give the instrumentation designer sufficient information for trade-off studies and decision making. If requirements vary significantly for different types of testing, then specify requirements individually for each.

4. Describe briefly how the data are to be used. The instrumentation designer is better able to make decisions and suggestions when he understands how the data are to be used. Not only those things which the user sees as requirements should be communicated to the instrumentation designer but also any items which the user does not consider important. This can prevent compromises in system performance resulting from requirements which are perceived but do not actually exist.

The key advantages and disadvantages of the different types of transient pressure measurement systems are indicated in Table 4.2-2. The comments in the table are relative and should not be interpreted as absolutes. The information in Table 4.2-2 is indicative of the types of trade-offs and decisions that face the instrumentation designer. Other factors to be considered are the cost and availability of transducers, compatibility with available signal conditioning, durability, data display, terminal devices, and allowable engine modification or access. All of these should be considered relative to the user's requirements, with on-going communication during the instrumentation system design process, to arrive at a best solution.

4.2.4 Signal Conditioning

Sections 4.2.1 through 4.2.3 dealt with the elements of the transient pressure measurement system which transmit the pressure from the sensor to the transducer and with the transducer which converts the pressure to an electrical signal. In this section, the additional system elements shown in Figure 4.2-1 will be discussed.

Signal conditioning requirements for transient pressure measurements should be considered as part of the overall system design. The user's data objectives, as discussed in Section 4.2.3, available resources, and the extent of allowable engine modifications will guide the designer in determining the most appropriate instrumentation configuration. Selection of a power supply, amplifier, and filter(s) follow directly from the user's data objectives or are dictated by the selection of other elements of the system.

4.2.4.1 *Power Supply*

A power supply (typically constant DC voltage) is required for excitation of the transducer. In general the selection of a transducer will dictate the power supply requirements but available resources and impact on overall system performance should be considered early in the design. The transducer output will be directly proportional to the excitation voltage as indicated by the output level of the transducer specifications in Table 4.2-1. As high an output as possible is generally desirable since the amplification (see Section 4.2.4.2) required to match the full scale input range of the terminal device is proportionately reduced. The manufacturer's specification should indicate the allowable excitation levels but most transducer characteristics are given only at one excitation voltage. The manufacturer should be consulted regarding the impact of different excitation levels on the characteristics of the transducer.

The primary consideration in power supply performance is stability and noise level of the excitation signal. A battery can provide excellent excitation since it is completely isolated from external noise sources and provides essentially constant DC voltage to the transducer over its useful life. However, a battery may not be suitable when battery life becomes limiting or when current requirements exceed battery capability.

Instrument power supplies are available with a variety of features. A typical example of a transducer power supply is shown schematically in Figure 4.2-27. The primary problem with instrument power supplies which should be avoided is capacitive coupling to other elements of the system, primarily to the power line and ground. This subject (discussed in Reference 4.2.12) should be reviewed for each installation to minimize noise in the data. Communication with the power supply manufacturer is recommended.

4.2.4.2 *Amplification*

Even "high-output" transducer signal levels (usually in the millivolt range) may be low compared to typical input voltage ranges of the terminal device (typically a data acquisition system). Amplification of the transducer output signal may therefore be required to avoid recording a data signal which is small compared to the noise level of the recording system. The required amplification can be calculated by dividing the recorder full scale voltage by the transducer output at the highest anticipated pressure level. The pressure level is estimated from the user's requirements (see Section 4.2.3) and the corresponding transducer output is calculated from the transducer output characteristic (transducer specification) and the excitation voltage. This relationship is indicated in the equation below:

$$\text{AMP} = \frac{\text{REC RANGE} \times 1000}{\text{TRANS SENS} \times \text{MAX PRESS}} \qquad 4.2\text{-}3$$

where

AMP	=	required amplification
REC RANGE	=	full scale voltage range of recorder
TRANS SENS	=	transducer sensitivity (mv/unit pressure) at a defined excitation voltage from power supply
MAX PRESS	=	highest anticipated pressure sensed by transducer

Noise is introduced by each element in the system. The noise contributed by the recorder is typically a fixed percentage of its full scale range and is therefore a constant level in the final data. For this reason, it is important to match the data signal level to the recorder range to keep the recorder noise floor effectively as low as possible. Noise originating in the transducer or through the excitation (power supply) is amplified the same as the data signal prior to being recorded. As a result, it is desirable to have a high transducer output and excitation level so that the required amplification is minimized. The inherent noise floor of the transducer is also typically a fixed percentage of its full scale output so it is desirable to match the transducer range to the maximum pressure of interest to the user. The best signal-to-noise characteristic is usually achieved by optimizing the system and its elements to require the least amount of amplification.

It is important to consider how the data are to be recorded when setting the output level of amplification. If the system is to be DC coupled and recorded on analogue tape, improved signal to noise ratio can be achieved by setting the lowest required value to the recorder lower band edge and the highest required value to the recorder upper band edge. This approach utilizes the full dynamic range of the system.

When high resolution of a limited range is required, consider using two tape channels to record a single pressure. One channel can be set up for overall or full range and the other with a higher gain to increase resolution over a limited range.

4.2.4.3 *Filtering*

Filtering of transient pressure data removes unwanted or erroneous portions of the signal. High, low, band-pass, or notch filters can be used to eliminate frequencies which are outside the useful range of the measurement system or outside the range of interest to the user. Examples of the characteristics of some typical filters are given in Figure 4.1-2. Filtering which is not required to preclude corruption of the recorded data (such as aliasing of digitized data) is better left as part of the data reduction task. This leaves the maximum amount of information to be recorded.

Transient pressure data are sometimes high-pass filtered to allow greater amplification of the signal for enhanced signal-to-noise ratio of the recorded data. This is beneficial when low amplitude, high frequency pressure signals are of interest to the user and large, lower frequency variations are not. High-pass filtering (or AC coupling) eliminates the low frequency pressure variations allowing a greater amplification of the higher frequency data relative to the recorder noise floor. The low frequency data are lost or must be recorded separately.

High or band-pass filtering is especially useful when a very specific characteristic is of interest and the frequency characteristics are well understood. In this case, the design of the system and signal conditioning can be tailored specifically to address the conditions of interest. Care should be taken when phase relationships between multiple pressure measurements are of interest since filters impact phase as well as amplitude (see Section 4.9.4).

4.2.4.4 *Averaging*

Manifolding of multiple pressure probes is discussed in Section 5.3.3 of Reference 4.2.1. It should be sufficient to note that the manifold pressure may deviate from the true average of the individual probe pressures when pressure differentials across the probes are not small. By nature, transient testing is more likely than steady-state operation to result in significant pressure differentials and internal flows which contribute to these errors. Also, the tubing length and volumes introduced by manifolding will impact frequency response of the recorded data. Summing amplifiers may be used to average the electrical signals from multiple pressure transducers prior to recording or display. It is advisable to record transient pressure measurements separately when possible and do any averaging as part of data reduction.

4.2.5 Calibration Procedures

Calibrations should be performed during both the design and the use of transient pressure measurement systems. Calibration data can verify manufacturers' specifications for various elements in the system which often represent nominal or minimum levels of performance with significant variation in individual component characteristics. The calibration also provides substantiation that the component is functioning properly and performance at least falls within the manufacturers' claimed tolerance. Data acquired during calibrations may be used in place of or in addition to manufacturers' specification values for the uncertainty analysis described in Section 3.

Calibrations of parts or all of the measurement system may be necessary to verify adequate response capability for the pressure transients of interest. Electrical and pneumatic calibrations can provide at least a qualitative indication of how the system will respond under anticipated test conditions. Such calibrations plus analytical predictions form the basis for assessing transient uncertainties discussed in Section 3. These calibrations could also reveal unexpected resonant characteristics, noise problems, or sensitivities to installation or environmental conditions. In general, calibration procedures provide the engineer with insight into the behavior of the measurement system or its components under controlled conditions.

Installed end-to-end checks assure continuity and polarity of the entire system including the terminal device. Steady-state calibrations are often possible with the system installed, at least with the engine not running. In-place calibration data may actually be used in data reduction or simply to verify that the system is properly set up and functioning.

4.2.5.1 *Accuracy Requirements*

The accuracy requirements for transient pressure measurements vary with how the data are to be used. Occasionally, a high degree of absolute accuracy is necessary. An example is presented in Section 4.2.6 for surge margin determination. More commonly the absolute accuracy is of secondary importance so long as the system's dynamic response is sufficient to record the general characteristic of the transient pressure waveform without unacceptable distortion over the frequency range of interest. This level of accuracy is sufficient to monitor the stability of engine operation or to determine the nature and cause of an instability if it occurs.

The methodology of Section 3 is suggested for quantifying the uncertainty of the measurement. The steady-state uncertainty of the pressure measurement represents an upper bound on the accuracy of the transient data. A very good treatment of the steady-state error sources is included in Reference 4.2.1. Transient errors are much more difficult to characterize and account for. Figure 3-7 indicates some typical sources of error in a transient pressure measurement system. The error sources are categorized as either steady state or transient. Figure 3-10 gives a format for error accounting. The magnitude of each error source must be assigned and classified as a bias or precision. A detailed discussion of this accounting methodology is contained in Section 3 of this report and an example applied to pressure measurement is presented in Section 4.2.6.

The user must state the required accuracy at specific operating conditions in order for the measurement errors to be properly evaluated. Section 4.2.3 indicates some of the information about the test which must be supplied. It is essential that the accuracy requirements be stated in such a way that a meaningful uncertainty analysis can be conducted.

For transient pressure measurements there are three primary factors which must be considered in the estimate of uncertainty for the instrumentation system. These should be defined at conditions where the stated accuracy is desired:

1) Flow conditions - flowrate/Mach number, pressure, temperature, flow angularity or swirl, and turbulence.
2) Environmental conditions - ambient pressure and temperature including transient conditions, vibration levels, and makeup of the fluid, i.e. air, combustion products, fuel, oil, etc..
3) Character of signal to be measured - representative frequencies and waveforms or pressure versus time histories for non-periodic signals.

The uncertainty in the measurement can then be evaluated at the test conditions of interest to the user. Situations where a high degree of accuracy is desired require the instrumentation system to be designed such that transient errors are negligible. The types and sources of transient errors, illustrated in Figures 3-7 and 3-10, must be considered in the system design and selection of components to achieve the desired level of confidence (see example in Section 4.2.6).

4.2.5.2 *Steady-State Calibrations*

Types and sources of steady-state pressure measurement errors and calibration techniques are covered in Section 5.4 of Reference 4.2.1. To determine which steady-state calibrations are appropriate for a transient pressure measurement system, consider the overall accuracy required to meet the user's data objectives and the approximate magnitudes of potential errors from the various sources. The calibrations which are necessary should become apparent based on these considerations. Effort should not be expended on calibrations for effects which are not of significant magnitude relative to the user's data requirements. Manufacturer's specifications, historical calibration records, or engineering judgement are sufficient for effects which are small compared to those from other sources.

Two steady-state error sources which typically dominate pressure measurement uncertainties are the probe calibration and transducer accuracy/environmental effects. Assuming good practice has been followed in the design of the sensor, the probe calibration error is primarily a result of the sensor location with respect to the measurand of interest. Pressure gradients and local flowfield effects should be accounted for by calibration of the probe. The best calibration technique is comparison of the transient pressure measurement with data from a more extensive set of steady-state instrumentation during operation over the speed range and test conditions of interest. A correlation with the steady-state performance data can then be established. If steady-state instrumentation records are not available, analytical models, historical data, or engineering judgement must be used to evaluate this error source.

An end-to-end pneumatic calibration of the instrumentation installed on the engine at test operating conditions is the ideal final check of the steady-state accuracy of the pressure data. This is possible with the ZOC system described in Section 4.2.2.3.3. The ZOC system can change the reference side pressure by a known increment or set a zero differential with the engine running at test conditions. The recorded pressure data provide overall sensitivity and zero offset. The calibration data can verify nominal system sensitivities and permit the offset to be adjusted out or recorded for data correction. System accuracy can be evaluated through statistical analysis of calibration data acquired during the course of the testing.

When a ZOC system is not used, there are still steady-state calibrations that can and should be accomplished. Pneumatic calibrations can usually be done when the engine is not operating through either the reference or sensing side of the transducer. The specific configuration of the transducer and reference pressure and facility capabilities will dictate what techniques can be used. The reference side of a transducer is often accessible so that known pressures can be applied. The front or sensing side may also be accessible or cell pressure can be varied in an altitude facility with the reference side held constant. These procedures can be used to verify sensitivity, continuity and polarity between probes and recorded signals when applied to probes individually. If applied to multiple probes simultaneously, sensitivities and polarity are checked. Application of even an uncalibrated pressure to individual probes is important to assure proper continuity and polarity.

Electrical calibrations verify setup and operation of the signal conditioning and terminal devices downstream of the transducer. A known voltage applied at the transducer output checks amplification and recording ranges. DC electrical calibrations should be accomplished periodically during the testing.

4.2.5.3 *Transient Calibrations*

Transient calibration procedures compare the response of the system or element(s) of the system to a reference measurement of a time variant input signal. Distortion of the signal results in the errors indicated in Figure 3-7.

In the case where high accuracy is desired, the system must be designed such that transient errors are negligibly small. Transient calibrations can help to demonstrate achievement of this goal. If absolute accuracy is not a primary concern, transient calibrations may only be necessary to assure that no unanticipated characteristics exist. Calibration results can indicate the potential magnitude of errors but typically do not provide a practical method of correcting measured data.

4.2.5.3.1 *Dynamic Pressure Calibration*

Properly designed pressure measurement systems are usually limited in frequency response by the characteristics of the tubing and volumes between the sensor and transducer. The dynamic response of the transducer and electronic elements should be many times higher than the frequency range of interest.

Pneumatic calibrations should be considered for any system where the transducer is not flush mounted. The calibration compares response of the measurement system to that of a flush-mounted transducer. Figure 4.2-28 shows a pneumatic calibration setup schematically. Examples of various types of dynamic pressure calibration devices are contained in References 4.2.3, 4.2.7, 4.2.9, 4.2.13, and 4.2.14. Use of a sinusoidal pressure wave generator with variable frequency allows direct evaluation of amplitude and phase effects versus frequency. Similar information can be derived from step or impulse input test results through Fourier transform of the measurement output waveform.

The two things which are most important for acquiring useful calibration data are realism in the system elements and installation, and a pressure signal with appropriate amplitude and frequency for the intended use of the system. The actual response of the measurement system can be affected by local geometry near the sensor, installation, routing of the transmission tube, and defects or irregularities in the tubing or other hardware. For these reasons it is important to use actual test hardware whenever possible for calibration. The system should be configured in a way that is representative of the actual installation including bends and connections in the tubing.

The pressure calibration signal used should be representative of the intended use of the system. Examples of calibration signals which could be used include a rapid increase/decrease (step), impulse, ramp up/down, sinusoid, square, triangular or other shape periodic wave, or a shock front. Which signal is most appropriate will depend on the what the system was designed to measure and how the calibration data are to be used. Figures 4.2-15 through 4.2-22 show some typical presentation formats which can be used for calibration results.

Transient calibration procedures are recommended to aid the instrumentation designer in choosing the proper configuration and elements for the transient measurement system. They provide assurance that acceptable characteristics are achieved in the system prior to installation on the engine and results should support the measurement response estimated using techniques presented in Section 3. Useful limits for the instrumentation can be established so that the data are appropriately used and not misinterpreted.

Also, first order estimates of the magnitude of transient errors can be made.

4.2.5.3.2 *Temperature Transients*

Significant shifts in the transducer output can result from changing temperatures. Manufacturers' specifications give tolerances for quasi-steady temperature shifts. The effect of a rapid temperature transient is much less predictable and must be checked experimentally if it is a concern.

The potential error can be quantified by monitoring transducer output while exposing it to changes in temperature consistent with what is anticipated during engine testing. A heat gun, oven, airjet, or submersion in liquid can be used to effect the temperature change. As an example, a 15% of full scale output shift is reported in Reference 4.2.14 for a rapid change in temperature of 20 K. If these calibrations indicate unacceptable error, temperature control of the transducer may be required.

4.2.5.3.3 *Electrical Calibrations*

Transient errors from the electronic components (amplifiers, filters, and terminal devices) should be well understood based on manufacturer's specifications. Electrical calibrations using periodic function generators verify data acquisition system performance across the frequency range of interest to the user. Phase errors are more likely to be a problem than amplitude attenuation. Acceptable phase shift between channels of pressure data and with the time base for other transient data should be verified. This can be done using electrical calibrations and is most important when the user intends to interpret data based on the relative phasing of individual measurements.

4.2.6 Design Example

The following example illustrates how pressure measurement systems are designed to meet the specific objectives of a transient engine test. Note the importance of stating requirements with sufficient detail that they can be applied directly to the instrumentation design.

The example of a surge margin determination test from Section 5.2 requires instrumentation for measuring total pressures at the compressor inlet (P25) and at the compressor discharge (P3) during a transient. It may not be convenient to measure the transient P3 directly, in which case it can be inferred from a measurement in the dome of the combustor (PS31). This approach has been used in the example in Section 5.2. The specific transient of interest is an intentional throttling to surge by rapidly increasing fuel flow to the combustor. The test procedure begins with the engine stabilized at the test speed and the acquisition of steady-state data to establish the initial conditions. Combustor fuel flow is then increased at such a rate that surge occurs with little or no change in speed.

Refer to Section 4.2.3 for suggestions on the specification of requirements.

<u>Description of Conditions at the Sensor:</u>

1) Two engine pressures, P25 and PS31, will be measured during the transients. The total pressure at the compressor discharge (P3) during the transient will be inferred from the measurement of the static pressure PS31 in the combustor (see Section 5.2.3.2). Steady-state data will be used to establish correlations between the single-point and station-averaged values for use in data reduction. It is assumed that a sufficient amount of instrumentation exists such that the steady-state operating pressure ratio (P3/P25) can be determined (see Reference 4.2.1 for methods applicable to steady-state performance testing).

2) Initially, the engine will be stabilized at 90% corrected core speed. The introduction of a fuel ramp will cause an increase in the compressor operating point at essentially constant speed up to the point of surge. It is anticipated that both P3 and P25 will increase prior to surge. The determination of the pressure levels at surge initiation are the data objective.

The transient test results will be used to estimate the location of the compressor surge line. A point on the surge line is defined by the ratio of station average total pressures at the compressor discharge and inlet. The nominal surge line is typically established during rig or component testing by extrapolation of steady-state data to the most throttled condition which can be maintained in quasi-steady operation. For consistency with this nominal reference, the higher frequency content of the pressure signals associated with turbulence, aerodynamic unsteadiness, and local flow disturbances from stall formation and propagation, which do not correlate with the quasi-steady results, are not of interest.

3) The test is to be accomplished in a ground level cell. Approximate ranges of pressure and temperature for operation of a large, moderate bypass, military engine between idle and takeoff are:

P25 = 100 - 415 kPa (14.7 - 60 psia)
T25 = 15 - 175°C (59 - 350°F)

P3 = 240 - 3450 kPa (35 - 500 psia)
T3 = 150 - 600°C (300 - 1100°F)
assuming standard day conditions.

4) The PS31 transient prior to surge will be a smooth rapid increase of less than 30% in as little as 0.050 seconds. Figures 5.2-3 shows the waveform of the transient pressure for this example. The P25 transient is anticipated to have a change of less than about 5% during this time period, Figure 5.2-4.

Data Requirements:

1) Pressure changes relative to initial stabilized levels are to be measured during the transient to surge. A true time relationship (no phase shift) must be maintained between the two measurements since pressure ratio is the parameter of ultimate interest.

2) The approximate test conditions are:

steady state -	at initial stabilized speed, (N2=90%)	
	P25=193 kPa (28 psia)	
	T25=82°C (180°F)	
	PS31=1186 kPa (172 psia)	
	T3=380°C (715°F)	
transient -	delta to point of surge onset	
	ΔP25 = +4 kPa (0.6 psi)	
	ΔPS31 = +365 kPa (53 psi)	

3) The desired overall accuracies of the individual pressure measurements at the point of surge onset are ±2% for P25 and for P3 as stated in Section 5.2.2.4. To measure the transient pressures which correlate with steady-state data and methods for mapping the surge line, the instrumentation must be able to track the overall pressure rise transient with this stated accuracy. The pressure transients prior to surge, shown in Figures 5.2-3 and 5.2-4, can be thought of as portions of periodic waves with a fundamental frequency of about 5 Hz (assume the pressure rise is one quarter of a cycle). A minimum frequency response several times higher than this fundamental will be required to allow for the non-sinusoidal shape. A specific method of estimating the required frequency response for the instrumentation is given in Section 5.2.2.5, which yields a 70 Hz requirement. The data can be further time averaged electronically or graphically during data reduction to arrive at the proper values for correlation with steady-state pressures. In this way the impact of filtering/averaging on peak pressure level and wave shape can be observed.

4) The pressure data will be acquired as described in Section 4.9. In addition to digital recording, the pressure signals should be available on-line to aid in conducting the test. This could be accomplished using a strip-chart recorder, X-Y plotter, or digital graphics display.

Sensor and Tubing Design:

It will be assumed for this example that radial pressure rakes (steady state) are installed at the compressor inlet and discharge. Steady-state measurements of the pressures seen by the transient instrumentation will be recorded for correlation with the steady-state data at stabilized operating conditions. These data will provide calibrations for the transient instrumentation as well as single point to station average pressure correlations. The pressure levels at the point of surge initiation will be calculated by adding the transient deltas to the initial steady-state data.

The transient pressure instrumentation configuration will be resonant systems for both P25 and PS31. For P25, the measurement will be made by a high-response transducer close coupled to a total-pressure probe mounted in the compressor inlet rake (Figure 4.2-29) (see also Section 5.2.2.1).

A check of the acoustic resonance frequency as suggested in Section 4.2.2.1.2 indicates that this should not be a problem. The acoustic speed at 82°C (180°F) is about 378 m/sec (1240 ft/sec), and the tube length is 203 mm (8 in). Then, from Equation 4.2-1,

$$f_R = 465 \text{ Hz}$$

A low-pass electrical filter with a suitable cutoff frequency will be selected to eliminate effects of acoustic resonances on the pressure data.

The pneumatic systems used to measure the transient magnitudes of P25 and PS31 consist of short lengths of relatively large diameter tubing and therefore behave approximately like second order systems with a simple time delay. The time delay, t_d, doesn't affect the amplitude of the measured peak but the peak is affected by the characteristic resonant frequency, f_R, and the damping constant, ξ. The short pneumatic pressure tubes used for transient measurements are lightly damped to achieve rapid response. In order to estimate the uncertainty we can use the sawtooth or terminated ramp approximation which (see Section 5.2.2.5) is more conservative than a terminated sinusoid. Using the solutions in Reference 4.2.6, it is found that there is a constant lag error ϵ_L, during the rise time of the ramp, of the following magnitude,

$$\frac{\epsilon_L}{\Delta P25} = \frac{2\xi}{2\pi f_a t_1} \qquad 4.2\text{-}5$$

where t_1 = the rise time of the sawtooth.

In addition, there is a superimposed oscillatory error ϵ_R that can be no larger than,

$$\frac{\epsilon_R}{\Delta P25} = \frac{1}{2\pi f_R t_1 \sqrt{1-\xi^2}} \qquad 4.2\text{-}5$$

In a lightly damped system the transient error dominates since $\xi \to 0$.

Since the pneumatic tubing length has been set at 203 mm (8 inches), constrained by the installation geometry and environmental temperature, and since the 203 mm tube will have a resonant frequency f_R = 465 Hz, we can estimate the transient uncertainty due to the pneumatic tube response to the sawtooth pulse by using Equation 4.2-5 and setting f_R = 465 Hz, damping constant $\xi \approx 0$, and time to reach the peak t_1 = 0.05 sec, then the maximum percent transient error due to the tubing is;

$$\epsilon = 1/(2\pi f_R t) = \pm 0.7\% \text{ (of } \Delta P25)$$

The ± sign is used here since the second order lightly damped system can either undershoot or overshoot depending on the detailed time behavior of the signal.

The time delay in the pneumatic tubing is approximately equal to the acoustic propagation time in the tube. From the data given above, the 203 mm tube would have a delay time of 0.5 msec.

For PS31, the transducer will be attached to the end of a tube from a static-pressure tap on the combustor case. The tube fitted to a modified fuel nozzle bolt will be about 46 cm (18 in) long with a 2.16 mm (.085 in) inside diameter. The reference pressure side of the transducer is connected to a tube to an adjacent fixed nozzle bolt through a remotely operated, fast-acting valve. This permits the use of a low range transducer which will improve system accuracy. A sketch of this configuration is shown in Figure 4.2-30.

A check of the acoustic resonance frequency, assuming the tubing is exposed to a temperature in the compressor bypass of 82°C, gives a resonant frequency of 205 Hz. Again, a low-pass electrical filter with a suitable cut-off frequency will be selected.

For PS31, the maximum transient error due to the tubing will be approximately ±1.5% of ΔPS31 and the delay time will be approximately 1.2 msec.

Reference Pressure System:

The reference pressures for both transducers are connected to the sensed pressures through remotely operated solenoid valves. The valves will be closed at the stabilized initial condition. This allows the transducer output to be set to zero (compensation for zero shift) electrically through adjustment of the bridge balance circuit resistance. During data reduction the initial output of the transient pressure measurement will be set equal to the steady-state value prior to the surge transient. In this way, bias errors due to temperature drift and installation effects are minimised. The solenoid valves are opened automatically when a facility detection circuit senses the surge. This protects the transducers from the large pressure excursions resulting from the throttle chop to idle following the surge.

Transducer Selection:

The reference pressure system described above permits the use of transducers with ranges selected to cover only the fuel ramp and initial surge transients. This results in significantly improved data accuracy since most transducer errors are fixed percentages of full scale output.

The P25 trace in Figure 5.2-4 indicates excursions of less than about 70 kPa (10 psi) from the initial level prior to and immediately following surge. The transducer indicated in Figure 4.2-31 with a 35 kPa (5 psi) range and 140 kPa (20 psi) overpressure capability would be appropriate. The manufacturer's specification data included in Figure 4.1-31 will be used in determining signal conditioning requirements and in the error analysis. The 120°C (250°F) temperature capability will be adequate for the transducer mounted outside the fan case at the compressor inlet with cooling provided by shop air.

The PS31 transient shown in Figure 5.2-3 indicates excursions of less than about 520 kPa (75 psi) from the initial level. The transducer in Figure 4.2-31 for PS31 has a 345 kPa (50 psi) range, sufficient for the transient prior to the surge and a 690 kPa (100 psi) overpressure capability. This transducer is rated to 274°C (525°F) which will not be exceeded inside a container cooled by shop air.

Signal Conditioning:

Excitation: 10 VDC is the rated value for both transducers

Amplification: requirements are calculated below using the procedure of Section 4.2.4.2 and assuming a 2 volt peak-peak full scale recorder range, from Equation 4.2-3 and Figure 4.2-31:

AMP (P25) = 66.7

AMP (PS31) = 19.2

Filtering: will be used to eliminate any effects of acoustic resonances in the pneumatic tubing. Low-pass analogue filters with suitable cutoff frequencies are 90 Hz for P25 and 70 Hz for PS31.

A schematic of the transient pressure instrumentation system for this design example is included as Figure 4.2-32.

Error Analysis:

P25 and P3 at surge will be calculated by summing the stabilized pressures (measured before initiation of the fuel step using steady-state instrumentation and data systems) with the pressure changes from stabilized to surge (ΔP25 and ΔPS31 - using transient instrumentation and data systems). The calibration procedures include the adjustment in pressures between the measured PS31 and the station average P3 (see Figure 4.2-33). Therefore, the total uncertainty in P25 and P3 at surge will reflect error sources in both the steady-state and transient instrumentation and data systems. Uncertainty in steady-state pressure measurements is discussed in Reference 4.2.1. For this design example, the uncertainty levels in Section 5.4.3 of Reference 4.2.1 are assumed for the initial stabilized pressures measured using steady-state instrumentation: $((\Sigma b^2)^{1/2} = \pm .052\%$ of reading and $(\Sigma s^2)^{1/2} = \pm .046\%)$.

Error sources for the ΔP25 transient pressure measurement are shown in Figure 4.2-34 and are numbered for reference in the following discussion. The uncertainties in the ΔPS31 transient pressure measurement are shown in a similar manner in Figure 4.2-35. As noted in Section 3.3 of this report, there are error sources associated with the dynamic response of transient measurement systems over and above what are accounted for in steady-state systems. Figures 4.2-34 and 4.2-35 therefore include steady-state and/or transient uncertainties for each error source as appropriate. The rationale for each value in these figures is given below. These uncertainties apply only to measurement of the pressure *change* (i.e. ΔP) from stabilized to surge but are presented as percentages of the absolute pressure level for consistency with uncertainties estimated for measurement of the stabilized steady-state pressures.

1) Transducer steady-state calibration - the same uncertainties used for the steady-state measurements have been assumed for the transient transducers and scaled to reflect the percentage of absolute level (steady state + transient).

2) Transducer dynamic calibration - assumed negligible relative to time response of the transmission tubing.

3) Voltmeter steady-state calibration - covered in item 1 above.

4) Voltmeter dynamic calibration - assumed negligible relative to the time response of the transmission tubing.

5) Time/frequency standards - see Section 4.9.

6), 7), and 8) Steady-state installation effects - are errors of method assumed negligible for properly designed pressure instrumentation (see Section 8.2 of Reference 4.2.1).

9) Time response of tubing (see above) - is the predominant transient error.

10) Calibration of transducer vs steady-state standards - for the transient pressure measurements is a correlation with steady-state data taken at stabilized conditions. The correlation will cover the pressure ranges of interest by acquiring data over a sufficient range of speeds. Hypothetical representations of the correlations are shown in Figure 4.2-33. The bias can be calibrated out and repeat points provide data to establish a random uncertainty in the calibration. These correlations are based entirely on steady-state data. An uncertainty of 0.25% is not untypical.

11) Transducer repeatability and linearity - are taken from the manufacturer's specifications. It should be noted that the transient measurements are added to the initial steady-state levels and make up only a portion of the absolute pressure. Therefore, the specification tolerances of 0.3 and 0.5% of full scale output for the differential transducers translate to random errors of less than 0.1% of absolute pressure.

12) Temperature drift - effect on zero shift is negligible due to the initializing procedure. There should be no appreciable change in transducer temperatures within the cooled environments over the short period of the surge test transients. The specification tolerance for thermal sensitivity shift would yield a typical random error of 0.1% for minor differences in transducer temperatures between the time that calibration data are recorded and when the test transients are run (1% full scale output sensitivity shift per 50°C (90°F) = 0.1% of the absolute level for 25°C (45°F) temperature difference.

13) Transient stress distribution - is accounted for in the on-line calibration procedure and inherent in the error in item 10 above.

The combined errors associated with the two pressure measurement systems are listed in Section 5.2 in Table 5.4 for P3 and Table 5.5 for P25.

4.2.7 Advanced Sensors

The pressure transducers available today give the instrumentation designer a variety of options in size, configuration, and input/output. A real limitation, however, is the impact of the operating temperature environment on the transducer. Most transducers must be kept below about 120°C (250°F), although some may be permitted as high as about 260°C (500°F). This requirement tends to negate some of the advantages of miniaturized transducers. Even within the operating temperature range, a significant variation in zero offset and sensitivity occurs with temperature transients.

The advancement needed is first an increased operating temperature capability so that transducers can be installed closer to the sensors. This would allow miniature transducers, without cooling, to be installed closer to the sensor.

Once the transducer can survive in a high temperature environment, compensation circuitry or thermal isolation needs to be improved to enhance accuracy/stability. Techniques such as electrical high-pass filtering or pneumatic coupling of the reference and sense pressures, used to overcome uncertainties caused by thermal shifts, reduce the information acquired by eliminating the low-frequency content. Enhanced thermal stability over an expanded operating temperature range could significantly increase the use of miniature transducers in flush mounted and close-coupled systems.

A second area where there is always room for improvement is in cost. As transducer capabilities are increased, the potential quantities of measurements go up, and the cost can become prohibitive. It is worth noting that in cases where the specification values for accuracy and thermal shifts are not acceptable, tighter tolerances may be obtainable at a premium price. The manufacturer is sometimes able to supply individual transducers which exceed specification values. Communication with the manufacturers is recommended.

Another area where improvement is needed is in pneumatic calibration techniques and available data for tubing for resonant and non-resonant transient pressure measurement systems. Experimental data are useful for developing systems with response characteristics sufficient to meet specific test data objectives. It is most important when conducting such experiments to use hardware which is typical of what might actually be used and under conditions which are appropriate for engine transient testing.

The tubing should be laid out in the laboratory in such a way as to represent conditions commonly found on the system as installed on the engine. Use hardware which is suitable for engine testing. Vary the length and type of tubing as well as number and severity of bends and connections. Evaluate the impact of kinks, flattening, or other discontinuities or deformities which are possible in the installed system. Long tubes should be restrained to varying degrees to check for problems related to motion. Multiple setups of complicated installations could be run to check for sensitivity to variations in configuration and installation.

The pneumatic signals used should be representative of the test data of interest in both amplitude and frequency. Most information in the literature deal with acoustic signals which are too high in frequency and much too low in amplitude to be applicable to engine pressure measurement systems. Steps, ramps, and periodic signals should be used covering the frequency range from steady state to about 500 Hz. Amplitudes of interest are up to about 20% of the operating pressure at higher frequencies and as high as 50% at lower frequencies.

Other factors which could be significant and might be considered for evaluation are the effects of operating pressures and temperatures. A range of pressure levels and temperature conditions could be tested to establish trends.

A comprehensive data set would provide the instrumentation designer with information necessary to define a system to meet his specific requirements. The data could also be helpful when estimating system characteristics as part of the uncertainty analysis. The need to bench check and calibrate systems prior to use would not be precluded but the likelihood of a satisfactory result would be increased.

4.2.8 References

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Table 4.2-1
Typical Transducer Specification Sheet - for Various Pressure Ranges
(semiconductor strain gauge types) (British units)

INPUT Pressure Range	5	10	25	50	100	200	300	500	1000	2000 PSI
Operational Mode	Absolute, Gage, Sealed Gage, Differential									
Over Pressure	20	20	100	100	200	400	600	1000	2000	3000 PSI
Burst Pressure	3 Times Rated Pressure									
Pressure Media	All Nonconductive, Noncorrosive Liquids or Gases									
Rated Electrical Excitation	10 VDC/AC									
Maximum Electrical Excitation	15 VDC/AC									
Input Impedance	500 Ohms (Min.)									
OUTPUT Output Impedance	500 Ohms (Nom.)									
Full Scale Output (FSO)	100 mV (Nom.)									
Residual Unbalance	±5% FSO									
Combined Non-Linearity and Hysteresis	±0.3% FS BFSL *See Note 1									
Hysteresis	Less Than 0.1%									
Repeatability	0.5%									
Resolution	Infinite									
Natural Frequency (KHz)	70	70	100	130	180	200	270	350	500	650
Acceleration Sensitivity % FS/g Perpendicular Transverse	.002 .0004	.001 .0002	.0005 .0001	.0004 .00008	.0002 .00004	.00013 .000026	.00012 .000024	.00009 .000018	.00008 .000012	.00005 .00001
Insulation Resistance	50 Megohm Min. at 100 VDC									
ENVIRONMENTAL Operating Temperature Range	−65°F to 250°F (-55°C to 120°C) Temperatures to 350°F (175°C) Available on Special Order									
Compensated Temperature Range	80°F to 180°F (25°C to 80°C) Any 100°F Range Within The Operating Range on Request									
Thermal Zero Shift	± 1% FS/100°F (Max.)									
Thermal Sensitivity Shift	± 1%/100°F (Max.)									
Steady Acceleration and Linear Vibration	1000g, Sine									
PHYSICAL Electrical Connection	4 Conductor 32 AWG Shielded Cable 24" Long									
Weight	5 Grams (Nom.) Excluding Module and Leads									
Sensing Principle	Fully Active Four Arm Wheatstone Bridge									
Mounting Torque	15 Inch-Pounds (Max.)									

Table 4.2-2 Transient Pressure Instrumentation Systems - Comparisons

TYPE	ADVANTAGES	DISADVANTAGES
o Flush Mounted	- Highest FrequencyResponse Capability - No Amplitude Attenuation/Phase Shift	- Installation can be difficult due to space and accessiblity restrictions - Potentially severe operating environment - temperature, FOD, vibrations - Often requires small transducer with associated costs, stability, ruggedness
o Resonant System	- Increased installation flexibility where space and accessibility are limited - Isolation from flowpath temperatures and FOD (dependent on tube length) - Temperature controlled environment may be possible - Use of larger more stable and rugged transducers may be possible	- System resonances present upper limit to useful frequency range when tube is short - System response characteristics (lags) limit useful range to relatively low frequencies when tube is long - Amplitude attenuation and phase shift must be evaluated (function of design)
o Non-Resonant System	- Eliminates resonances which preclude use of a resonant system for some combinations of required frequency and tube length necessary for installation - Isolation from flowpath temperature and FOD (same as resonant system) - Temperature controlled environment is possible (same as resonant system) - Use of larger more stable and rugged transducers may be possible (same as resonant system)	- Amplitude attenuation and phase shift are generally greater than a resonant system with similar tubing length - Space requiredfor downstream tube (may be integrated with steady-state system) - System response characteristics (lags) present upper limit to useful frequency range (function of design)
o Differential	- Accurate measurement of small difference between two high pressures	- Limited frequency response capability with available transducers - Absolute pressure not measured
o Engine Control	- In place and non-intrusive - Response characteristics well understood - Generally accessible with minor engine/control modification	- Response characteristics cannot be modified to suit the user's data objective

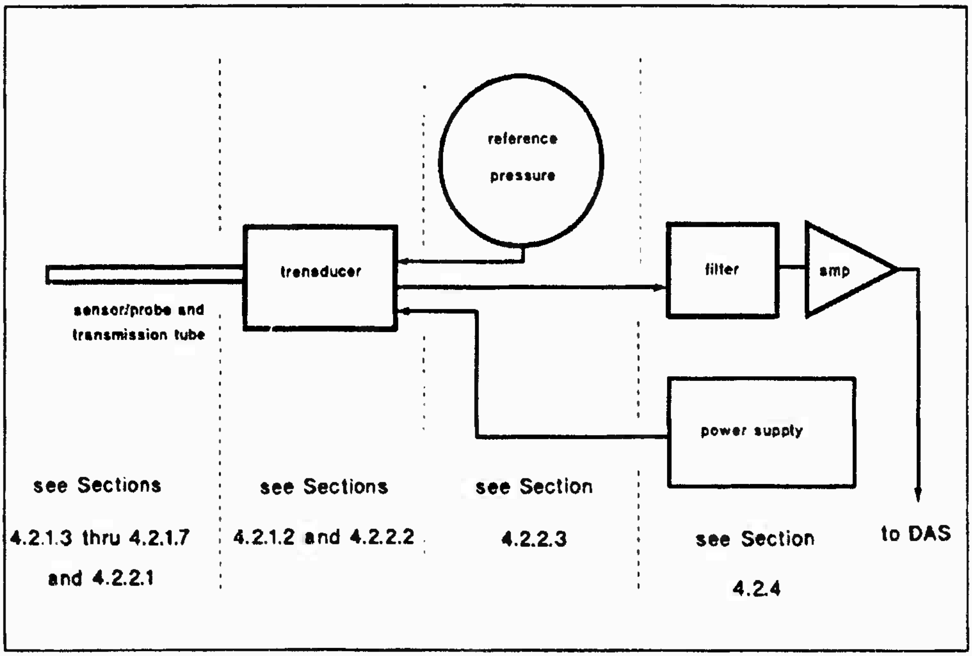
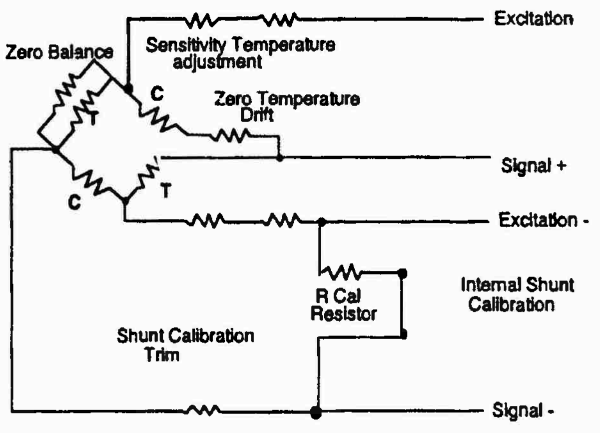


Figure 4.2-1 Pressure Measurement System



Wheatstone bridge, showing compensating resistors

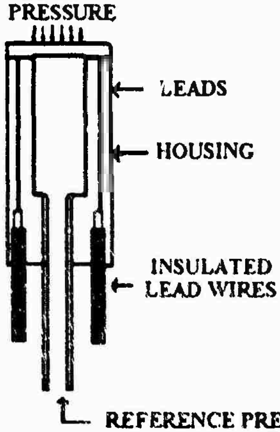


Figure 4.2-2 Strain-Gauge Pressure Transducer Schematic

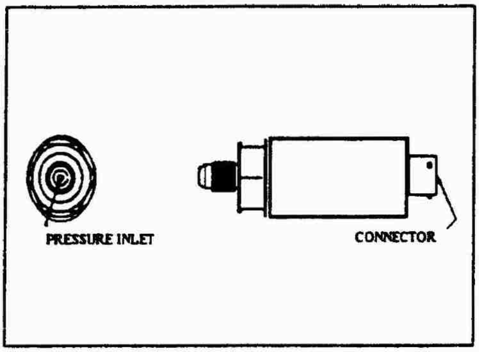


Figure 4.2-3a Standard

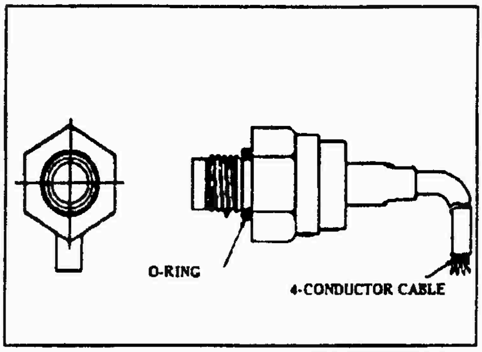


Figure 4.2-3b Miniature Threaded

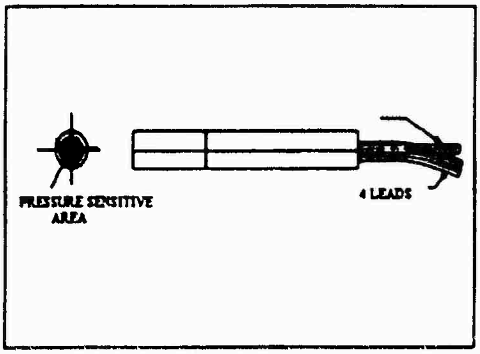


Figure 4.2-3c Miniature

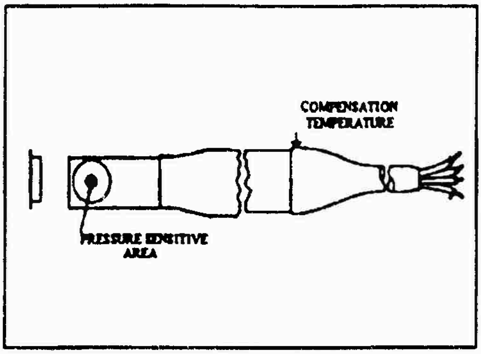


Figure 4.2-3d Surface Mounted

Figure 4.2-3 Typical Pressure Transducers

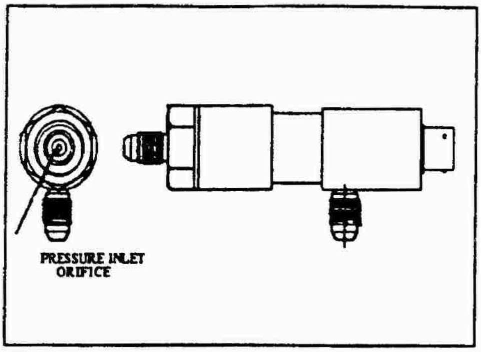


Figure 4.2-3e Differential

Figure 4.2-3(cont'd) Typical Pressure Transducers

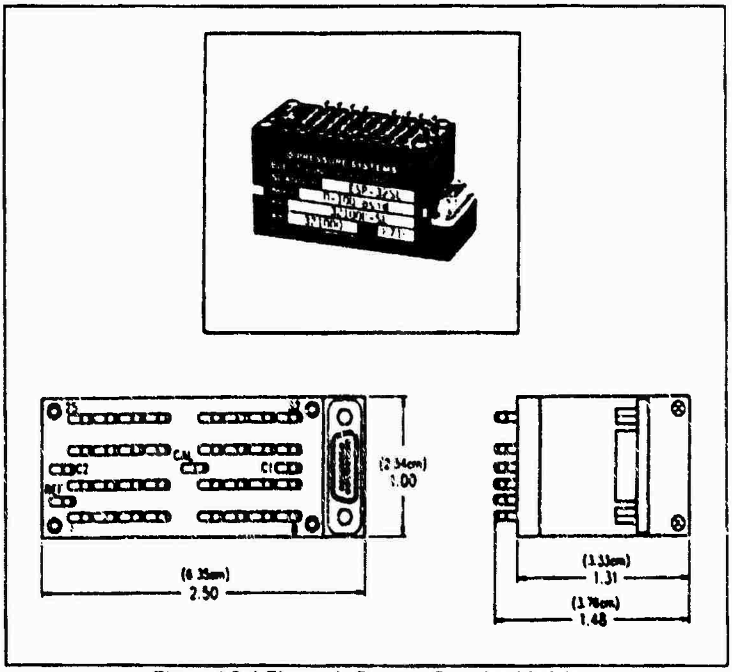


Figure 4.2-4 Electronic Pressure Scanning Module

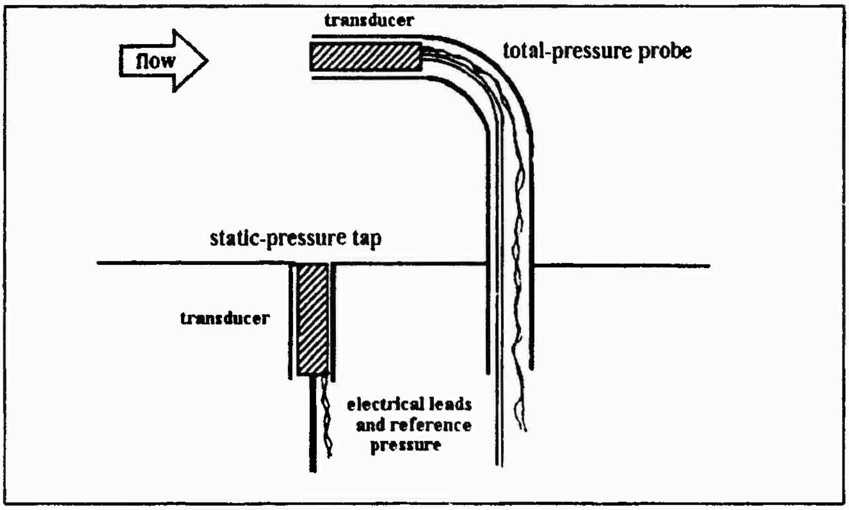


Figure 4.2-5 Flush-Mounted Transducers

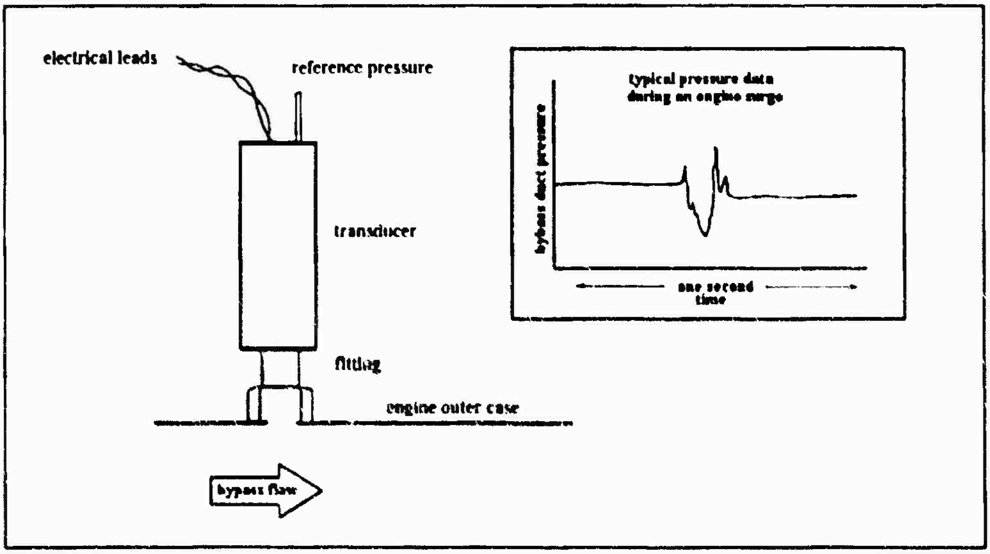


Figure 4.2-6 Flush-Mounted Transducer Installation

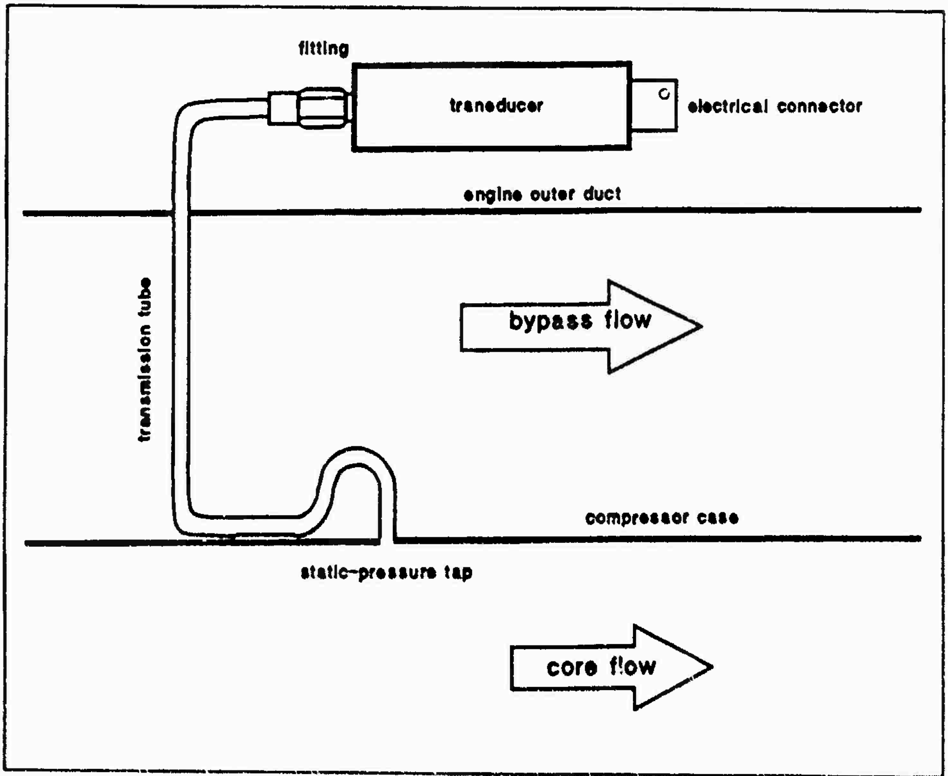


Figure 4.2-7 Resonant System Installation

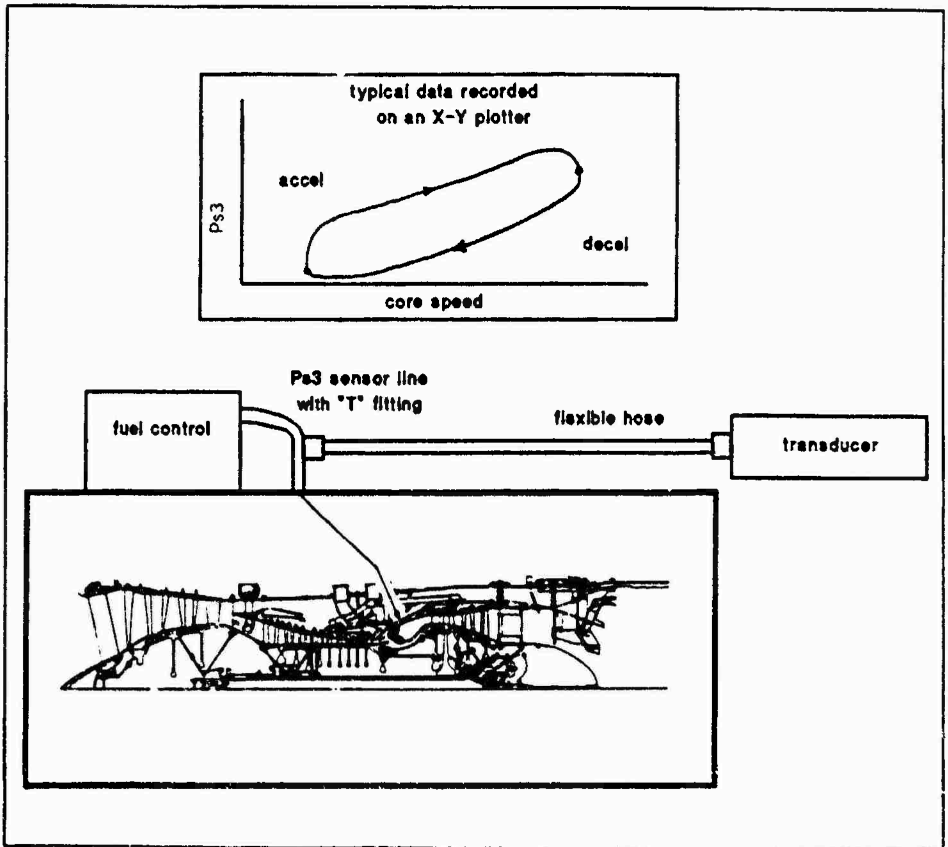


Figure 4.2-8 Example of a Resonant System Used to Measure Static Pressure

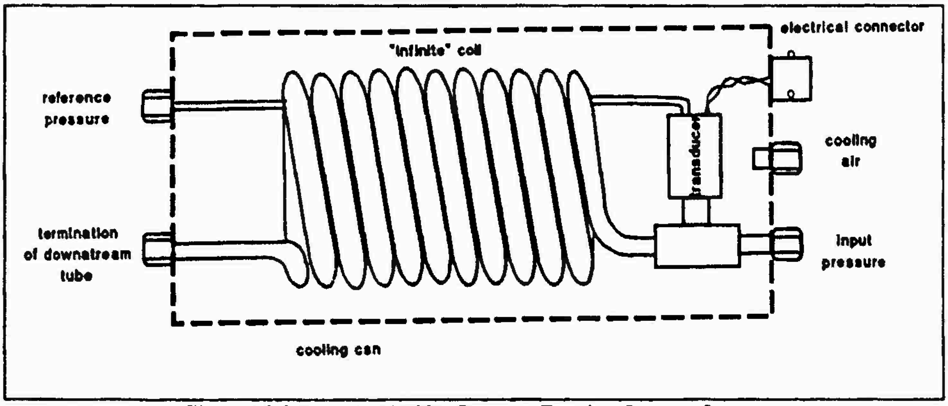


Figure 4.2-9 Example of a Non-Resonant Transient Pressure System

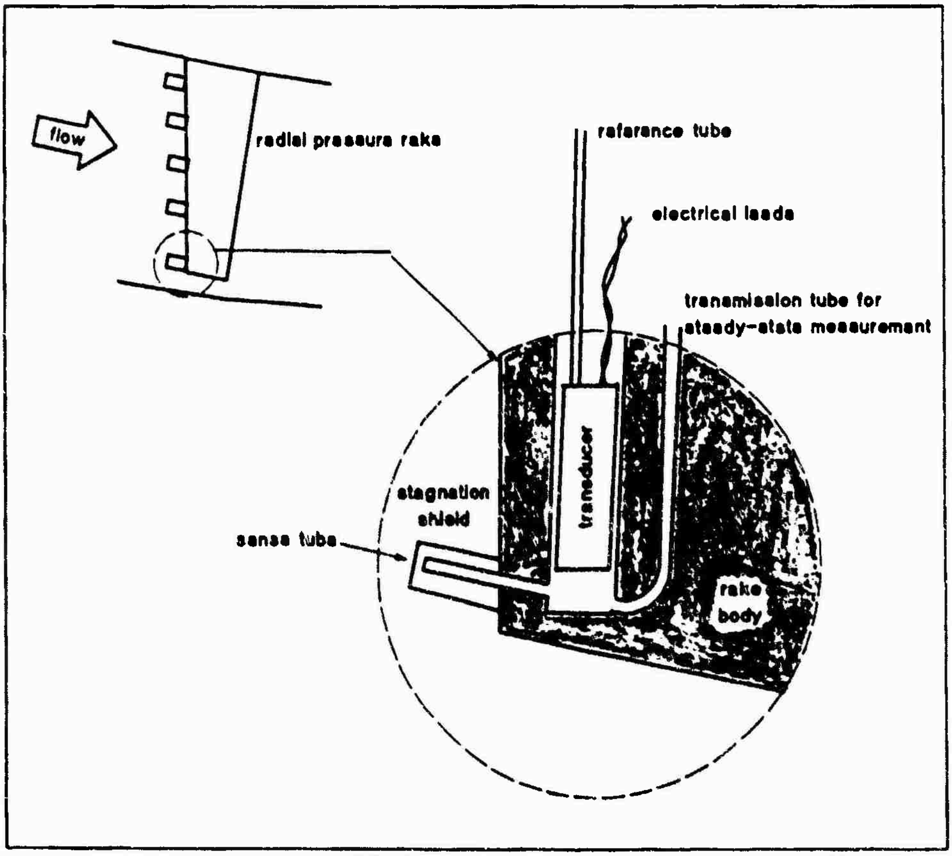


Figure 4.2-10 Rake-Mounted Total Pressure Sensor Using a Non-Resonant System

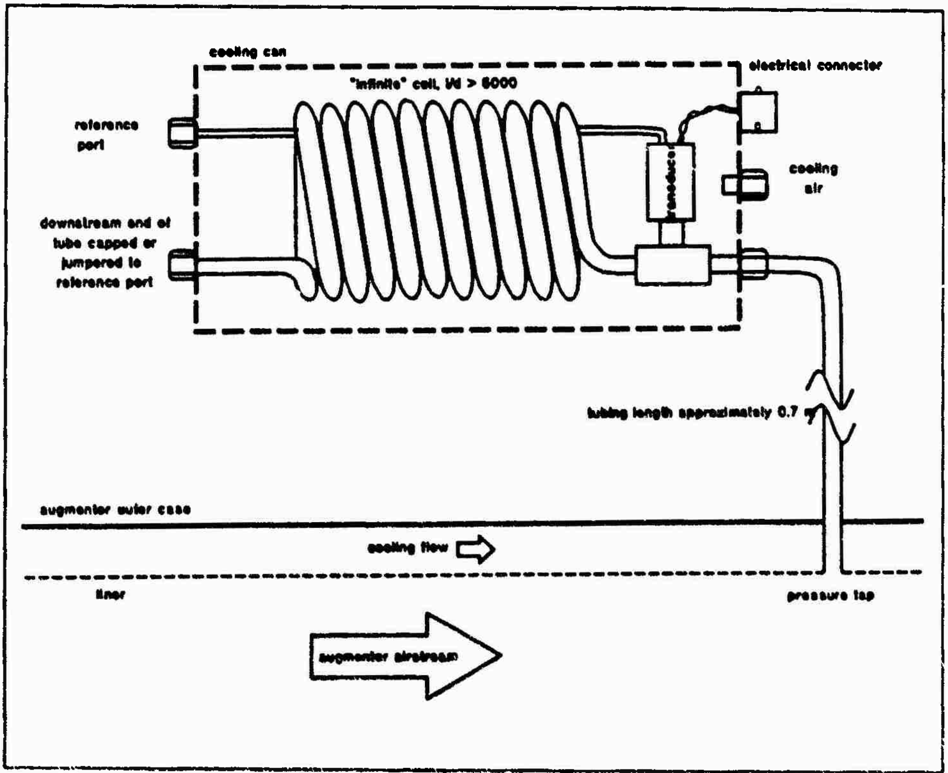


Figure 4.2-11 Non-Resonant System to Measure Static Pressure

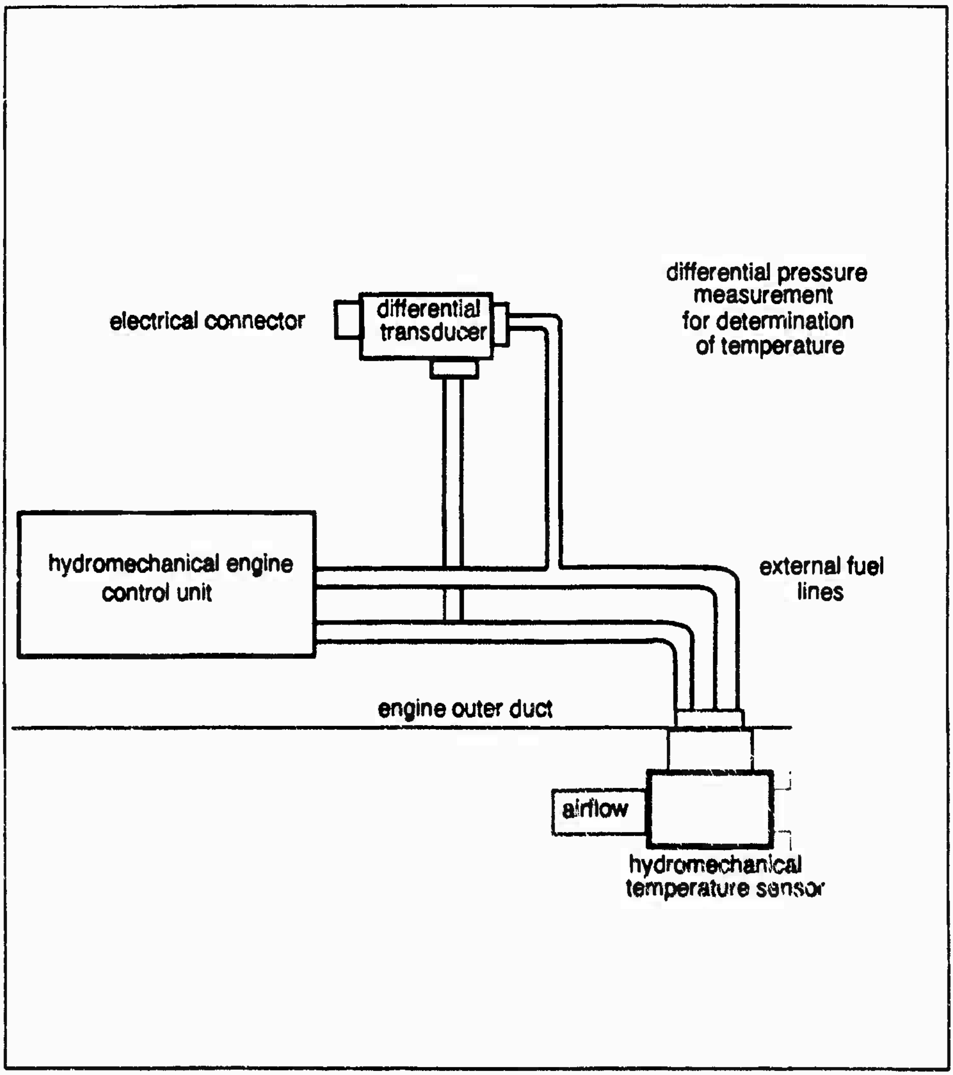


Figure 4.2-12 Hydromechanical Control Sensor Differential Pressure Measured Using a DP Transducer

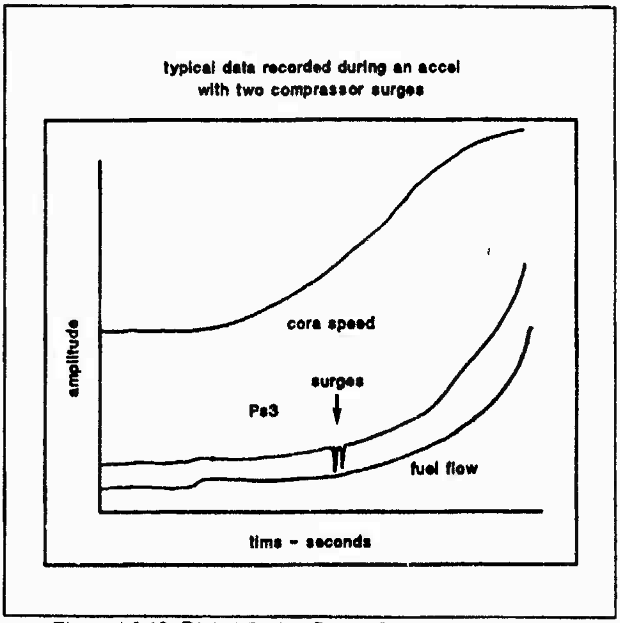


Figure 4.2-13 Digital Engine Control Parameters Accessible at the Data Buss

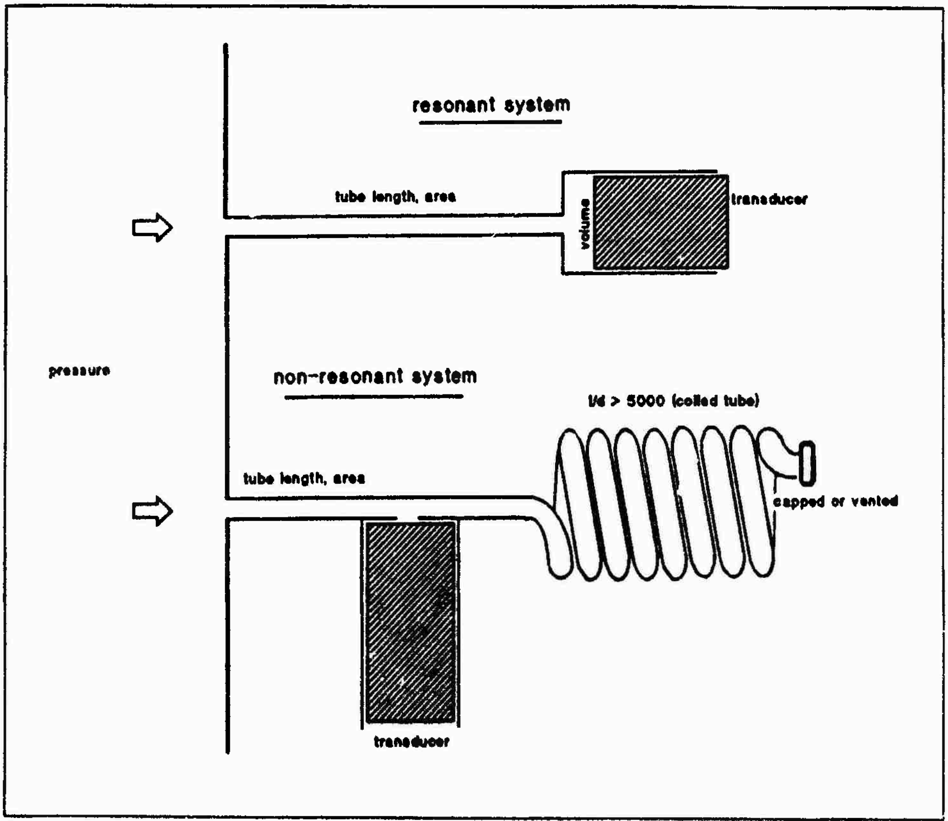


Figure 4.2-14 Pressure Sensor Transmission Tube - General Model

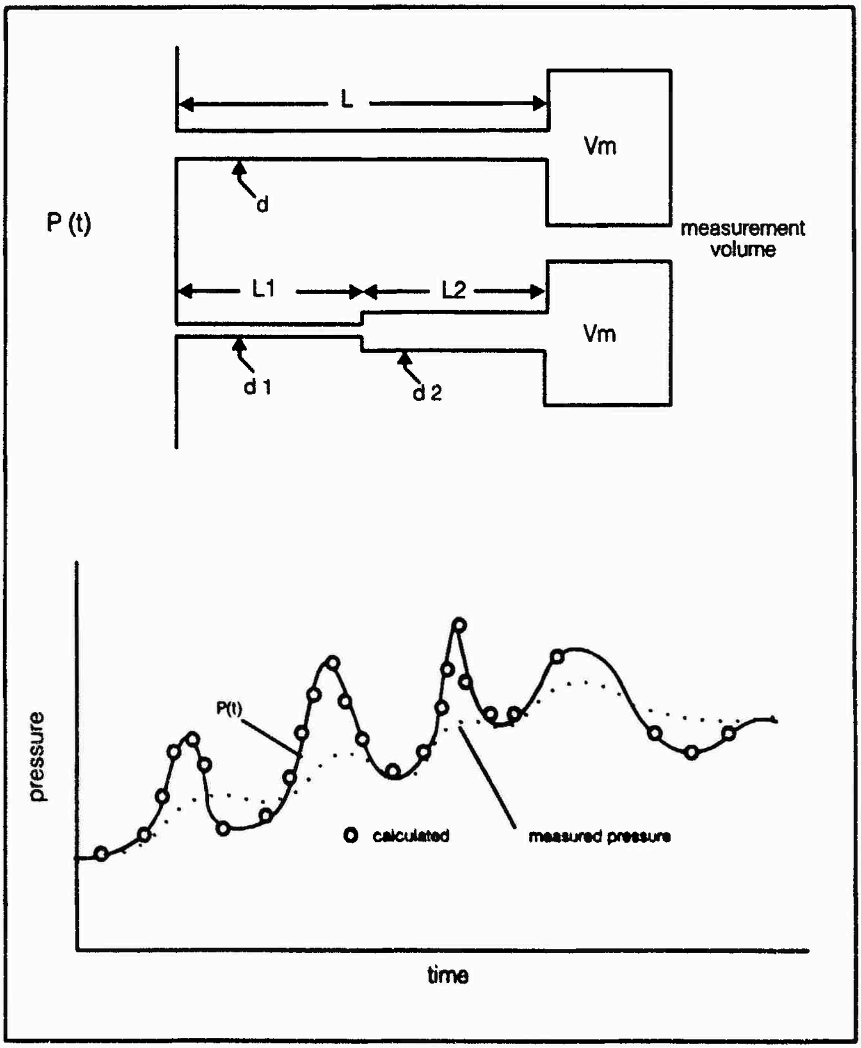


Figure 4.2-15 Pressure Sensor Transmission Tube Model (Reference 4.2.3)

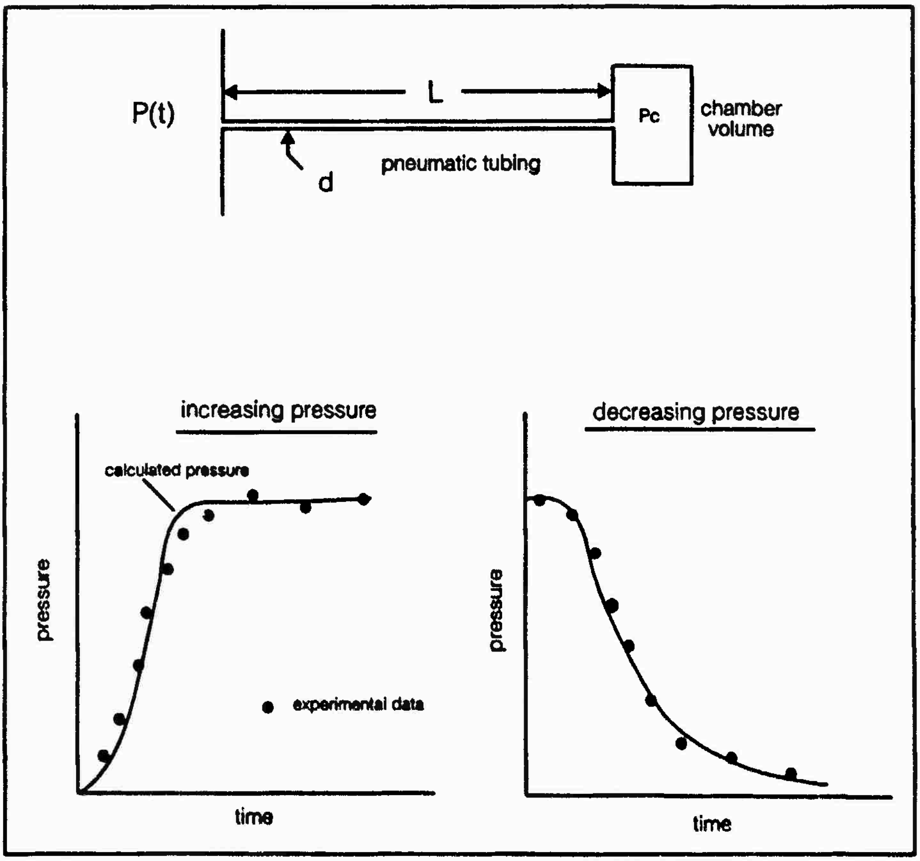


Figure 4.2-16 Pressure Sensor Transmission Tube Model (Reference 4.2.4)

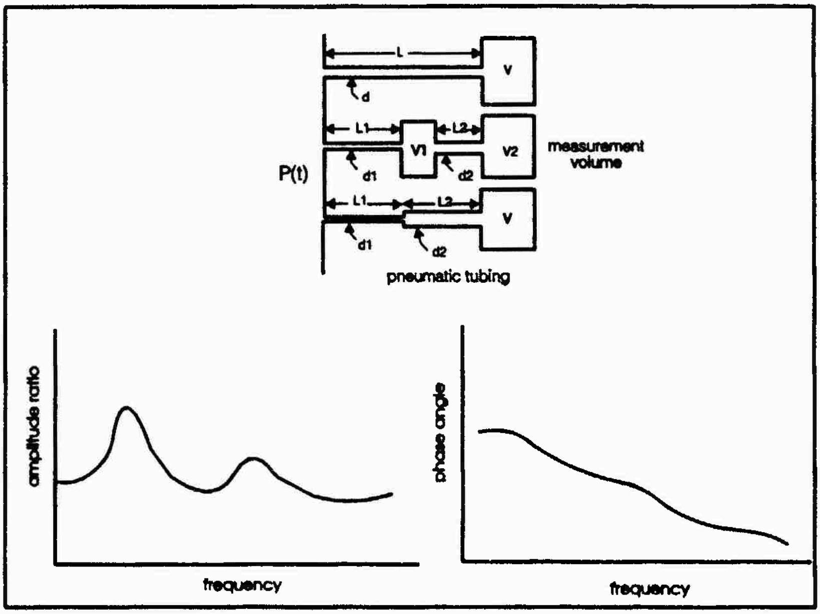


Figure 4.2-17 Pressure Sensor Transmission Tube Model
(Reference 4.2.5)

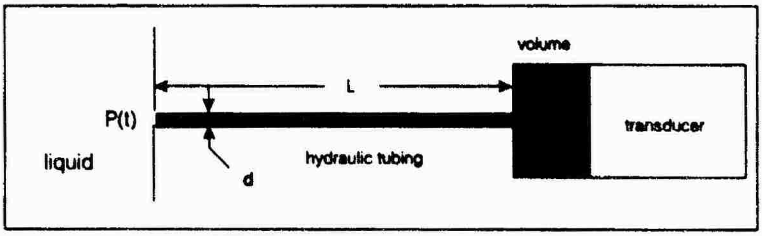


Figure 4.2-18 Pressure Sensor Transmission Tube Model
(Reference 4.2.6)

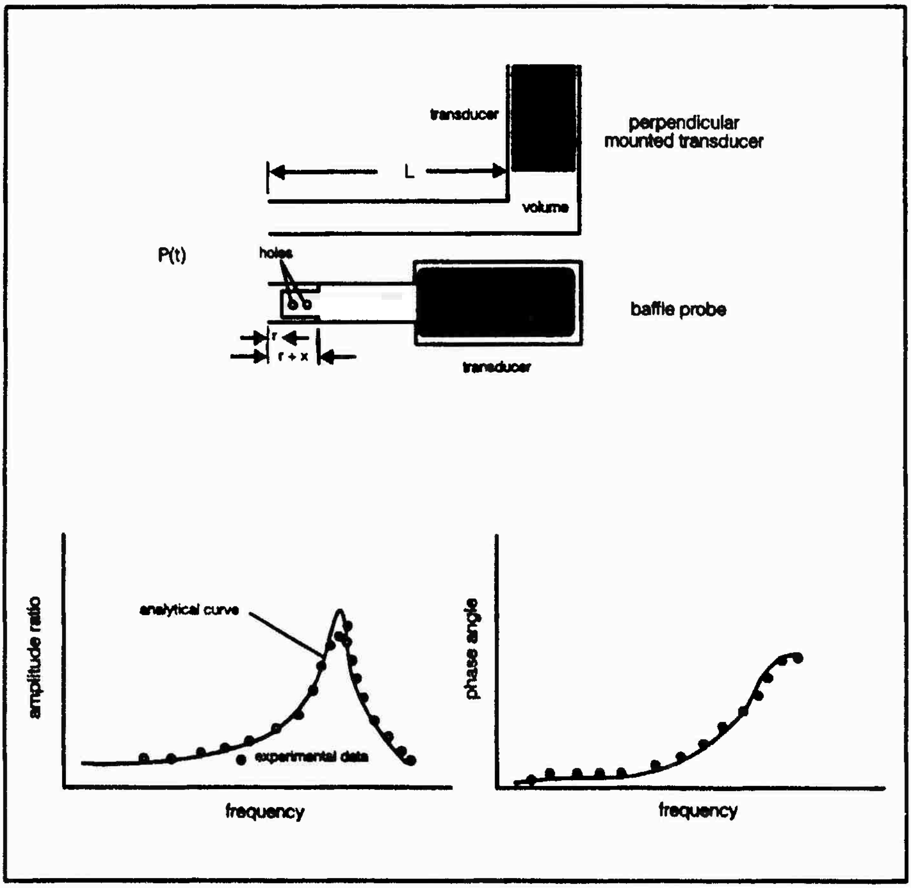


Figure 4.2-19 Pressure Sensor Transmissiion Tube Model (Reference 4.2.7)

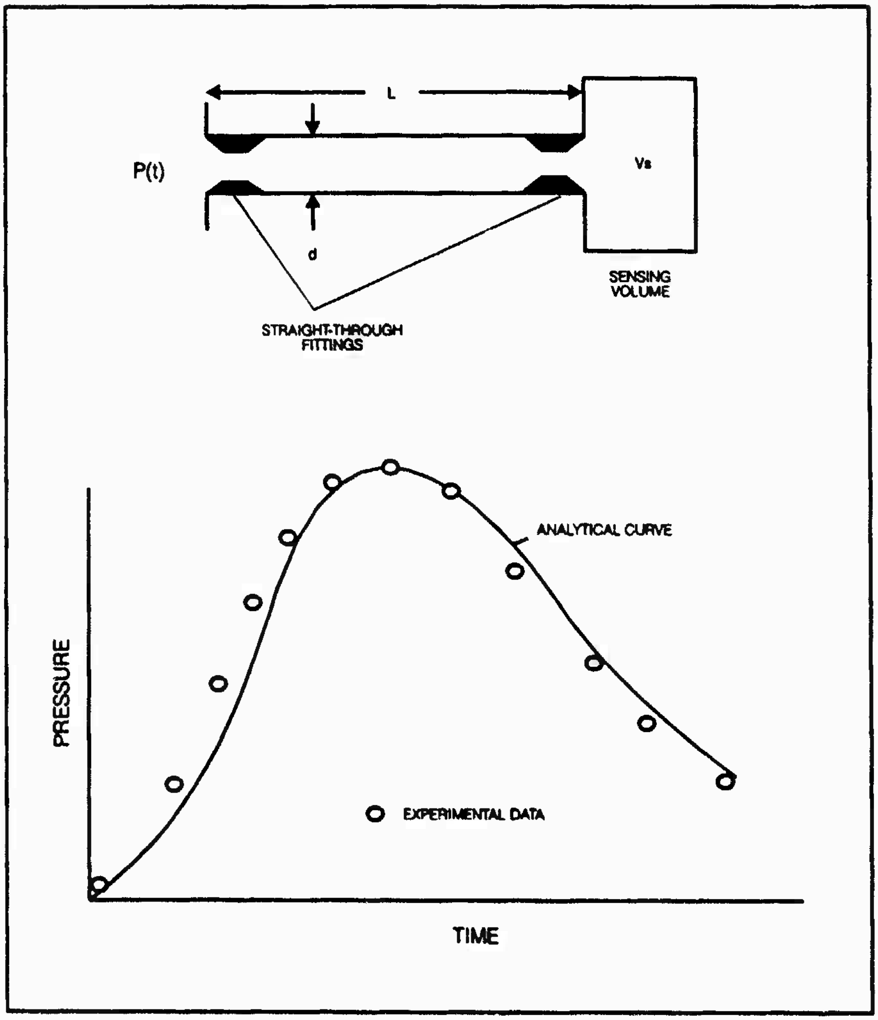


Figure 4.2-20 Pressure Sensor Transmission Tube Model
(Reference 4.2.8)

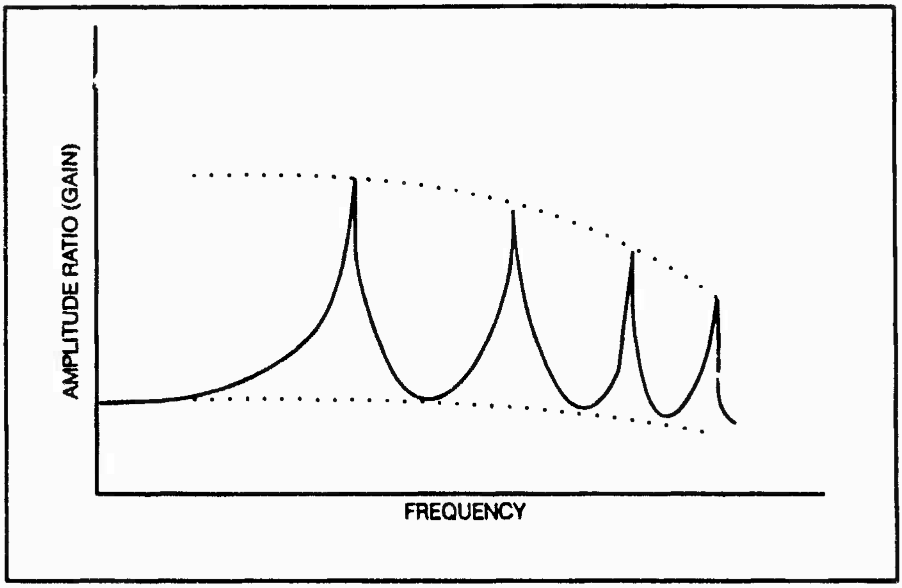


Figure 4.2-21 Pressure Sensor Transmission Tube Model Response (Reference 4.2.9)

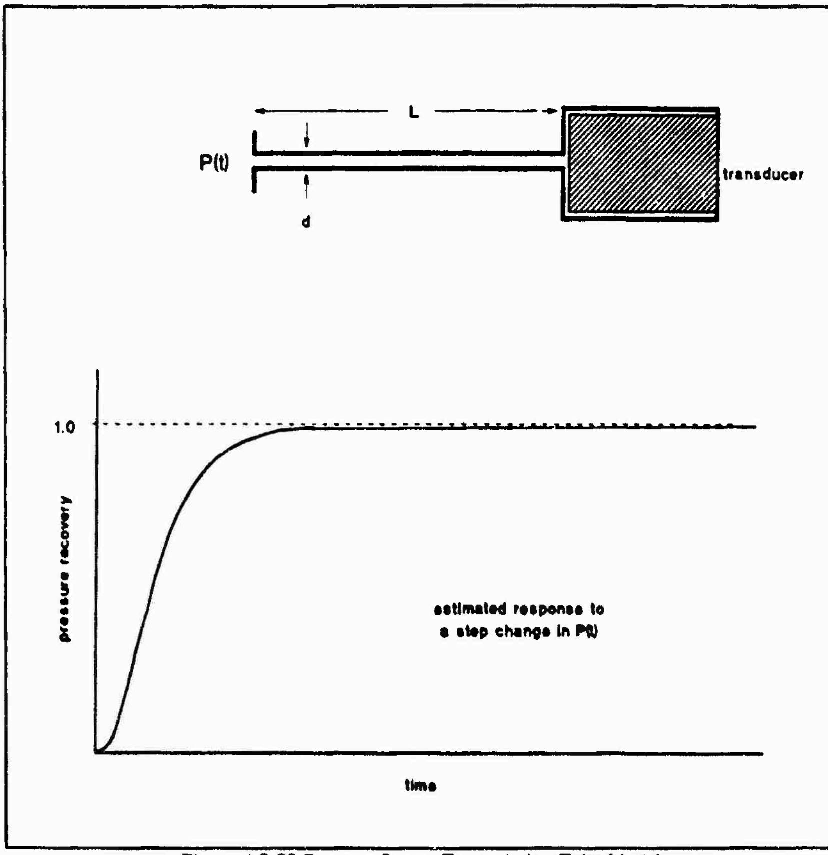


Figure 4.2-22 Pressure Sensor Transmission Tube Model
(Reference 4.2.10)

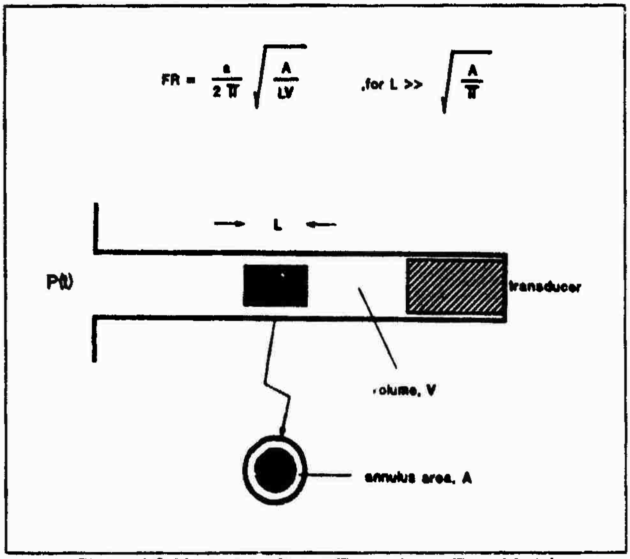


Figure 4.2-23 Pressure Sensor Transmission Tube Model
(Reference 4.2.11)

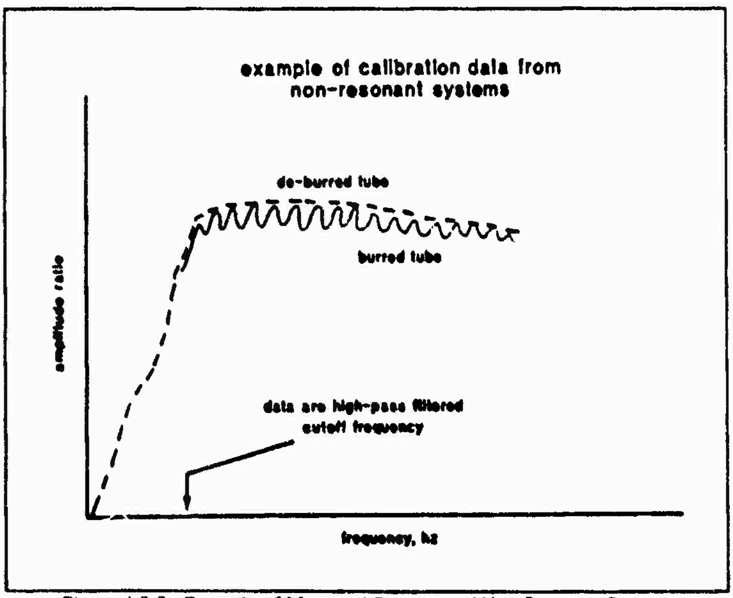


Figure 4.2-24 Example of Measured Response of Non-Resonant Systems

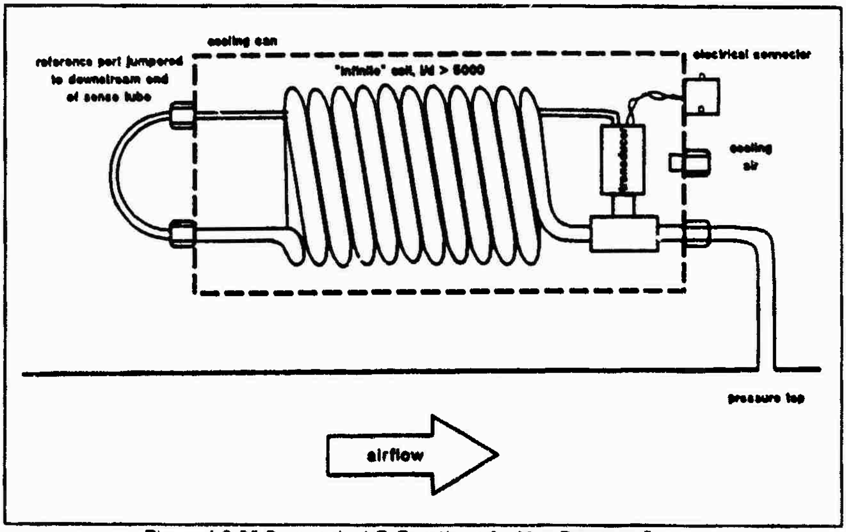


Figure 4.2-25 Pneumatic AC Coupling of a Non-Resonant System

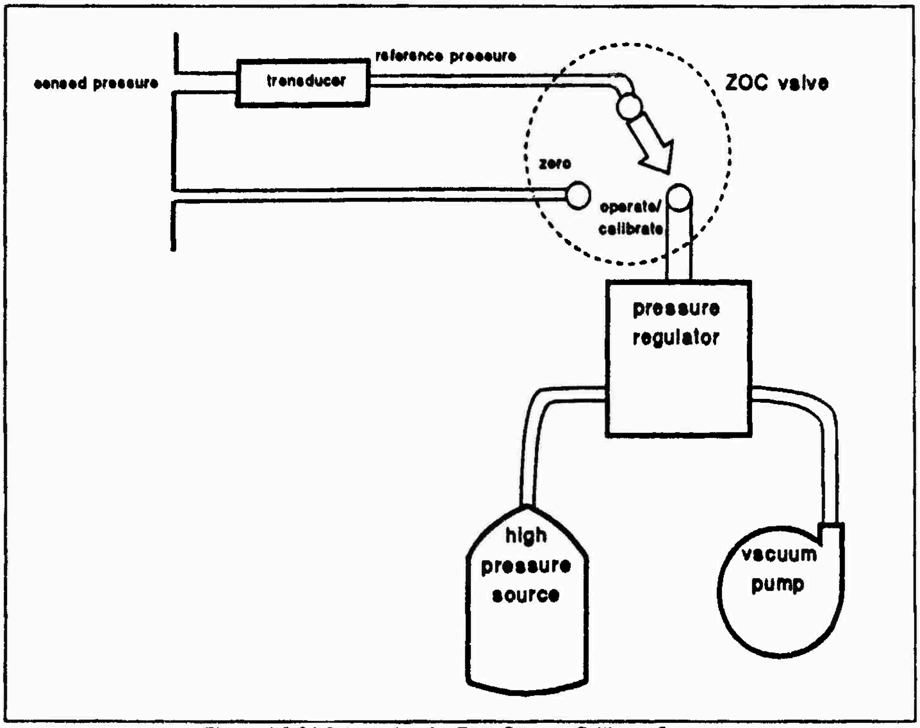


Figure 4.2-26 Schematic of a Zero-Operate-Calibrate System

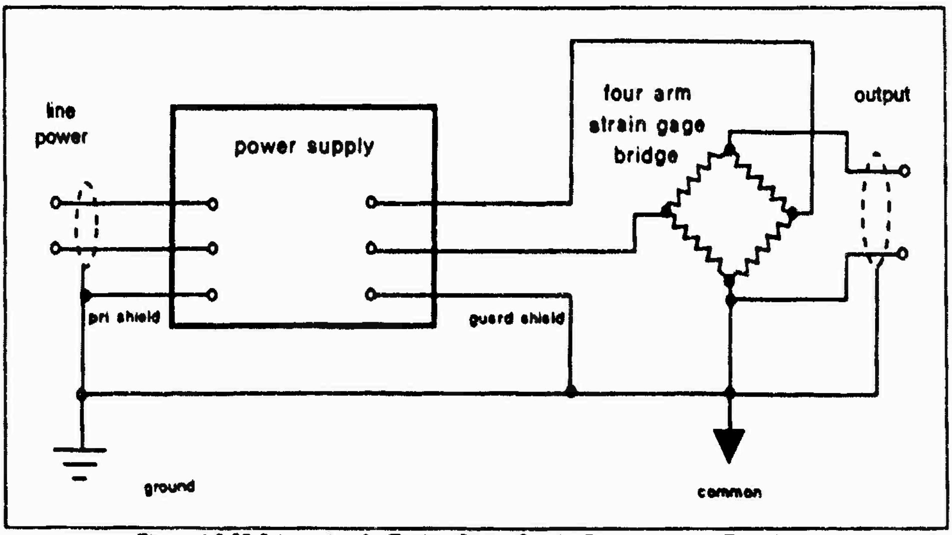


Figure 4.2-27 Schematic of a Typical Power Supply Connection to a Transducer

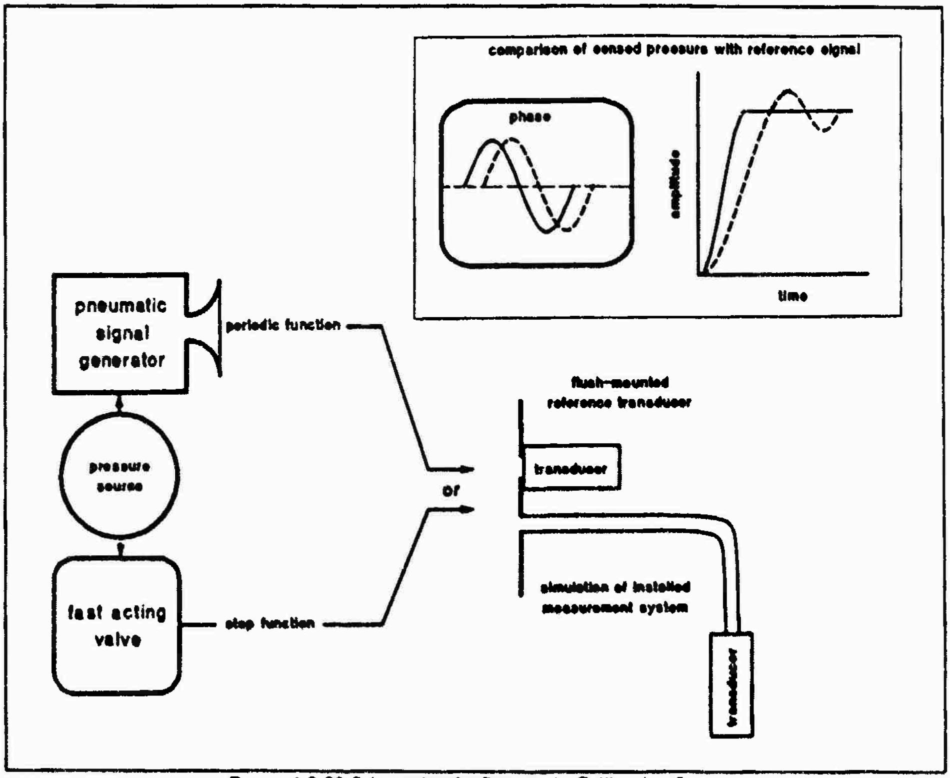


Figure 4.2-28 Schematic of a Pneumatic Calibration Setup

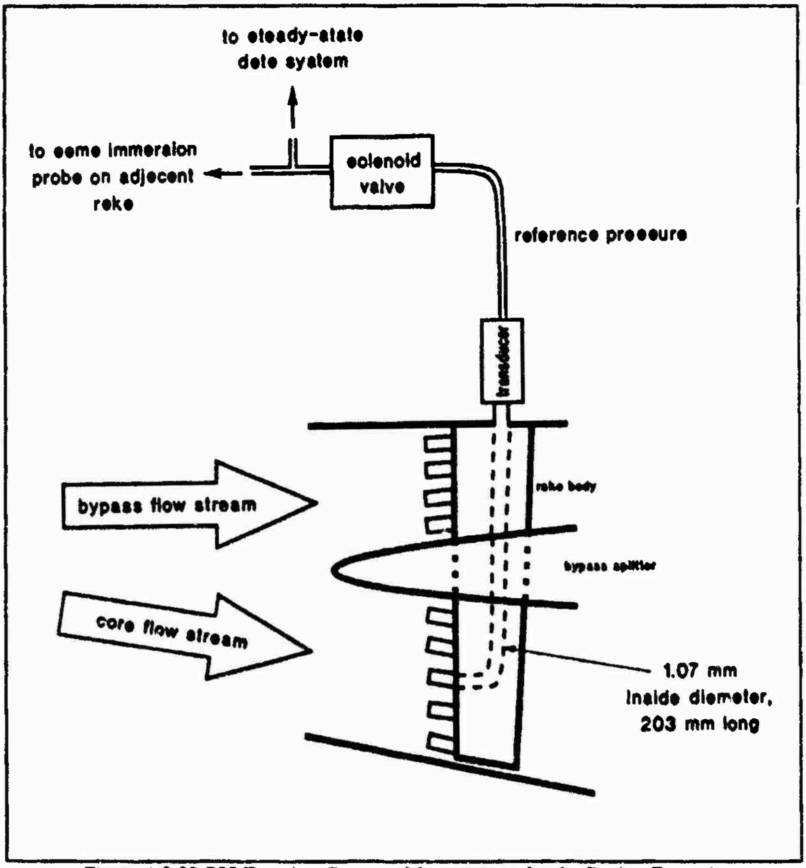


Figure 4.2-29 P25 Transient Pressure Measurement for the Design Example

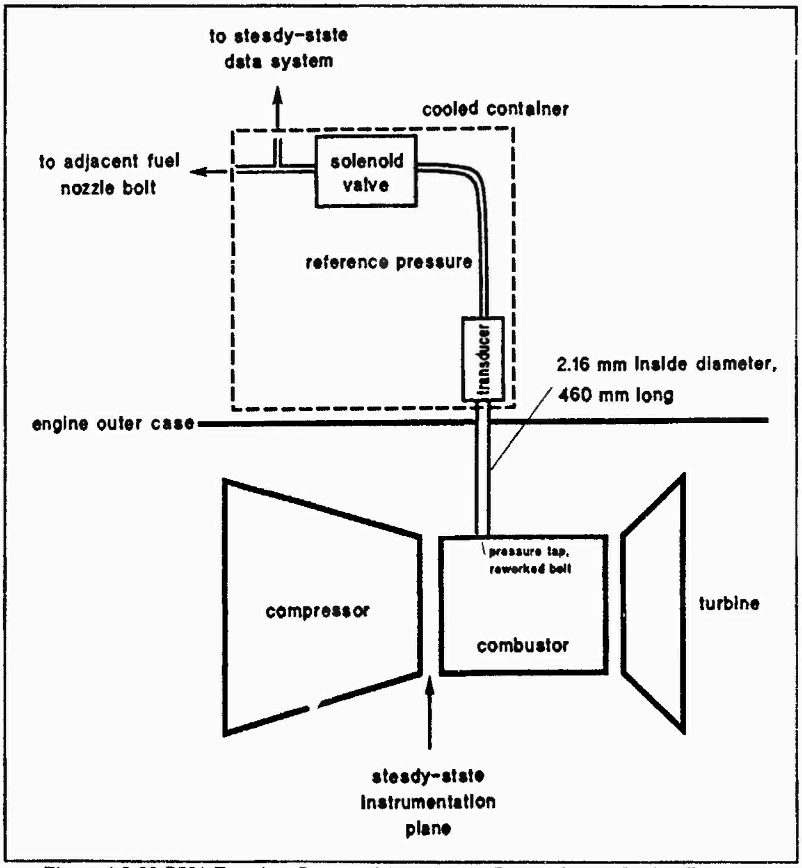
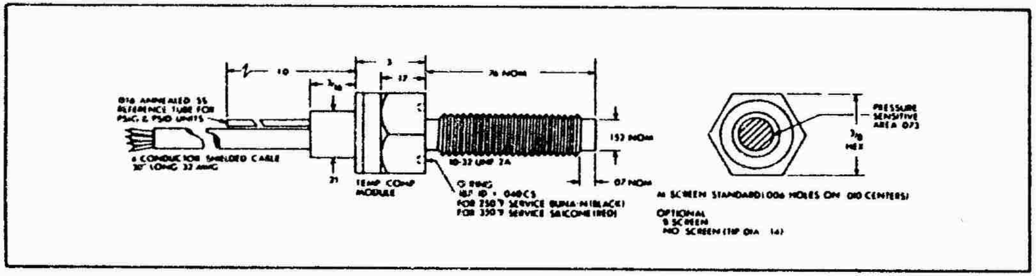


Figure 4.2-30 PS31 Transient Pressure Measurement System for the Design Example



PT25

INPUT										
Pressure Range	5	10	25	50	100	200	300	500	1000	2000 PSI
Operational Mode	Absolute, Gage, Sealed Gage, Differential									
Over Pressure	10	20	100	100	200	400	600	1000	2000	3000 PSI
Burst Pressure	3 Times Rated Pressure									
Pressure Media	All Nonconductive, Noncorrosive Liquids or Gases									
Rated Electrical Excitation	10 VDC/AC									
Maximum Electrical Excitation	15 VDC/AC									
Input Impedance	500 Ohms (Min.)									
OUTPUT										
Output Impedance	500 Ohms (Nom.)									
Full Scale Output (FSO)	100 mV (Nom.)									
Residual Unbalance	±5% FSO									
Combined Non-Linearity and Hysteresis	±0.3% FS BFSL *See Note 1									
Hysteresis	Less Than 0.1%									
Repeatability	0.5%									
Resolution	Infinite									
Natural Frequency (KHz)	70	70	100	120	180	200	270	350	500	650
Acceleration Sensitivity % FS/g Perpendicular	.002	.001	.0075	.0004	.0002	.00013	.00012	.00008	.00006	.00005
Transverse	.0004	.0002	.0001	.00008	.00004	.000026	.000024	.000016	.000012	.00001
Insulation Resistance	50 Megohm Min. at 100 VDC									
ENVIRONMENTAL										
Operating Temperature Range	-65°F to 250°F (-55°C to 120°C) Temperatures to 350°F (175°C) Available on Special Order									
Compensated Temperature Range	80°F to 180°F (25°C to 80°C) Any 100°F Range Within The Operating Range on Request									
Thermal Zero Shift	±1% FS/100°F (Max.)									
Thermal Sensitivity Shift	±1%/100°F (Max.)									
Steady Acceleration and Linear Vibration	1000g, Sine									
PHYSICAL										
Electrical Connection	4 Conductor 32 AWG Shielded Cable 24" Long									
Weight	5 Grams (Nom.) Excluding Module and Leads									
Sensing Principle	Fully Active Four Arm Wheatstone Bridge									
Mounting Torque	15 Inch-Pounds (Max.)									

PS3

25	50	100	200	300	500 PSI
Absolute, Gage, Sealed Gage, Differential					
50	100	200	300	450	750 PSI
3 Times Rated Pressure					
All Nonconductive, Noncorrosive Liquids or Gases					
10 VDC/AC					
15 VDC/AC					
1200 Ohms (Min.)					
1000 Ohms (Nom.)					
75 mV (Nom.)	100 mV (Nom.)	100 mV (Nom.)	100 mV (Nom.)	100 mV (Nom.)	100 mV (Nom.)
±5% FSO					
±0.5% FS BFSL					
Less Than 0.1%					
0.5%					
Infinite					
100	100	130	200	270	350
.0005 .0001	.00025 .00005	.0002 .00004	.0002 .00004	.0001 .00002	.00008 .000016
50 Megohm Min. at 100 VDC					
-65°F to 525°F (-55°C to 273°C)					
80°F to 450°F (25°C to 235°C)					
±2% FS/100°F					
±2%/100°F					
5% FS (Max.)					
1% FS (Max.)					
1000g, Sine					
4 Conductor 32 AWG Shielded Cable 24" Long					
5 Grams (Nom.) Excluding Module and Leads					
Fully Active Four Arm Wheatstone Bridge					
15 Inch Pounds (Max.)					

Figure 4.2-31 Pressure Transducers for the Design Example

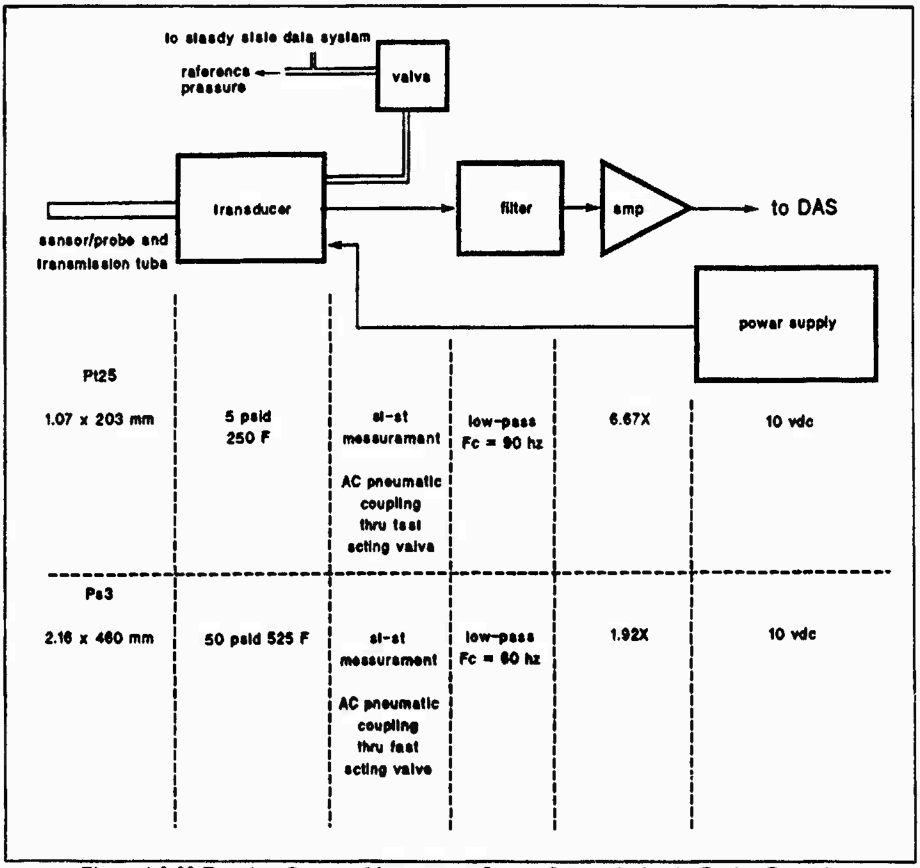


Figure 4.2-32 Transient Pressure Measurement System Schematic for the Design Example

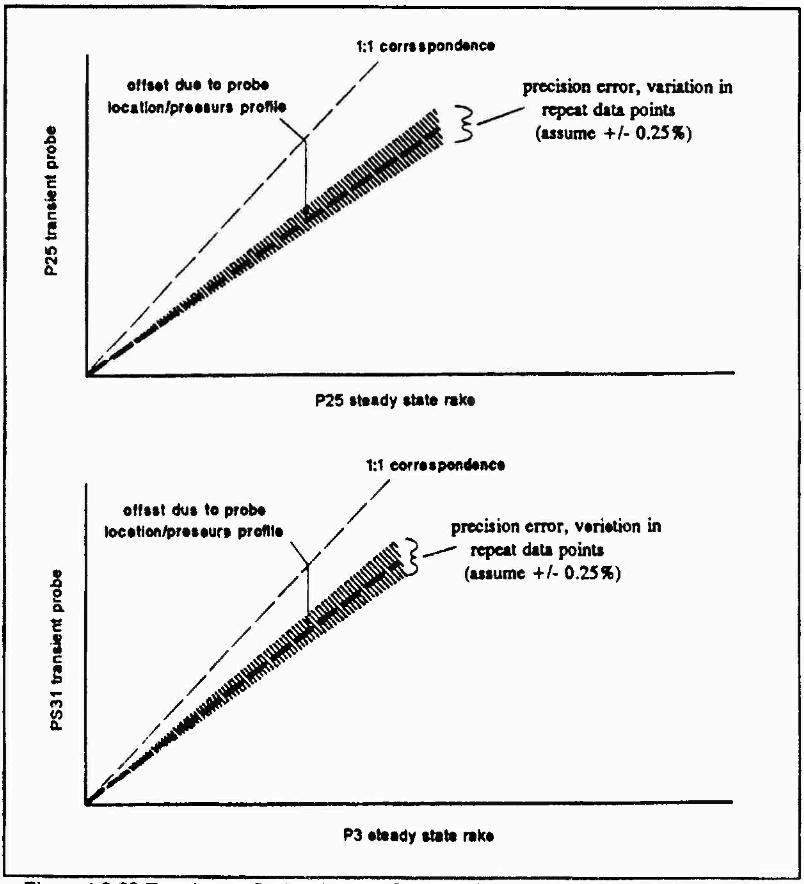


Figure 4.2-33 Transient to Station Average Pressure Correlations for the Design Example

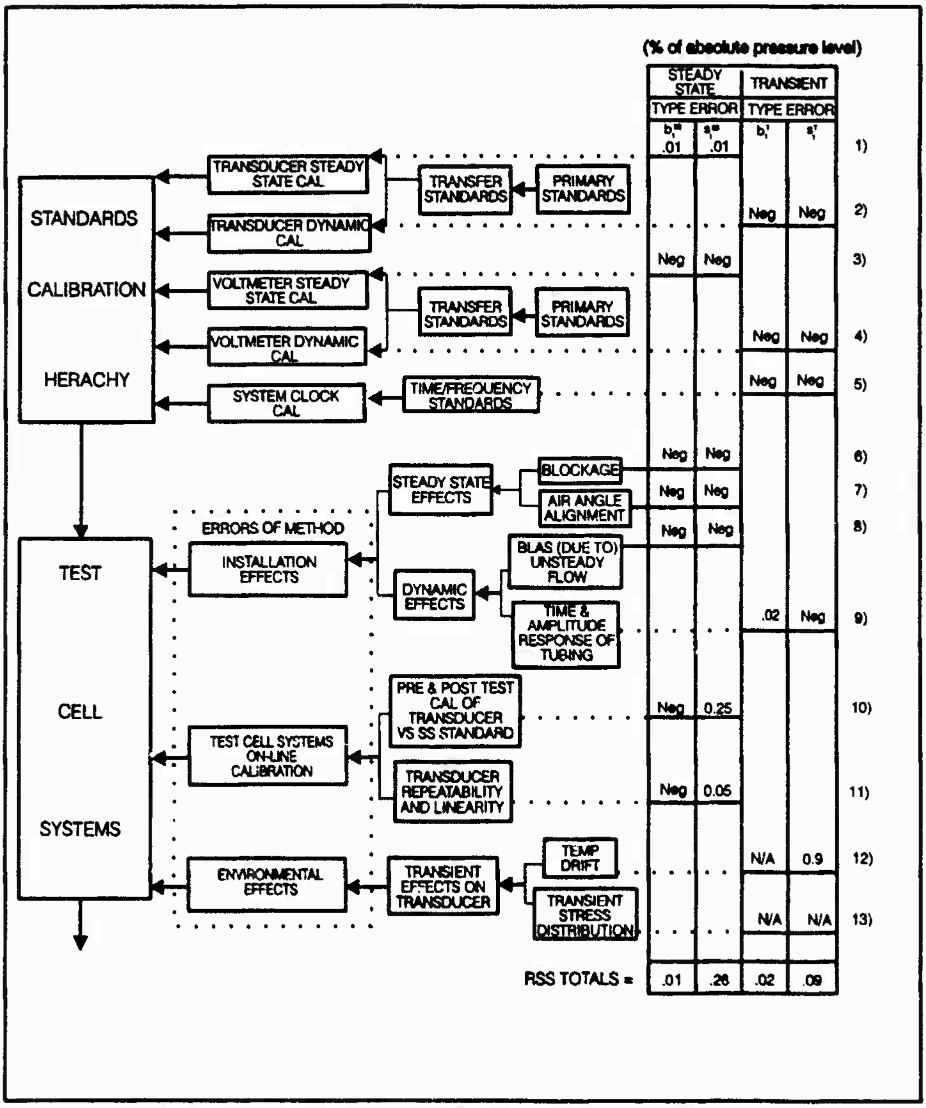


Figure 4.2-34 ΔP25 Error Source Diagram for the Design Example

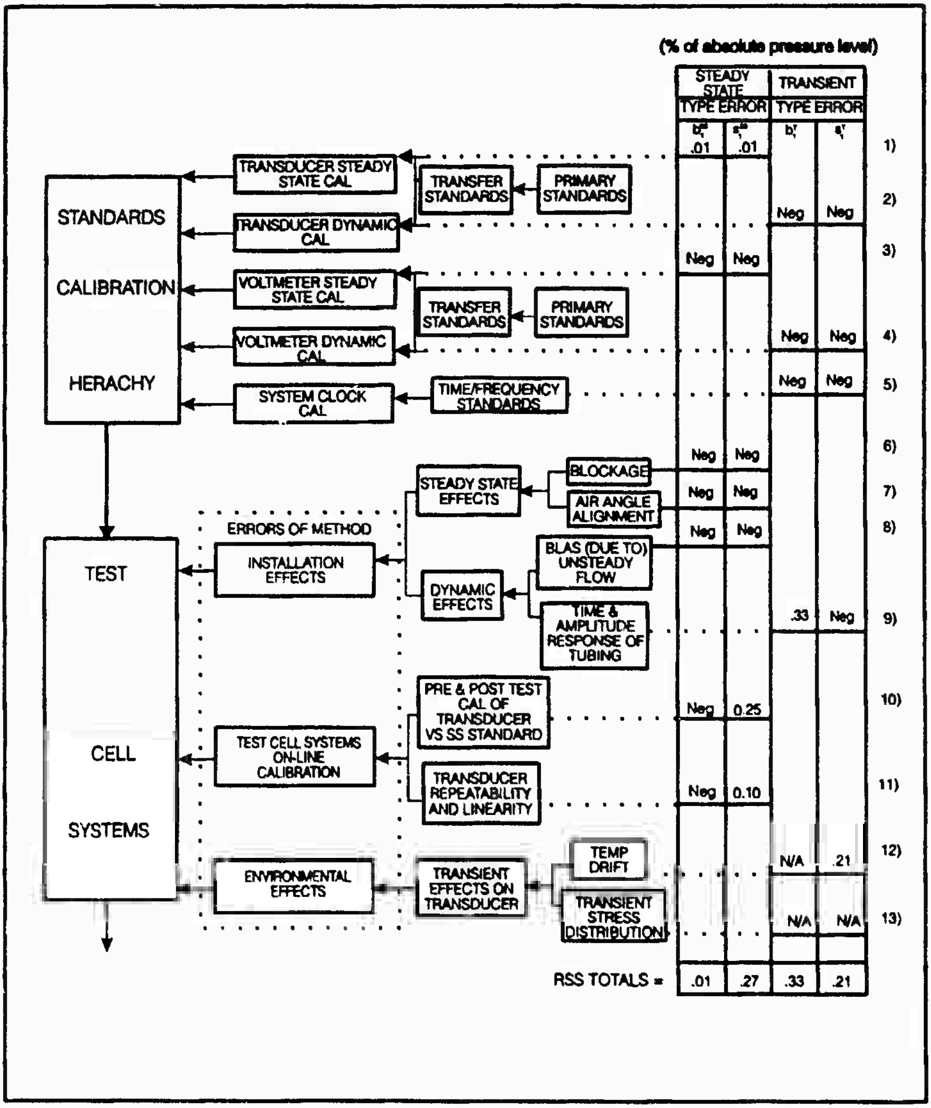


Figure 4.2-35 ΔPS31 Error Source Diagram for the Design Example

4.3 TEMPERATURE[1]

4.3.0 Introduction

As described in Section 2.5, transient temperature measurements are a requirement in starting, relight, shutdown, afterburning ignition, engine control system development, structural investigations and diagnostic tests. Transient temperature measurements, such as time to ignition and temperature excursion on light up, are generally made on every test vehicle (Table 2.4-4). So, although transient measurements of temperature can be considered in the perspective of special test requirements, there are sensors in every engine that must be capable of making both reliable steady state measurements over extended periods of time and responding to rapid transient excursions.

Temperature measurements for steady-state component performance evaluation are described in Reference 4.3.1. The considerations for steady-state design of the sensor set the foundation on which the transient design characteristics are based. The following descriptions of transient temperature sensors will first introduce the basic requirements of the steady-state design and then expand into the specific requirements for transient measurement. It must be emphasised that it is essential to clearly define the test requirements as it is often the case that trade-offs between steady-state and transient needs occur, resulting in a compromise between longevity, accuracy and response time.

The primary temperature measurements made in engines under test are Gas, Solid Surface and Liquid. The most common methods for sensing these temperatures are Thermocouples and Resistance Temperature Devices (RTD's). For convenience, because of the differences in approach required for making measurements in the three environments due to differences in heat transfer, chemical, electrical effects and response times, the subject of temperature measurement has been separated into the three major headings. Where the process is basically the same in the solid and liquid environments as that in the gas, then only the major differences are highlighted in those sections and the reader is referenced to the relevant sections of 4.3.1 for more detailed information.

4.3.1 Total Gas Temperature

4.3.1.1 *Introduction and Definitions*

The most common sensors used at present for gas temperature measurements are thermocouples, primarily due to their ruggedness, ease of fabrication, tolerated (if not acceptable) response time and relatively low cost to use.

Resistance Temperature Devices (RTDs) and hot wire anemometers are now being applied more often but each has its limitations either in size, ruggedness, signal processing or cost compared to the more common thermocouple. Thermistors are not generally used due to their low limited temperature range which is usually below 100°C.

Steady state probes, with a few exceptions, e.g., sonic flow pyrometer (aspirated probe), are not suitable for transient measurements. Steady state probes are generally designed to bring the gas to near zero velocity at the sensing element. Sufficient time is then allowed for equilibrium to be reached between the gas temperature and the sensing element. Unfortunately, the heat transfer rate is slow and the probe has, as a consequence, a long time constant.

4.3.1.2 *Basic Theory*

Thermocouples, RTDs and hot-wires have a number of common application problems which will be addressed through the use of the thermocouple as an example.

For transient conditions the sensing element must be permitted to rapidly follow the gas temperature. A fully exposed element, or close to, such as illustrated in Figure 4.3-1 is required.

Thermocouples and other gas immersed temperature measuring sensors are exposed to a number of errors due to their presence in the gas stream. The steady-state errors and corrections will be considered first, then the effect of transient conditions on these corrections will be examined.

4.3.1.2.1 *Steady -State Considerations*

(a) <u>*Velocity Error* Y_v</u>

There is a velocity error that must be considered. In a

[1] Tables and Figures for Section 4.3 begin on page 4-84

probe, the gas is not brought to rest adiabatically and, as a consequence, the indicated temperature of the junction, T_J, is lower than T_T, the total temperature of the gas. This error can be expressed in terms of the velocity of the gas flow at the junction and a recovery factor (Reference 4.3.2).

$$Y_V = T_T - T_J = (1-r)\frac{\frac{\gamma-1}{2}Ma_J^2}{1+\frac{\gamma-1}{2}Ma_J^2}T_T \qquad 4.3\text{-}1$$

where Y_V = velocity error
γ = c_P/c_V
Ma_J = Mach number of the flow at the junction
r = recovery factor

and where the thermocouple recovery factor r is defined as

$$r = \frac{T_J - T_S}{T_T - T_S} \qquad 4.3\text{-}2$$

where T_J = junction temperature
T_S = static temperature of the gas
T_T = total temperature of the gas

Recovery factors can be determined experimentally. For bare thermocouple wires, the values for r have been measured (Reference 4.3.2) as:

wires normal to the flow $r = 0.68 \pm 0.07$
wires parallel to the flow $r = 0.86 \pm 0.09$

These values are adequate for $Ma = 0$ to 1.0.

(b) *Conduction Error Y_K*

In the steady-state condition, the heat transfer to the thermocouple is balanced by thermal conduction along the wires and radiation to and from the surrounding environment (Reference 4.3.2). The conduction error under steady state conditions is given by:

$$Y_K = T_T - T_J = \frac{T_T - T_M}{\cosh L\left(\frac{4h_c}{d_w k_w}\right)^{1/2}} \qquad 4.3\text{-}3$$

where Y_K = conduction error
T_T = total temperature
T_J = junction temperature
T_M = metal temperature
L = length of exposed wire
d_w = diameter of the wire
h_c = convective heat transfer coefficient
k_w = thermal conductivity of the wire.

(c) *Radiation Error Y_R*

In general, the radiation error due to radiation between the sensor and the surrounding wall under steady state conditions is as follows (Reference 4.3.2):

$$Y_R = T_T - T_J = \frac{\sigma e}{h_c}(T_J^4 - T_W^4) \qquad 4.3\text{-}4$$

where Y_R = radiation error
T_T = total temperature
T_J = junction temperature
T_W = wall temperature
σ = Stefan-Boltzman constant
e = emissivity
h_c = convective heat transfer coefficient

Changes in the emissivity can occur due to catalytic effects and the accumulation of debris on the exposed junction. For short duration tests, the emissivity should not vary appreciably.

Errors due to flame radiation are difficult to predict and it is recommended that precautions be taken to keep the sensor out of the line of sight of the flame. Gas radiation effects are not fully understood and are not generally considered.

For simple, unshielded thermocouple configurations, radiation corrections can be estimated adequately by utilizing the following equation (Reference 4.3.3):

$$Y_R = \frac{K_{rad}}{\sqrt{Ma\ PS/PS_0}}\left(\frac{T_J}{T_0}\right)^{3.82}\left[1.0 - \left(\frac{T_W}{T_J}\right)^4\right] \qquad 4.3\text{-}5$$

where K_{rad} = radiation correction coefficient, K
Ma = stream Mach number
PS = stream static pressure, MP_a
PS_0 = reference static pressure of 0.1 MP_a (1 atm)
T_J = probe indicated temperature, K

T_0 = reference temperature, 555 K
T_W = enclosure duct wall temperature, K

For unshielded, type K (chromel-alumel), probes the value of K_{rad} can be expressed empirically by:

$$K_{rad} = 2.5 d_w^{0.45} \qquad 4.3\text{-}6$$

where the wire diameter d_w is in mm.

4.3.1.2.2 *Transient Considerations*
Keeping the above steady-state requirements in mind, we can now consider the additional steps that are imposed by the defined transient conditions.

(a) Velocity Effects

The heat transfer to the sensing element is in most cases primarily dependent on the unit mass flow of the gas.

The time response of a thermocouple is given by (Reference 4.3.4):

$$-m\, c_p \frac{dT_J}{dt} = h_c\, A\, (T_T - T_J) \qquad 4.3\text{-}7$$

where h_c = is the average convection heat transfer coefficient at the junction
A = the surface area of the junction
T_T = the gas total temperature
T_J = the temperature indicated by the thermocouple junction
t = time
m = the mass of the junction
c_p = the specific heat of the junction

Rearranging gives:

$$Y_T = T_T - T_J = \frac{m\, c_p}{h_c A} \frac{dT_J}{dt} \qquad 4.3\text{-}8$$

where it is convenient to set

$$\text{Time constant } \tau = m \frac{c_p}{h_c A} \qquad 4.3\text{-}9$$

Considering the sensing element, this time constant formula applies to both thermocouple and resistive devices. For the shortest time constant, h_c must be maximized to transfer as much heat to the junction in as short a time as possible and A minimized as this directly relates to volume and hence the total thermal mass of the wire. Therefore, the time constant is dependent on the unit mass flow for any element exposed directly to the measurand. In the determination of the time constant to be applied in compensating for uncertainty due to temporal variations, the mass flow change and temperature change must be taken into consideration. For the same temperature step change, the time constant for a bare bead thermocouple will be different if the mass flow is changed from a high flow compared to a similar change from a low mass flow. An extreme case would be excursions from and to zero mass flow.

As an example, referring to Figure 4.3-2, for a thermocouple at 715K (800°F):

Time constant when mass velocity changes to 195 kg/m^2 sec (40 lbs/ft^2 sec) ≈ 0.8 secs;

Time constant when mass velocity changes to 29.3 kg/m^2 sec (6 lbs/ft^2 sec) ≈ 2.0 secs.

For measurements made where there are small changes in mass flow and temperature (say, ± 10%), the time constant remains essentially constant and passive electronic compensation can be applied.

Total temperature and mass flow effects on a bare thermocouple junction are illustrated in Figure 4.3-3. The response time can be seen to vary from 0.62 to 5.5 sec for a 1.30 mm (16-gauge) wire for temperatures from 344K to 1145K (160°F to 1600°F) and mass velocities from 9.8 to 244 kg/m^2 sec (2 to 50 lbs/ft^2 sec).

The effect of wire diameter on response time is illustrated in Figure 4.3-4.

If the time constant is known at a reference temperature and pressure, then the value under a new set of conditions can be determined from Equation 4.3-10 (Reference 4.3.3):

$$\tau = \frac{\tau_0}{\sqrt{Ma\ PS/PS_0}} \left(\frac{T_J}{T_0}\right)^{-0.18} \qquad 4.3\text{-}10$$

where τ_0 = reference time constant for the particular probe
Ma = stream Mach number
PS = stream static pressure, MPa (atm)
PS_0 = reference static pressure, 0.1 MPa (1 atm)
T_J = probe indicated temperature, K
T_0 = reference temperature, 555 K.

For unshielded, type K (chromel-alumel), probes, τ_0 can be expressed as

$$\tau_0 = 0.52 d_w^{1.15} \qquad 4.3\text{-}11$$

Where d_w is the diameter of the wire in a range 0.03 to 1.02 mm.

Orientation of the thermocouple to the flow direction also affects the response time. Rotation of the loop formed by the thermocouple junction in a gas flow at a temperature of 810K (1000°F) showed the effects summarized in Table 4.3-1 (Reference 4.3.4).

The junction used was 13 wire diameters long, with the wires parallel, and two wire diameters apart. More dense shapes may be affected by orientation to a greater extent, as might the shorter junctions.

(b) <u>*Conduction Effects*</u>
Errors due to conduction can be pronounced during transients, particularly if the length of the exposed wire is small. This error can be reduced significantly by increasing the amount of wire exposed to the gas stream and using lower conductivity thermocouple wire. Figure 4.3-5 illustrates the effects of the length of exposed wire for a 1.30 mm (16 gauge) chromel alumel thermocouple (Reference 4.3.4). A ratio of exposed wire to wire diameter of >10:1 is recommended. Mechanical support of the exposed wire may be necessary to retain mechanical integrity.

An increase in the weld bead size raises the response time, but does not have the same impact as increasing the wire diameter to the same size. Table 4.3-2 (Reference 4.3.4) gives, as an example of the impact, the measured values of τ for three weld bead sizes on 1.02 mm (0.040 inch) diam. wire compared with τ for uniform diameter wire of the same diameter as the weld beads.

To minimize the response time, the sensing element mass is kept small. In the case of RTD's and hot-wires the wire diameters are kept as small as is practical. For thermocouples, the weld bead as well as the wire must be made as small as possible, preferably with the bead the same diameter as the wire (Reference 4.3.4).

$$\frac{\tau}{\tau_o} = \left(\frac{d_B}{d_w}\right)^{0.375} \qquad 4.3\text{-}12$$

where τ = time constant with weld bead
τ_o = time constant without weld bead
d_B = diameter of weld bead
d_w = wire diameter

The shape of the junction also affects the response time. By aiming to keep the bead size the same as that of the wire itself, this potential source of error is eliminated.

(c) <u>*Radiation Effects*</u>
In the above, we have been addressing the application of the bare thermocouple bead. Since the bead is fully exposed, radiation to, and from, the surrounding environment will have an impact and this must be evaluated as to its contribution to the response of the sensor.

The effects of radiation to cold walls on response time of a bare 1.27 mm (0.051 inch) round wire, loop junction thermocouple with an 1145K (1600°F) gas temperature have been measured with the results shown in Table 4.3-3 (Reference 4.3.4).

4.3.1.2.3 *Sonic Flow Pyrometers*
Sonic Flow Pyrometers (aspirated probes) remove much of the dependence on the measurand mass flow but add the complication of additional equipment to operate. An example of a probe is shown in Figure 4.3-6. A pressure differential must be maintained across the nozzle so that the air flow is sonic at that location. Under low measurand pressures a suction pump will be required to maintain that pressure differential. This is often the situation when calibrating using a source at atmospheric pressure. In high pressure situations the probe may be vented to atmosphere. The pumping arrangement must handle the high temperatures that are seen in the high pressure regions of gas turbine engines. Because gas is being extracted from the gas flow past the bead, this probe is less susceptible to errors due to flow angle changes.

A comparison of the typical change in time constant between a bare thermocouple junction in the free stream and the sonic pyrometer is illustrated in Figure 4.3-7. The sonic pyrometer's response is essentially independent of the free stream Mach number.

4.3.1.2.4 *Summary*
The time dependancy characteristics of a thermocouple instrumentation system are illustrated in Figure 4.3-8. The contributions to the bias and precision errors in the steady state and transient modes are shown in Figure 4.3-9.

To obtain a rapid response, the sensing elements need to be in direct contact with the flowing gas. In order to reduce the uncertainty in the data and extend the life of the sensing element the following must be consid.red in the design and installation.

1. Temperature range
2. Response time required
3. Mounting of the sensing element, housing, structural constraints
4. Projected mass flow variations
5. Mechanical limit on wire diameter for life expectancy
6. Recovery factor of the sensing element
7. Effects of orientation of the sensing element to the flow and projected flow directional changes
8. Effects of radiation from and to the surroundings
9. Conduction errors through the wires
10. Signal conditioning, averaging spatially and temporally
11. Reference system, calibration of the sensor

The relative importance of each of the above must be evaluated against the specific data sought. Where the sensor must have proven durability, the size of the wire needed may increase the response time, which is a trade-off that the designer must accept. Similarly, the design of the probe housing may be mechanically constrained due to the location and anticipated stress levels such that the design may not take fully into account the projected flow variations or have sufficient size to use conduction error compensating techniques. Each of the listed items interacts to a greater or lesser extent with each of the others and cannot, therefore, be considered in isolation.

4.3.1.3. *Advantages and Disadvantages*

In the introduction to Section 4.3., it was noted that basic design criteria for thermocouple and resistance probes applied to both steady-state and transient probe design.

Fine wire butt-welded thermocouples have been demonstrated in use with time constants of the order of 5 msec (Reference 4.3.5) and thin tungsten wires (5-10 μm) as equilibrium temperature probes with response times of 10 msec (Reference 4.3.6). Thin film sensors deposited on filaments of quartz can be produced with short time constants but tend to be fragile and only usable in relatively smooth steady gas flows.

Advantages:

Thermocouples-
- Small size
- Point measurement
- Probe housing easy to design
- Installation easy
- Fine wire butt-welded thermocouples have been demonstrated in use with time constants of the order of 5 msec (Reference 4.3.5)
- Wide range of applications
- Diversity
- Available as bare or sheathed wires
- Low cost (except noble metals)
- Self-generator
- Easy to build into probes

RTDs-
- Accuracy
- Fidelity (Selected as reference for calibration up to 600°C)
- Good interchangeability
- Easy conditioning

Disadvantages:

Thermocouples-
- Measurement precision requiring a lot of care (calibration)
- Low output levels
- Risk of aging
- Sensitivity to environment

RTDs-
- Size
- Operating temperature limited to 600 to 650°F
- Must be mounted in a strain-free environment
- External power supply needed
- Self-heating error and low recovery factor

4.3.1.4 *Signal Conditioning*

The outputs from thermocouples, RTDs, thermistors and hot-wires are electrical signals. The electronics used to process these signals differ. Even so, the biggest impact on the ability to measure the changes with minimum uncertainty is the response of the sensing elements themselves. Compensation, either through passive networks in the electronics or through algorithms in software, can be applied. The nature of the measurand and its predicted changes with time must be evaluated to make use of the data obtained from the sensor.

Typical system configurations for thermocouples and RTDs are illustrated in Figure 4.3-10. The same arrangements as for steady state recording apply with the exception that the elements of the system must be capable of following the transient event. So, for thermocouples, the leads should be shielded, an ice point junction (or similar reference) or a uniform temperature reference unit installed and an amplifier with low pass filtering used. The recording medium depends on the test requirements. Filtering for noise rejection, etc., may be required. The response of various low pass filter designs is given in Section 4.9.4. The whole system must be calibrated, in dynamic, as well as static, mode, where possible.

Advanced sensor systems, described in Section 4.3.1.7, have their own built-in signal conditioning which determines their overall transfer function.

4.3.1.5 *Calibration Procedures*

The calibration of sensors for transient measurements is not as straight forward as for steady state probes. If there is knowledge of the specific test requirements that permit the prediction of the measurands behaviour over the operating ranges then simulated calibrations can be performed. If the test requirements have not been sufficiently detailed then families of curves will be required that can be called upon after the test, based on observations during the test program. This is not desirable. As stated above, the sensing elements must be of the smallest diameter within the mechanical limit of wire diameter for life expectancy. There is a high level of risk that the life of the wire will be short due to under design and that the test data may be lost after expending time and money on excessive calibration and lost component test time and program delays.

As well as taking precautions, as with steady state conditions, of minimizing errors due to connections, to wire inhomogeneities in areas away from the sensor, to unwanted noise generated through electrical interference,etc., there is a need to consider the repeatability and measurement of the changes in the calibrator temperature and mass flow rate as seen by the sensor being calibrated. The need to calibrate will depend on the accuracy required of the test data. If the test is primarily to observe the overall response characteristics then a calibration may not be necessary. On the other hand, for accuracies approaching those of the steady state performance a transient calibration will be required.

The most straight forward approach is to impose a step change where either the probe is inserted/withdrawn from a calibrated flow (Reference 4.3.7) or the probe is held in position and the calibrated flow diverted (Reference 4.3.8). These two methods are illustrated in Figures 4.3-11 and 4.3-12. In Figure 4.3-11, the probe is initially held in the retracted position shielded from the nozzle flow. A cooling flow may be passed through the shield to keep the sensor at a steady regulated temperature. When stable conditions have been established in the nozzle flow, the probe is rapidly moved into the flow stream by the actuator. The change in output voltage of the probe is recorded on an oscilloscope, digital data system or other appropriate media. The time constant is determined from the rise time of the recording. In Figure 4.3-12, the probe is held in a fixed position and a shield, that diverts the flow from the nozzle around the probe, is rapidly retracted so that the probe is exposed to the flow. Reversing the above procedures, that is, retracting the probe or covering the probe rapidly, will give the time constant for return to the lower temperature and cooling rate of the cooling air flow. Mass flow and temperature of the calibrating air flow must be recorded for each calibration condition.

The outputs from the sensors for the step change will be as illustrated in Figure 4.3-13. The time constant τ may be estimated from the response of a first order system to a step change in input (Equation 4.3-13):

$$\tau = \frac{t}{\ln \dfrac{V_T - V_o}{V_T - V}} \qquad 4.3\text{-}13$$

where V = Voltage at time t.
V_T = Voltage when sensor is stabilized at temperature T @ t = infinity.
τ = Time constant (Response time).
V_0 = Voltage at time t = 0

From Equation 4.3-13, τ will be the time at which $(V - V_0)$ reaches 63 % of $(V_T - V_0)$.

4.3.1.6 *Design Examples*

There are many forms of transient tests that range from relatively steady slow changes such as throttle controlled accelerations to faster impacting fuel spikes. The same principles apply in each case, the differences being primarily in the temporal correlation of the recorded data.

Reference literature has limited test data on time constant determination. The majority of designers of thermocouple probes for transient tests establish their own data files based on the specific needs of the tests they perform in their own test beds and unique installations.

<u>EXAMPLE 1</u> (see Section 5.2)

In this example, a fuel spike is introduced to observe the stability of the engine at the selected operating point (see Section 5.2). Temperature of the air flow is measured at the T25 location.

The temperature T25 is used to normalise the data at the operating point just prior to the onset of surge. Although the temperature of the air may change slightly during the pressure change just prior to the surge, the measurement required is essentially steady-state. In this case, suitable steady-state rakes , as described in Reference 4.3.1, will be used. The flow profile is assumed to be uniform and the average station temperature dervied from three five-point rakes, the probes being located at centres of equal area. Tfhe temperature was measured as 82°C (180°F). This value is used in the calculation of the mass flow as described in Section 4.4.7.6. [Note: To follow the transient temperature change during the surge would required a probe with a time constant of the order of 10 msec. the wire diameter to meet this requirement would be about 0.025 mm (.001 inch) diameter.]

The overall uncertainty in this measurement is detailed in Figure 4.3-14. Only the steady-state uncertainty is required in this example and this has been determined to be a bias of ±0.37 C° and a precision of ±0.17 C° for the instrumentation system. The overall uncertainty, including the data acquisition and processing systems, is given in Section 5.2.

EXAMPLE 2

The objective of the test is to establish the value of the peak of the gas temperature, T5, to which engine metal surfaces will be exposed. Here we shall look at the measurement of the exhaust gas temperature (T5) for an acceleration over a period of 5 secs (Figure 4.3-15). The temperature range is from 365°C to 813°C (689°F to 1495°F).

The thermocouple, due to its mass, acts as a thermal integrating device. The measurement system recording is a trace that is a smoothed representation of the measurand. Since the metal surfaces also act as integrators, they will respond to this smoothed representation of the measurand, ignoring short term perturbations.

The design must first consider the trade-offs of short time constant, implying small diameter wire, against lifetime of the thermocouple, upper limit of the temperature excursion and mechanical integrity of the assembly. Another factor to consider is the use of commonly available, off the shelf, materials to reduce cost and lead time.

At the present time, standard sizes for thermocouple wires themselves typically range from 0.038 mm (0.0015 inch) dia up to 1.02 mm (0.040 inch), with corresponding outside sheath diameters from 0.25 mm to 6.35 mm (0.010 inch to 0.250 inch). The thermocouple may be provided complete by the supplier or constructed in-house in the formats illustrated in Figure 4.3-1. Special designs similar to that developed in Reference 4.3.9 are available from some suppliers (Figure 4.3-16).

In selecting the thermocouple design, consideration must be given to both the time constant and the estimated uncertainty. This may require an iterative process. The uncertainty estimation will allow a determination of the estimated accuracy for the test; the time constant will allow the development of the 'true' temperature-time variation from the recorded temperature-time record.

For the recording, a thermocouple of the type of Figure 4.3-16 was used. Utilizing the techniques and formulae above, and available historical data, the thermocouple wire diameter most likely to have the desired characteristics based on the projected mass flow of the gas, the temperature range, durability and temporal correction of the data was selected and incorporated into the probe. To maximize the response to transient events,the probe would have, ideally, a projection of the bead into the flow stream from the face of the housing of at least ten times the wire diameter. For the selected wire diameter of 1.27 mm (0.051 inches) the bead should extend at least 12.7 mm (0.51 inches) into the flow. For this application a compromise was reached in choosing a loop design which reduced the overall height of the sensing element while providing a more rigid supportive assembly with a length to diameter of wire ratio of 6 to 1. The design incorporated two elements, one for control of the engine exhaust area, and the other exclusively for the test measurement.

During the transient (Figure 4.3-15), the core flow in the test engine levels out at approximately 20 kg/sec (45 lbm/sec) after 2.2 sec. The nozzle area at the T5 location is approximately 1045 cm^2 (162 sq. ins.). For this example, the flow conditions around the probe are considered to be 195 kg/m^2-sec (40 lbm/ft^2-sec) at a temperature around 800°C (1470°F) with no radiation from flames or hotter sufaces. Under these conditions the time constant from Figure 4.3-3 is approximately 0.7 sec. The core flow is essentially constant during the period from 3.0 to 4.2 sec and so it can be assumed that the time constant remains constant.

If dynamic calibration data on the instrumentation system is not available then the transient response of the system can be estimated from the recording.

From the recorded trace between 2.7 and 4.2 sec, the compressor mass flow and speed are essentially constant. If we also consider, as a first approximation that the EGT (T5) is stable over that same period, and that there is a first order response, then we can take the slope of the trace at the 2.7 sec point and note the time when that slope intersects the peak temperature level of the recording. this can be seen to be of the order of 0.6 to 0.7 sec. Conversely, one can measure the time from the 2.7 sec point to where the temperature recording reaches 63% of the difference in temperature between the starting point and the peak at 4.2 secs. This also gives an order of 0.6 to 0.7 sec for the time constant.

The thermocouple was calibrated in a steady state flow stream and the time constant determined as described in Section 4.3.1.5, adjusted for test conditions. For the probe selected, the time constant varied from approximately 1.2 sec at the lower temperature and mass flow to 0.7 sec at the higher values (Figure 4.3-15). Over the period leading to the peak value, between 0.3 and 4.2 sec, the core mass flow is relatively constant. Over the temperature range 600 to 813°C (1112 to 1495°F) the effects on the time constant are small and the time constant can be considered to be a constant value of 0.7 sec.

The estimated measurement uncertainties are summarized in Figure 4.3-17. The higher temperature range in this example leads to higher calibration uncertainties than those shown in Example 1.

The effect of the thermocouple time constant on the 'true' temperature-time variation can be estimated in several ways. The example of Figure 4.3-15 has a complex response of temperature against time. The determination of the maximum temperature reached by the gas cannot be determined accurately directly from the trace. However, a useful estimation of the maximum temperature can be calculated if simplifying assumptions are made.

A very simple approach to the estimation of the maximum temperature will be described in some detail. Assume that we can substitute for the trace preceding the peak value of T5, over the period from 3.0 to 4.2 sec, a quarter cycle of a sinusoid with amplitude 88 C° and period 4.8 sec. If we also assume that a first order relationship exists between the measurand and the recorded signal, then we can conclude that, to generate that quarter-cycle of sinusoid, the measurand must have a fundamental element that is sinusoidal. Here we shall neglect any random perturbations since we cannot see them in the trace, and are therefore not able to recreate them. We can however, predict the peak transition of the smoothed value of the measurand by calculation, relating the input sinusoid to the attenuated phase-lagged sinusoid on the trace. Ignoring the history of the measurand prior to the start of the sinusoid, we are able to use a single value of 0.7 sec for the time constant corresponding to the flow and temperature conditions as described above.

For a sinusoidal input/output, the relative amplitudes are given by:

$$\Delta T_o = \frac{\Delta T_i}{(1+(\omega\tau)^2)^{1/2}} \qquad 4.3\text{-}14$$

and the relative phase by

$$\tan\beta = -\omega\tau \qquad 4.3\text{-}15$$

where:
- ΔT_o = indicated temperature amplitude (output) = 88°C
- ΔT_i = gas temperature amplitude (input)
- ω = frequency = $(2\pi/4.8)$ = 1.31 radians per second
- τ = time constant = 0.7 secs
- β = phase lag

The calculated peak reached by the measurand will be:

$$T_{gas} = \Delta T_o(1 + \omega^2\tau^2)^{1/2} + (T_{peak\ thermocouple} - \Delta T_o) = 844\ °C$$

The phase lag is given by $\tan\beta$ = -0.917 = -42.5°, i.e. a time lag = 0.57 secs. The simplified model of the true gas variation is shown in Figure 4.3-18. Note that the mathematical relationship has the input signal passing through the peak of the output which corresponds with the expectation that the slope of the trace will be zero when the input equals the output.

The effect on the uncertainty due to the selection of the period of the sinusoid will show itself as a difference in ω. This will impact the amplitude and phase shift used in the above equations.

Although the above is a simplification of the actual variation of the measurand, it does indicate that the actual peak temperature could well be some 31 °C higher than the recorded value.

A more precise determination of the peak value can be made by correcting for the changing time constant for each point on the recording to reconstruct the measurand. This is a significantly more complex process than that described above.

4.3.1.7 *Advanced Sensors*

The most significant advanced sensors that are being developed for steady state measurements are Optical Fibre Thermometers, Coherent Antistokes Raman Scattering (CARS), Infra-red Monochromatic Radiation and Absorption (IMRA) and Atomic Fluorescence. The Optical Fibre technique with suitable interfacing lends itself to analogue recording. The other techniques rely on high speed digitising and processing which produce vast quantities of data which can be difficult to handle and, therefore, they are not considered as being suitable for transient testing in the near future.

The Optical Fibre Thermometers use fibre optics to transmit the heat energy radiated from a source to the detector. For transient measurements of gas, the sensing element is a thermally conductive cap encasing the end of a fibre element which is extended into the gas path. The cap acts as a black body radiator, the radiation being conducted down the fibre to the detector as illustrated in Figure 4.3-19. As with the wire and thin film sensors, the thermal mass of the end cap plays a major role in the response time of the device. A thin metallic film deposited on and around the tip has the lowest thermal mass but suffers from vulnerability to erosion by particles in the gas stream and thermal stress at the adherence point between the metal film and quartz/sapphire rod. In addition, the quartz/sapphire rods are fragile and require special care in installation.

The CARS, IMRA and Atomic Fluorescence measurement techniques are more applicable in the higher temperature ranges down stream of the compressors i.e., combustor, turbines, re-heat and exhaust. Each technique uses a pulsed excitation of the gas in a preselected volume in space. Depending on the electronics used, multiple measurements as short as 1 msec apart can be made. During a transient test spanning several seconds this results in thousands of measurement points for each location. Since the measurements are made in a very short period of time, the "noise" level can be very high particularly in the combustion chamber and re-heat section. Careful consideration must be given to filtering out the general noise generated by the combustion process whilst preserving the response required to study the transient behaviour under investigation.

Other temperature sensors such as acoustic devices exist (Reference 4.3.10), which with electronic compensation, can give responses in the order of 50 msec. An edge-tone resonator acts like an organ pipe. If the Mach number within the inlet nozzle is kept constant, the frequency is proportional to the square root of the absolute temperature. These devices have a number of drawbacks which include the fact that the gas being measured must pass through the cavity and the cavity volume must be kept constant.

4.3.2 Solid Surface Temperature

4.3.2.1 *Introduction and Definitions*

The surface temperature can be measured by contacting and non-contacting techniques. The most common contacting sensors are surface bonded thermocouples and thin films. The non-contacting method most often used is the Optical Infra-red Pyrometer. Other techniques include surface deposited phosphors, imbedded fibre optics, noise thermometry, ultrasonic thermometry and Raman measurement techniques (Data extracted from Reference 4.3.11 are shown in Table 4.3-4).

4.3.2.2 *Basic Theory*

The use of thin film and wire thermocouple and resistive devices are often most convenient (Figure 4.3-20). Here, the thermal coupling between the sensor and the surface plus conduction down connecting tracks or wires will affect the response relative to the surface. The sensors must be small, the smaller the better. Difficulties can arise due to thermal gradients along the leads, e.g. if the sensor is at a remote position such as near the tip of a blade then, during the transient test, differential tip to root temperatures can be significant. The order of magnitude of the impact of such gradients can be evaluated by applying a differential temperature gradient during the calibration procedure. Thermocouples with inhomogeneities are particularly prone to these types of errors.

The time dependent elements of a thermocouple system are illustrated in Figure 4.3-8 where the probe assembly is in fact the thermocouple. The contributions to be considered in determining the bias and precision errors in the steady state and transient modes are the same as shown in Figure 4.3-9. For RTDs the uncertainty due to the reference junction is replaced by the uncertainty of the excitation module.

As with any dynamic measurement, every attempt must be made to reduce the modification of the component time constant due to the addition of the sensing system. For surface measurements, non-contacting optical pyrometry offers the best response with minimized effect on the measurand. Nevertheless, the use of optical methods requires considerable care. Techniques requiring a surface finish to be applied obviously impact the whole heat transfer process and, although the sensing system in itself offers a fast response, the actual surface being observed may not, so caution must be taken to consider the total impact of the addition of films to the surface under observation. The basic Optical Pyrometer, commonly used in engine development and control applications, does offer rapid response to changes in surface temperature without modification to the subject surface under scrutiny. During temperature transients in the gas path such as during start-ups and surges, temperature variations of the turbine blades can be significant and readily observed with a radiation pyrometer. The first step is assuring access to view the surface of interest. If access is practical, then the general conditions of the surface (that can affect the emissivity level) and the surrounding environment (that can create errors due to radiation, reflection and absorption) must be taken into account. The complexities of designing even a simple Optical Pyrometer are illustrated in Figure 4.3-21, where it can be seen that mirrors and lenses are exposed to the environment and must be kept cool by water circulation and purging inert gas that also maintains a positive pressure at the aperture thereby reducing the ingress of foreign matter onto the optics. Clean optics are essential in minimizing the uncertainty of the measurements. The reader is directed to the reference material that gives a more in-depth understanding of the application of Optical Pyrometry.

4.3.2.3 *Advantages and Disadvantages*

Table 4.3-4, from Reference 4.3-11, gives a comparison of the techniques at present used for surface temperature measurement.

The most common devices readily available and relatively easy to apply are thermocouple, thin film RTDs and optical pyrometers.

The application of thermocouples and thin film RTDs to stationary parts is straight forward. The main concern is the temperature range of operation and the effectiveness of the surface attachment. The application to rotating components requires the use of slip rings or telemetry. When determining the uncertainty in the measurements, corruption of the signal due to the introduction of these additional elements must be included in the calculations. The choice of which is most appropriate for the particular test depends on the required accuracy versus cost and performance. FM telemetry is more costly than slip rings but slip rings can be noisy.

Radiation Pyrometers have advantages in that from a stationary location they can observe remotely the temperature profiles of the passing turbine blades. They are, however, generally bulky and susceptible to environmental influences such as flame, reflected radiation, contaminants in the gas, etc. Maintaining the optics at relatively low temperatures through inert gas cooling or water circulation increases the bulk of the support equipment. In general, the upper temperature range of pyrometers is greater than the maximum temperatures of the surfaces that they measure.

4.3.2.4 *Signal Conditioning*

See Section 4.3.1.4 for thermocouple and resistive temperature devices. The other measurement techniques tabulated in Table 4.3-4 require their own individual electronic processing systems unique to the application. The potential for use in a particular test requires a detailed evaluation of the total measurement system transfer function.

4.3.2.5 *Calibration Procedures*

For thermocouple and RTDs the transient calibration very much depends on the size of the part that requires calibration. Individually instrumented blades that are of comparable size to aerodynamic probes may be readily subjected to immersion into a furnace, the test jig being arranged to give the anticipated thermal gradient through cooling at the root while heating the tip.

For large parts, such as complete guide vane assemblies, it may not be possible to perform the calibration as desired. In this case, the transfer function of the attached sensor can be evaluated on a small sample that can be readily inserted in an oven. As long as the sensor mass is small compared to the part to which it is attached and the thermal coupling is high, then the overall thermal response of the part itself will dominate and the sensor can be considered as following the surface temperature of interest with no lag.

Radiation pyrometry is more straight forward in that the surface of interest can be heated in an oven and the radiation to the pyrometer switched on and off with a shutter. The sensor response is therefore determined independently of the rate of heating of the surface of interest. The relationship of the conditions at calibration and in operation can be critical. As materials are heated, the surface finish can change, which results in changes in calibration. It may be prudent to heatsoak the test component to stabilise the surface finish. This will help in maintaining the coefficient of emissivity. In the actual test environment, oil, soot and other materials can contaminate the surface. Alternate methods of on-line calibration, such as a discretely placed thermocouple to which the pyrometer can be pointed while testing is underway, can greatly increase confidence in the quality of the data being recorded, particularly in transient tests where repeatability is more critical than the absolute value of the measurement.

4.3.2.6 *Design Considerations*

Thermocouples are the most common method of measuring surface temperature, either in the attached wire format or as thin film sensors. The wire may be spot welded either as a bead on the surface or the two wire elements individually attached a small distance apart. In either case, the thermocouple mass is kept as small as practical for the environment, small compared to the bulk material to which they are attached. This means, then, that the response to temperature change is dictated by the bulk material and that the thermal lag of the sensing element is sufficiently small that the sensor temperature can be considered to be that of the material.

For an acceleration of 5 secs duration, such as in the example of Section 5.3, components such as the burner case, guide vanes, disks and similarly bulky parts, generally have a response that exceeds 15 secs. The uncertainty in the surface temperature measurement on these components will be close to the uncertainty in the steady-state temperature. For this statement to be acceptable, precautions must be taken to keep the leadwire exposure length to the gas stream to a minimum, preferably directing the leadwires to a cooler zone away from direct contact with the hot gases as close to the measurement point as is practically possible.

Unless there is significant induced interference in the signal, it is not necessary to use a low pass filter. The inherent noise generated by the thermocouple is generally low compared to the emf produced by the thermocouple at the lowest temperature of 260°C (500°F).

Components such as the burner lining will change temperature more rapidly, somewhere between the gas and bulk parts. Using the criteria for gas measurements as a guide, the sampling rate can be set as described above. The burner generates high ionic activity which will induce high levels of steady and pulsed noise. A filter would be required for the thermocouple signals from this area.

For small components of low thermal mass, e.g. turbine blades, the addition of multiple sensors will increase the thermal mass. Prior to a test, the effect on the response of the component to temperature changes must be evaluated either in a simulated gas flow or immersion in a liquid bath taking precautions to ensure that the liquid will not affect the material properties of the blade when it is run in the engine. The use of thin film technology is recommended where practical to minimize the overall thermal mass.

Radiation pyrometers have significant advantages with rotational components, being able to sweep review the surface temperature while being located in a static position. Their use is recommended for transient investigations on turbines where access is possible. They are not as convenient as thermocouples for static surfaces and in most instances are not cost effective. In addition, the lower limit on present systems is around 425°C (800°F) which restricts their use to the hot sections, an inhospitable zone under the best of conditions.

4.3.2.7 *Advanced Sensors*

The advanced sensors are listed in Table 4.3-4 (Reference 4.3.11).

4.3.3 Liquid Temperature

4.3.3.1 *Introduction and Definitions*

The response of sensors to changes in liquid temperature is far more rapid than for gases due to the greater thermal capacity of the measurand and closer thermal coupling. Difficulties are presented by contamination of the sensing element by the fluid, by the electrical characteristics of the fluid and, in some instances, by high pressures. The necessary protection of the sensing element results in an increase in the response time of the probe.

The most common methods of measurement are thermocouple and resistance temperature devices (RTDs).

4.3.3.2 *Basic Theory*

Liquids have a significantly larger capacity for heat retention than gases. Therefore, heat transfer to a sensor from the measurand is relatively high. The problems encountered, such as electrical conductivity of the measurand, corrosion effects, flammability and high pressures, require that the sensing element be protected. This protection generally takes the form of a metallic sheath Figure 4.3-22. The sheath becomes the dominant factor in determining the response time of the system (Reference 4.3.12).

The model of a thermocouple system is illustrated in Figure 4.3-8 where the probe is replaced by the immersion assembly. The contributions to the bias and precision errors in the steady state and transient modes will be as shown in Figure 4.3-9, except there will be no contributions for recovery or radiation..

4.3.3.3 *Advantages and Disadvantages*

A comparison of different designs of thermocouple probes are given in Reference 4.3.13. The reference also details calibration equipment and procedures for different fluids. The results show that bare wire thermocouples immersed in water had response time constants of 10 to 15 msecs. The sheathed junctions had successively longer time constants depending principally upon the mass of the entire assembly. Time constants as large as 800 msecs were recorded.

In the data obtained from transient measurements, one must consider changes in the time constant due to changes in the measurand. These changes include aeration, changes in the physical properties of the fluid, turbulence, air pockets, etc.

4.3.3.4 *Signal Conditioning*

See Section 4.3.1.4 for thermocouple and resistive temperature devices.

4.3.3.5 *Calibration Procedures*

Calibration is not as straight forward as it may at first appear. Since the sensing element is protected by a metallic housing of significant thermal mass with high thermal conduction, the diameter of the pipe into which it is installed will affect the response rate. For transient testing, the probe should be calibrated in the pipe which it will be used to make the actual measurements.

A basic rig for determination of the response rate is shown in Figure 4.3-23. The time constant (Equation 4.3-13) is determined from the rate of change of the temperature as indicated by the sensor. Using a logarithmic scale for the sensor output against time, the slope of the straight line section will give the time constant assuming that the relationship is a first order equation.

4.3.3.6 *Design Examples*

The rate of change of temperature in liquids, such as lubrication systems, is normally relatively slow compared to gas temperatures. Also, the temperature excursions are small being generally in the 66°C to 121°C (150°F to 250°F) range.

Various probe designs are illustrated in Figure 4.3-22. Taking the insulated sensors only, the time constants established in Reference 4.3.54 were as follows:

c_1	55 msec
c_2	44 msec
c_3	110 msec
d_1	250 msec
d_1+d_2	500 msec

Details of the design process for fluid temperature measurement are given in Reference 4.3.14. The outside diameters of probes c_1 and c_2 are less than 2.5mm (0.1 inches) which makes them suitable for installation in fuel and oil lines.

For the example of Section 5.2, the temperature of the fuel, supplied to the engine during the transient leading to the surge point, must be measured to allow appropriate corrections of the viscosity and specific gravity to permit calculation of the fuel flow (see Section 4.4.2.6.2). Because the transient is very short, taking place in approximately 50 msec, the steady state calibration factors are sufficient. Typical values for the uncertainty factors for the fuel flow temperature measurement are shown in Figure 4.3-24. Depending on the specific objectives of the test the sampling of the fluid temperature channels can be at the same rate as the gas channels or at a much slower rate.

4.3.3.7 *Advanced Sensors*

At this time there are no direct reading sensors suitable to substitute for thermocouple and RTD's for transient tests.

4.3.4 References

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Table 4.3-1 Effect of Thermocouple Junction Orientation on Time Constant τ
(Reference 4.3.4)

Plane of Loop	G kg/m^2sec (lb/ft^2sec)	τ sec
Parallel to flow	24.4 (5)	2.39
45 deg to flow	24.4 (5)	2.31
90 deg to flow	24.4 (5)	2.37
Parallel to flow	48.8 (10)	1.80
45 deg to flow	48.8 (10)	1.77
90 deg to flow	48.8 (10)	1.77

Table 4.3-2 Examples of the Variation of Time Constant τ with Bead Size and Wire Size
(Reference 4.3.4)

Diameter	τ, sec For a 1.02 mm (0.040 inch) wire diam - weld bead size, as given in Col. 1	τ, sec For variable wire diam, as given in Col. 1 - no weld bead
1.02 mm (0.040 inch)	2.4	2.4
1.22 mm (0.048 inch)	2.6	3.0
1.52 mm (0.060 inch)	2.8	3.9

Table 4.3-3 Effect of Radiation from Thermocouple to Cold Walls on Time Constant τ
(Reference 4.3.4)

G kg/m^2sec (lb/ft^2sec)	T_{wall} K (F)	τ sec
24.4 (5)	608 (635)	1.62
24.4 (5)	934(1222)	1.50
48.8 (10)	705 (810)	1.28
48.8 (10)	1024(1383)	1.16
97.6 (20)	733 (950)	0.92
97.6 (20)	1066(1460)	0.89

Table 4.3-4 Surface Temperature Measurement Concept Characteristics

	Upper Temperature Limit Deg C	Life Hr	Time Response Sec	Uncertainty %	Resolution %	Surface Mod.	Spatial Resolution mm	Deficiencies	Comments
Thermocouples Chromel-alumel (Type K)	1260	25	>0.1	2	0.2	No	1	o Oxidiziog atmosphere recommended o Grounded	o Spot weld to metal surface o Adhesive to non-metallic surfaces
Thin Film Thermocouples Platinum Rhodium alloys (Non silicon substrates or Insulating films)	1300 1500	25 10	>0.1	2	0.2	No	1	o Requires careful match of substrate properties o Volatile oxide limits temperature	o Should work on alumina substrate o Development of coatings may extend temperature rauge
Ceramic and Intermetallic Alloys - Sic, MoSi2, WSi2	1300 1600	50 20	>0.1	3	0.1	No	1	o Calibration stability not known o Oxidation effects may limit temperature	o New technology o Should work on silicon alloy substrates o Coatings may improve life
Indium-Rhodium	1300 1600	10 1	>0.1	2	0.2	No	1	o Indium oxide highly volatile o Calibration stability not known	o Coating may improve performance
Tungsten-Rhenium alloys	2000	1	>0.1	2	0.2	No	1	o Oxygen impervious top coat required	o Development of top coat is major challenge
Acoustic thermometer - attached sensor	1900 1500	50 50	0.5	±2	±1	Yes	5	o Attachment of sensor presents problems o Senses average temperature over sensor length	o Not useful for many applications
Acoustic thermometer - intrinsic type (non-contact)	None	N/A	7	7	7	No	7	o Technology not well developed	o Laser generated acoustic pulse
Noise thermometer	1600	50	>1			No	5	o EMI sensitive o Isolation from substrate difficult at high temperatures	o Thin film configuration suitable only for low EMI environments (No reference to thin film configuration in literature)
Fibre optic sensor (Polarimetric type)	1700	10	0.001			Yes		o Sensitive to leadpath temperature variations o Very difficult to install and lead out sensor	o Applied sapphire sensor
Resistance thermometer Pl Pl Ceramic	 1100 1300 1600	 50 50 50	0.01	1 5	0.3 0.1 0.5	No	5	o Must be isolated from strain o Must be isolated from incompatible substrate materials o Oxidation will cause drift	o Thin film sensor configuration

Table 4.3-4(cont'd) Surface Temperature Measurement Concept Characteristics

	Upper Temperature Limit Deg C	Life Hr	Time Response Sec	Uncertainty %	Resolution %	Surface Mod.	Spatial Resolution mm	Deficiencies	Comments
Radiation Pyrometers Single wavelength 0.4 - 1.2 μm	None	N/A	10E-6	±10	±0.3	No	1	o Seriously affected by reflected radiation o Surface emittance must be known	o Rework required to obtain sight psth
Single wavelength 8 μm	None	N/A	10E-6 10E-1	±5	±1.0	No	5	o Some detectors must be cooled or chopped o Special optical materials required to transmit at 8 μm	o Rework required to obtain sight path o Response time depends on detector
Dual wavelength 0.4 - 1.2 μm	None	N/A	10E-6	±10	±0.3	No	1	o Some require knowledge of combustion gas temp. o Emittance must be same at both wavelengths	o Rework required to obtain sight path o Calculation intensive - data reduction
Multiple wavelength (6), 0.4 - 1.2 μm	None	N/A	10E-8	±7	±0.3	No	0.16	o Not able to compensate for reflected radiation	o Rework required to obtain sight psth o Calculation intensive - data reduction o Emittance not required
Multiple wavelength (200), 0.4 - 1.2μm	None	N/A	7	±7	±0.3	No	0.10	o Not able to compensate for reflected radiation	o Rework required to obtain sight psth o Calculation intensive - data reduction o Assumes remittance to be a linear function of wavelength
Rejection of reflected radiation by polarization	None	N/A	7	±7	±0.3	No		o Ability to differentiate between emitted and reflected radiation by polarization for ceramics is uncertain	o Rework required to obtain sight path
Thermographic phosphors	1200 1960	30 10	0.01	±3	±1	Yes	2	o Requires coating sensing area o Coatings for use above 1200 C not well identified o Complex excitation detection	o Not sensitive to emittance or reflected radiation o New technology
Raman scattering	?	N/A	10E-6	±3	±1	No	10	o Limited range of materials o Signal amplitude decreases at higher temperatures	o Feasibility not well defined o For nonresponsive substrates, coatings may work

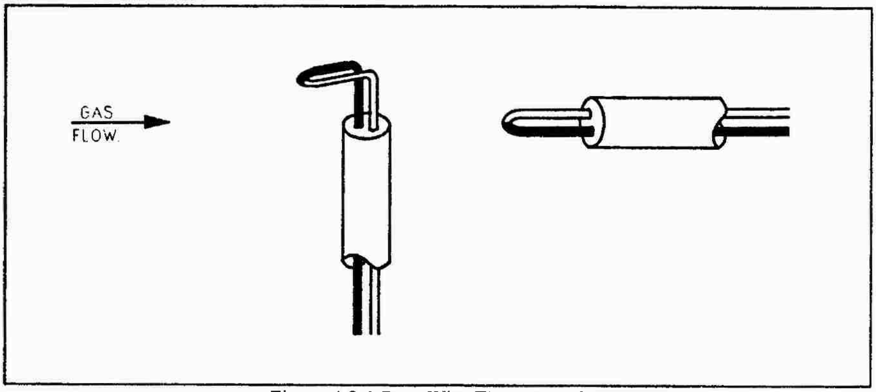

Figure 4.3-1 Bare Wire Thermocouples

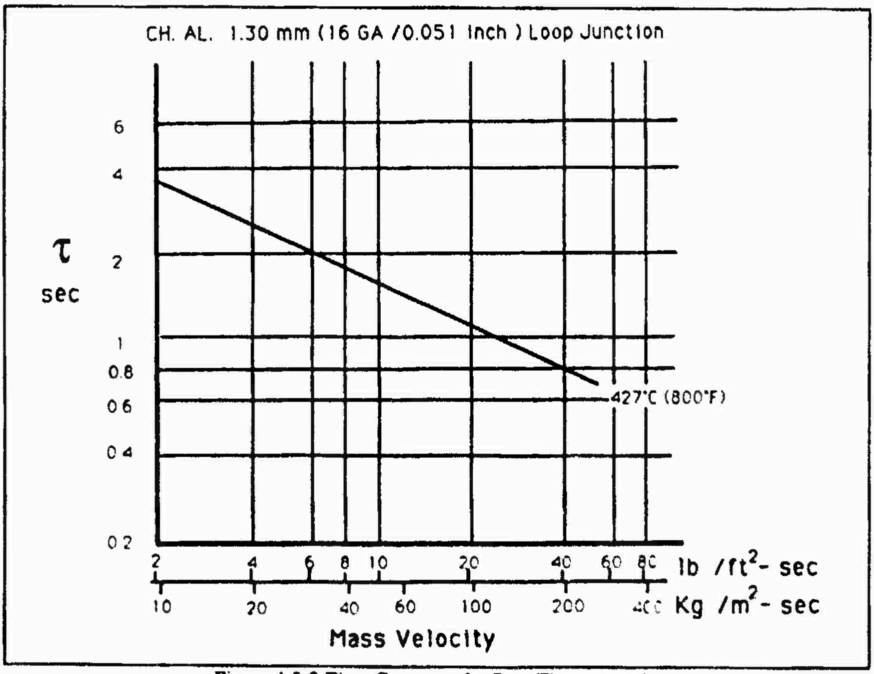

Figure 4.3-2 Time Constants for Bare Thermocouple
(Reference 4.3.4)

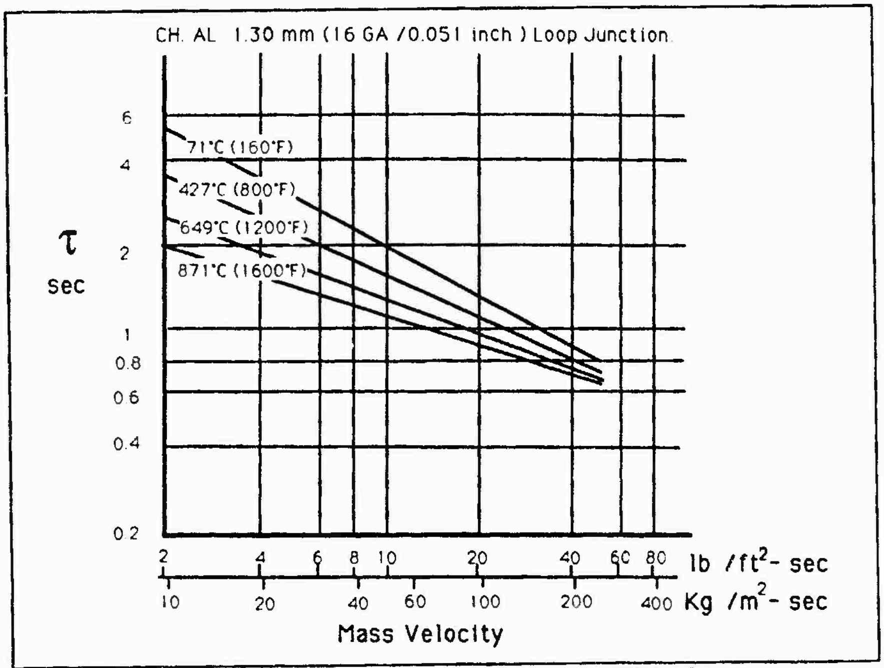

Figure 4.3-3 Effect of Total Temperature on Thermocouple Time Constants (Reference 4.3.4)

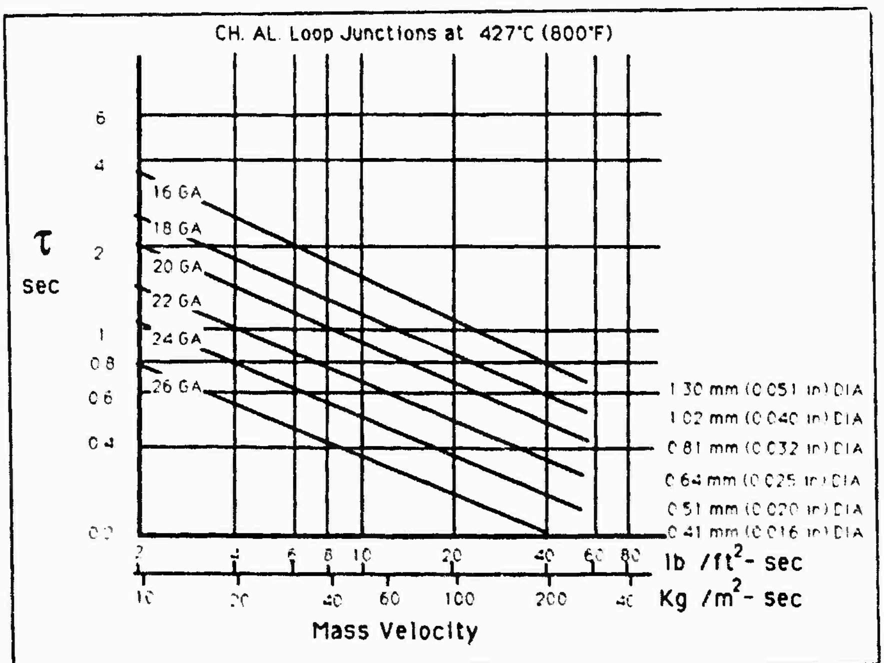

Figure 4.3-4 Effect of Wire Diameter on Thermocouple Time Constants (Reference 4.3.4)

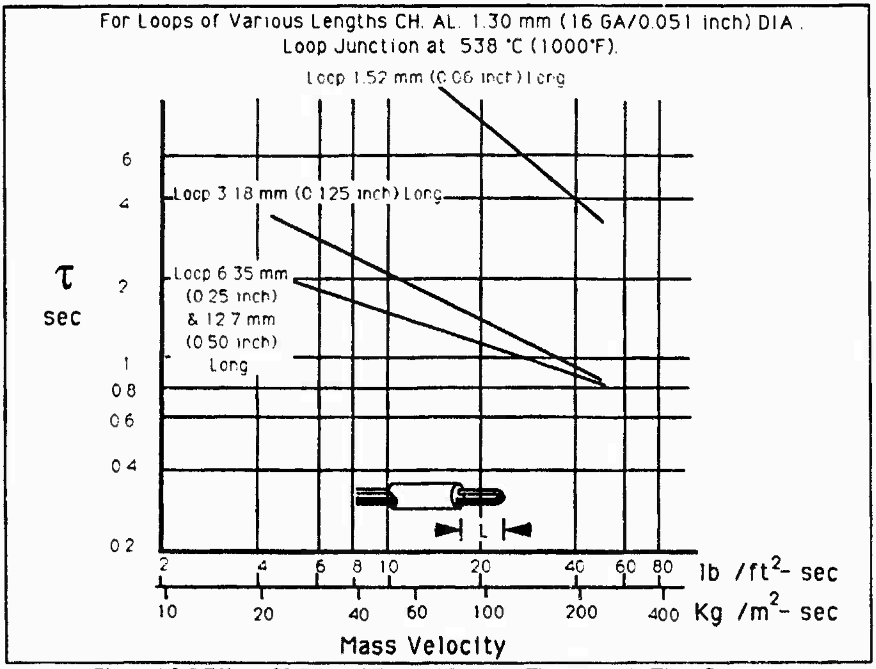

Figure 4.3-5 Effect of Length of Exposed Loop on Thermocouple Time Constants (Reference 4.3.4)

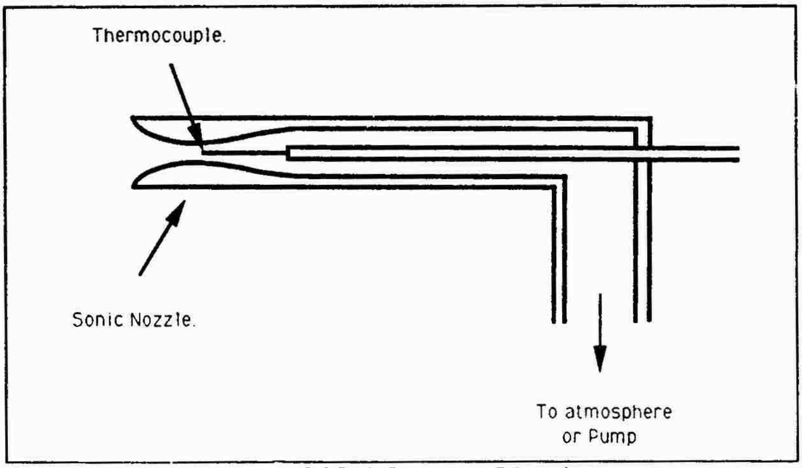

Figure 4.3-6 Sonic Pyrometer - Schematic

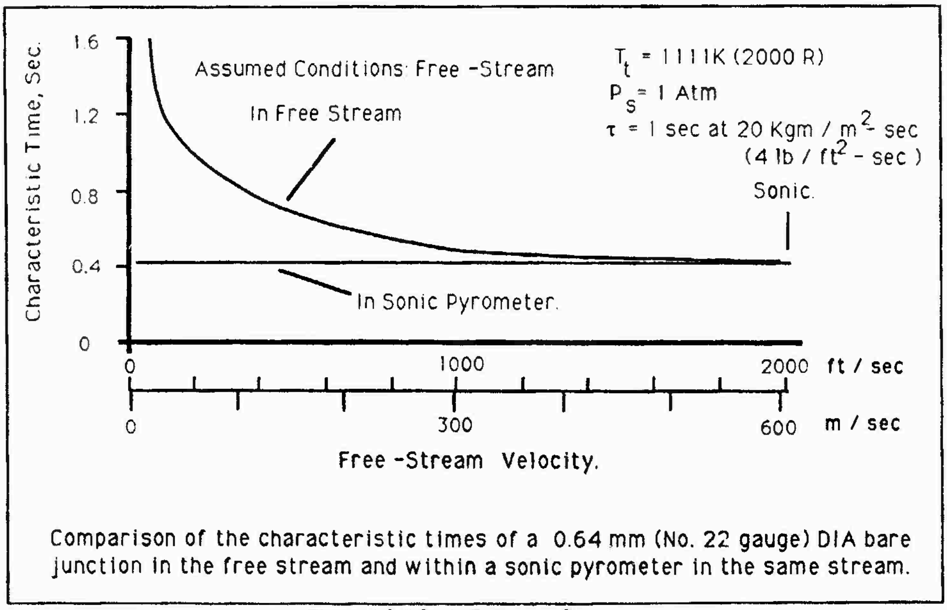

Figure 4.3-7 Sonic Pyrometer Response

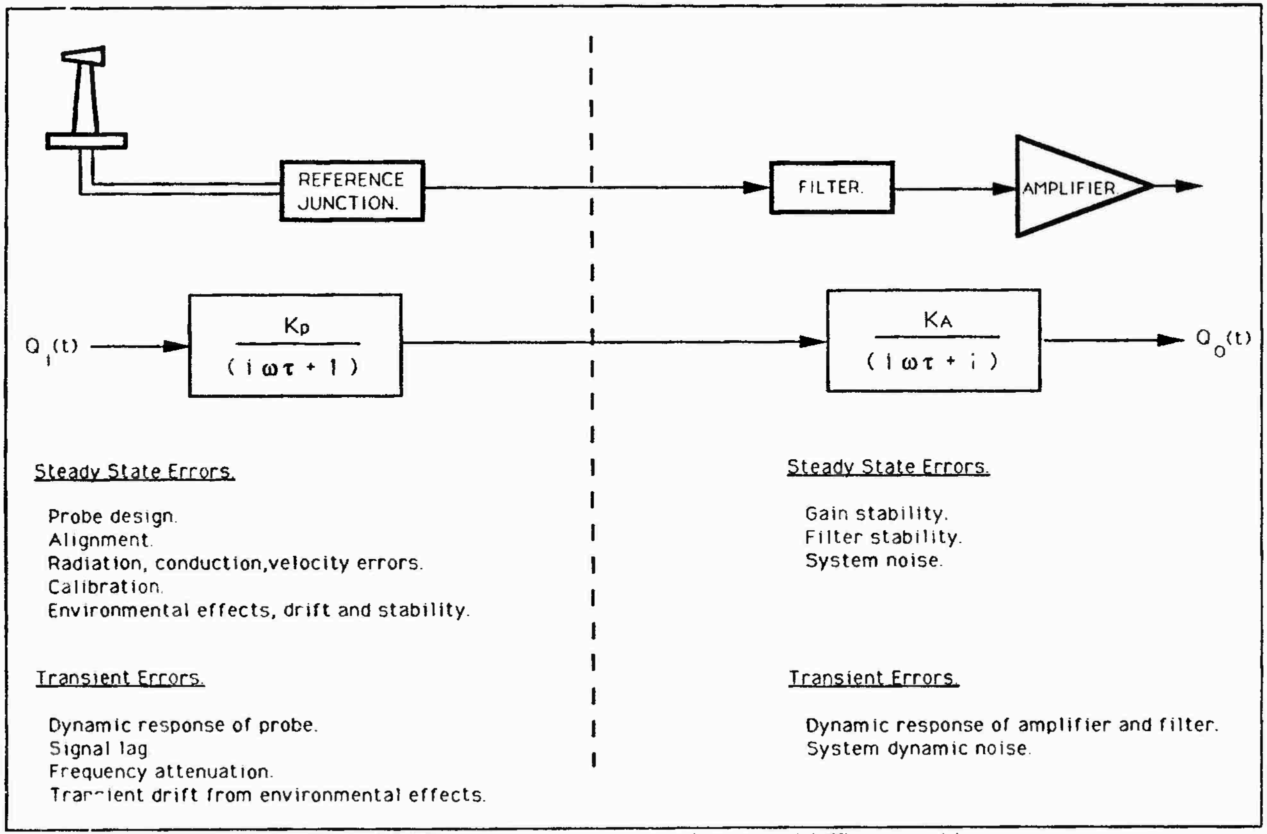

Figure 4.3-8 Temperature Instrumentation System Model (Thermocouple)

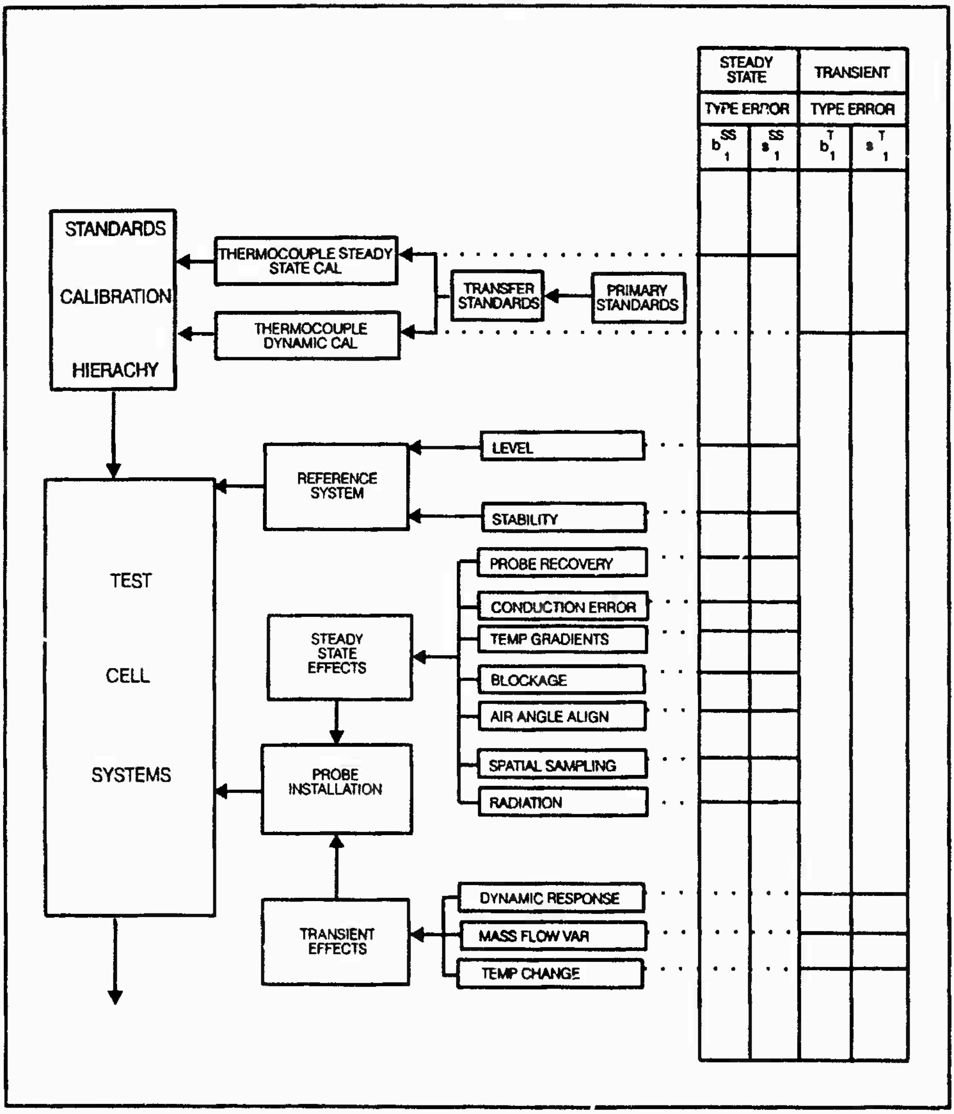

Figure 4.3-9 Transient Temperature Error Source Diagram - Gas Flow

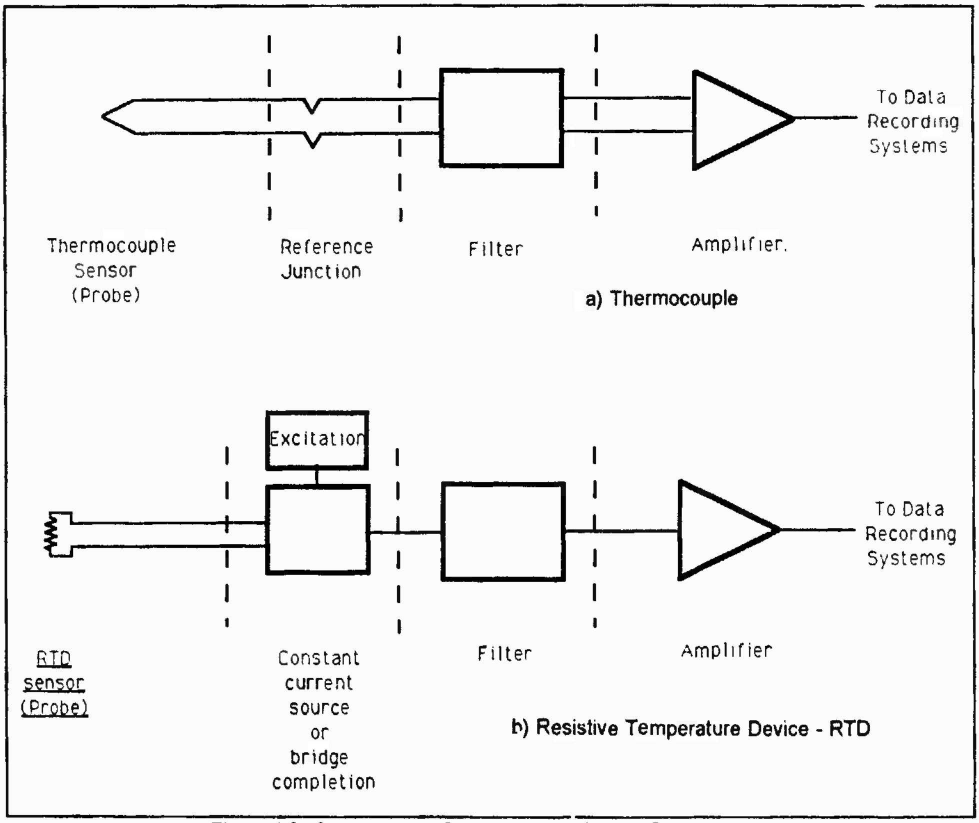

Figure 4.3-10 Temperature Instrumentation System Configurations

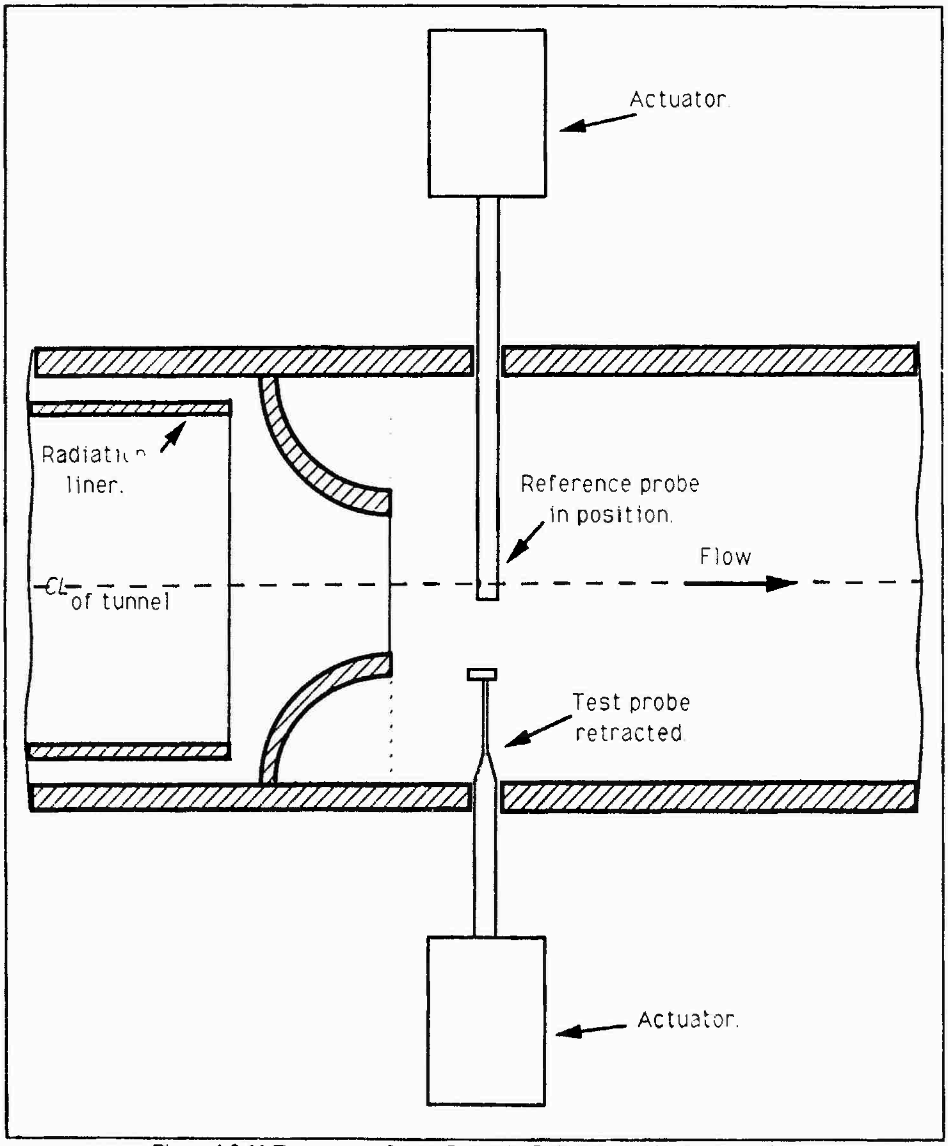

Figure 4.3-11 Temperature Sensor Dynamic Calibration by Probe Retraction

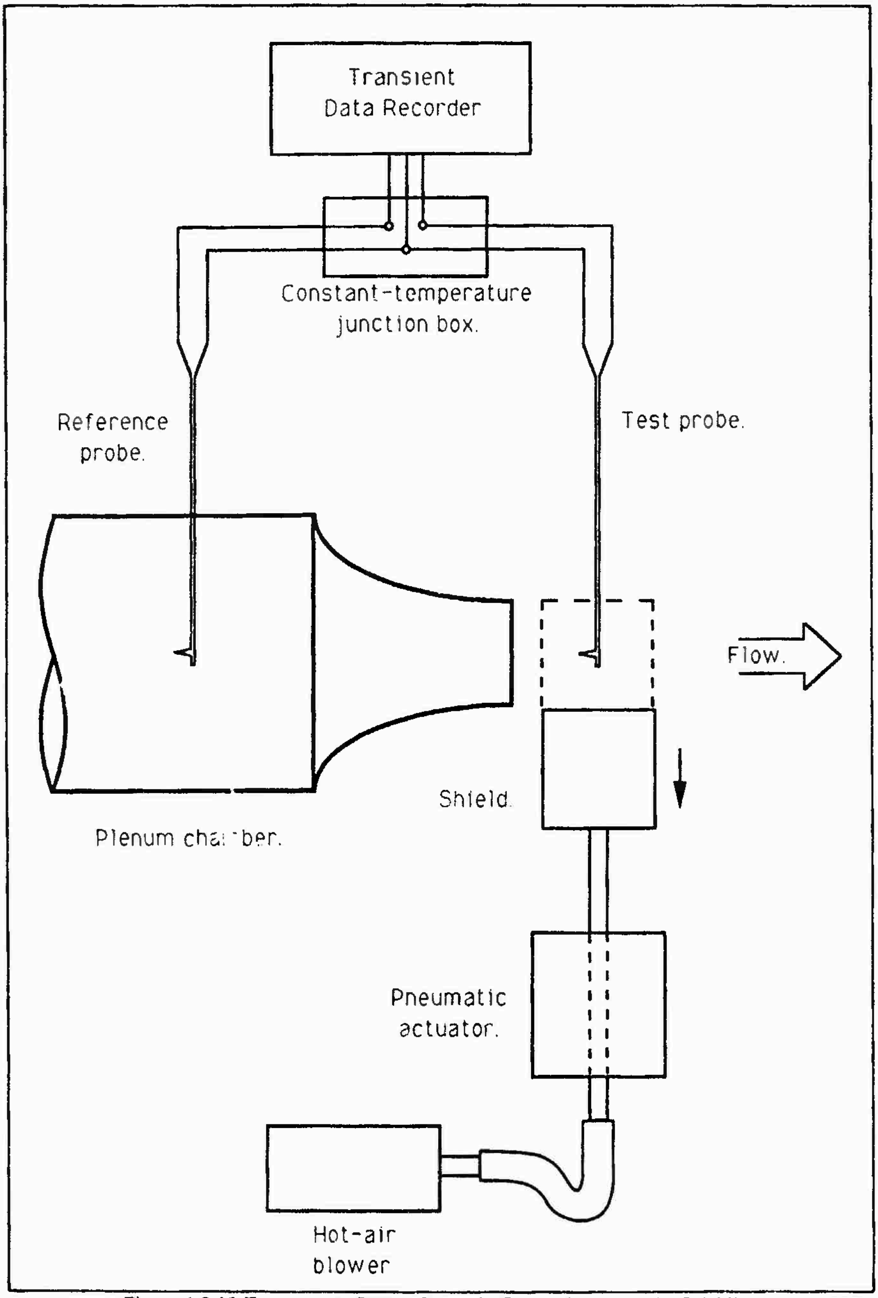

Figure 4.3-12 Temperature Sensor Dynamic Calibration by Probe Shielding

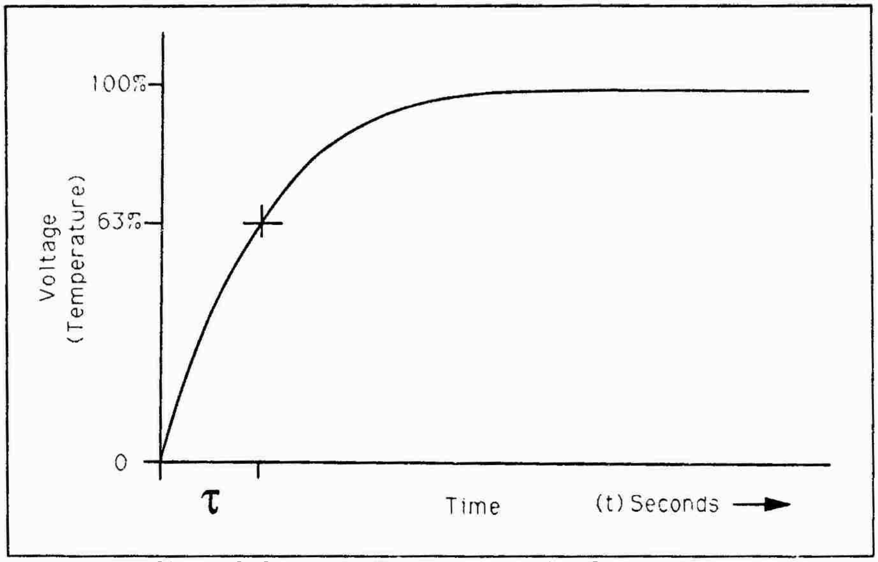

Figure 4.3-13 Temperature Sensor Output for Step Change in Input

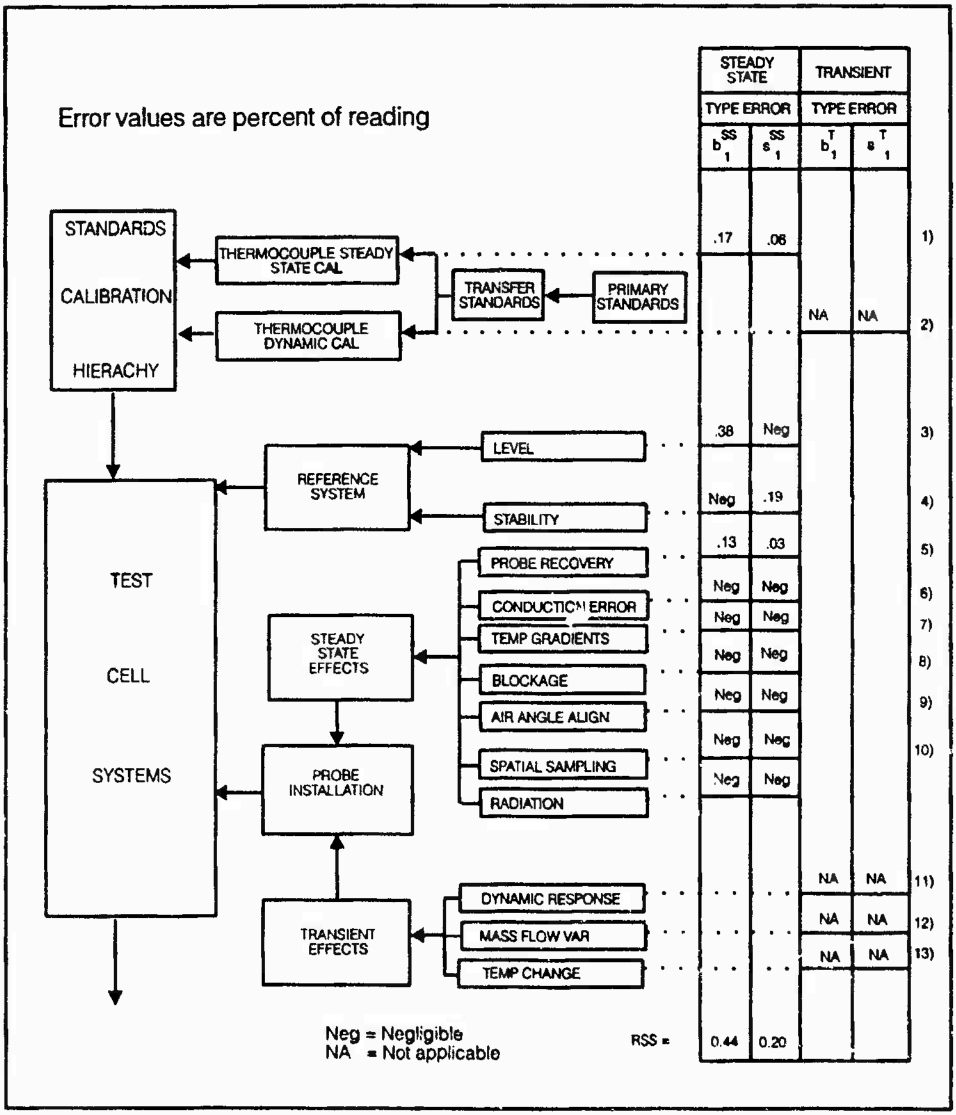

Figure 4.3-14 Transient Temperature Error Source Diagram - Gas Flow - T25

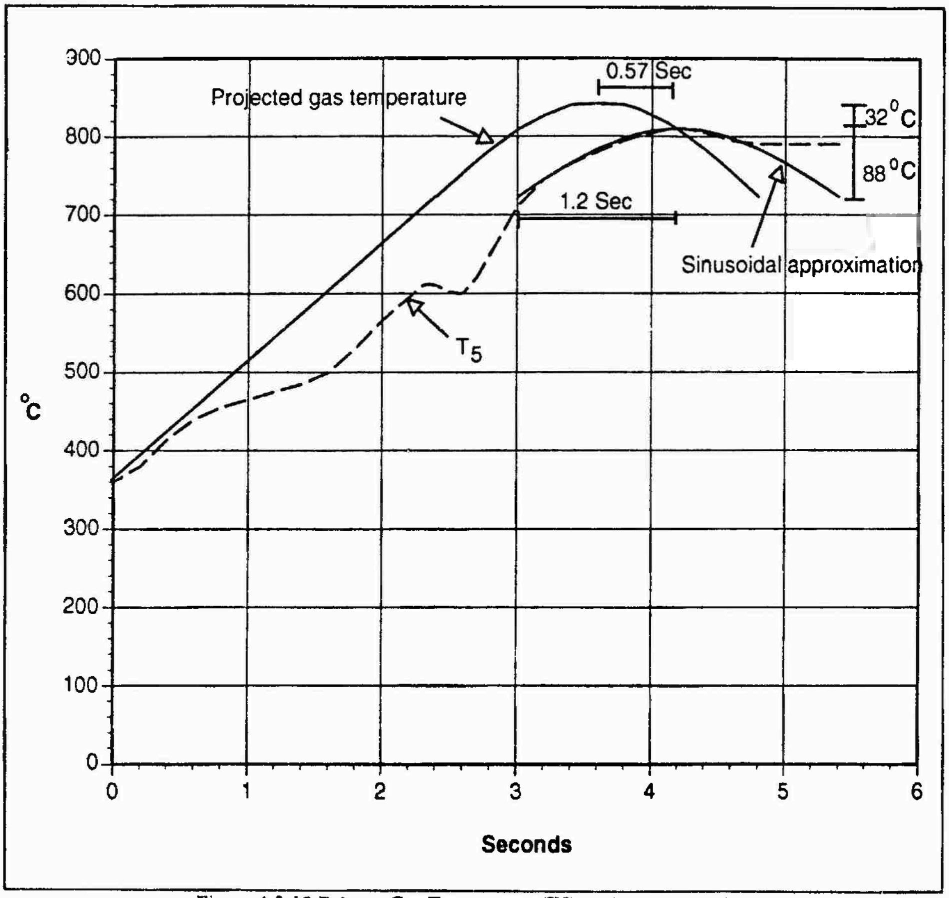

Figure 4.3-15 Exhaust Gas Temperature (T5) during Acceleration
(--- recorded temperature)

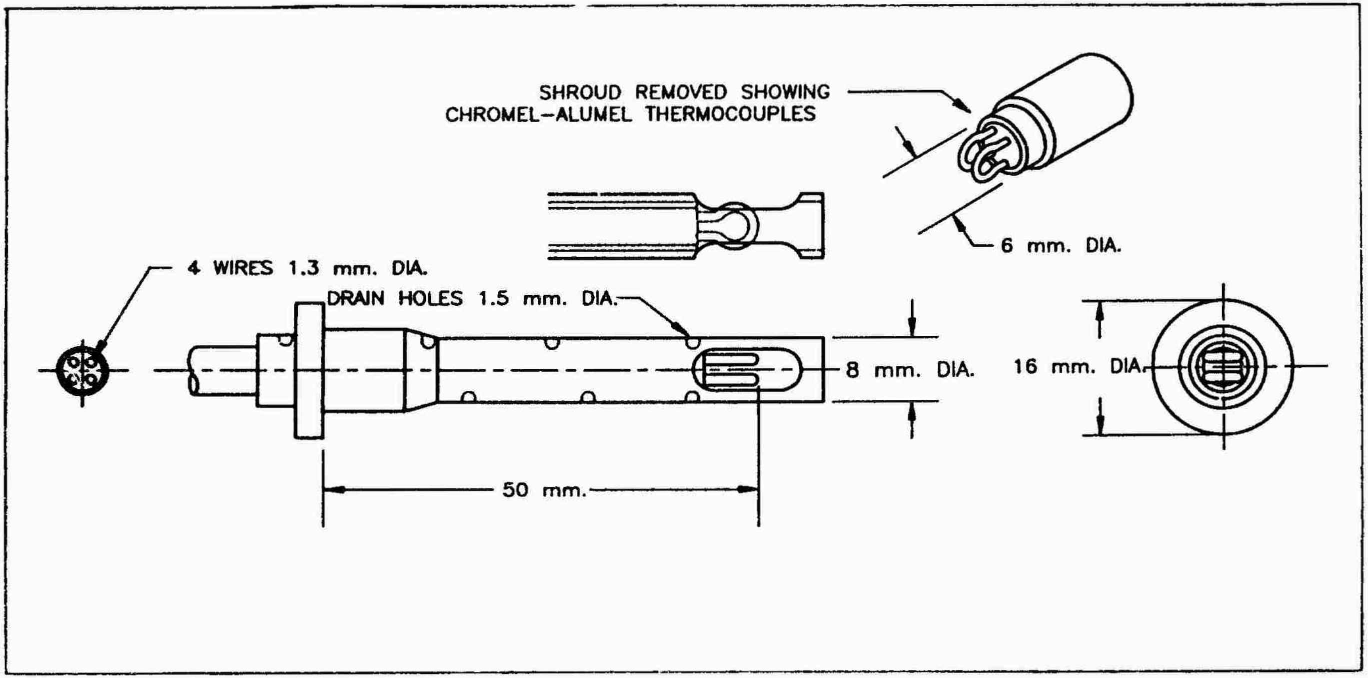

Figure 4.3-16 Typical Engine Thermocouple Sensor for Gas Temperature

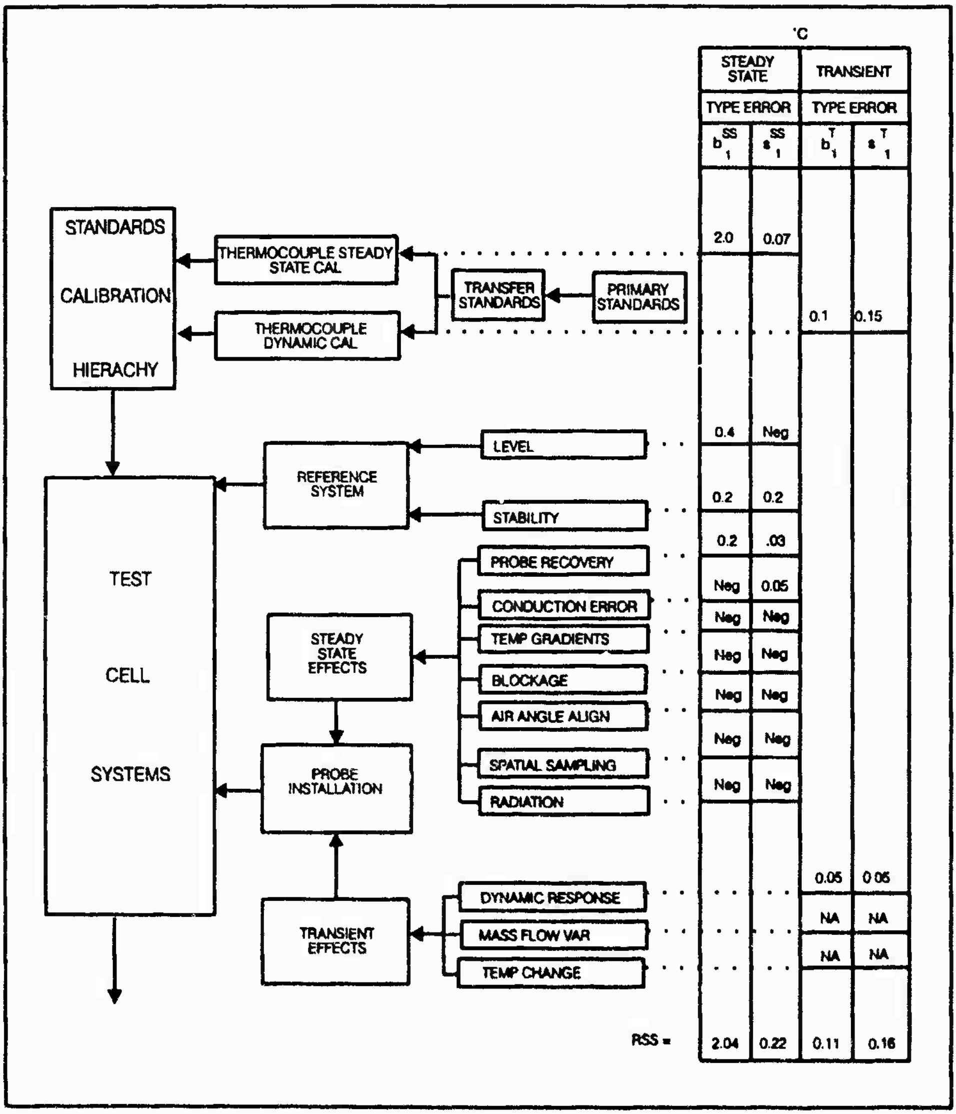

Figure 4.3-17 Transient Temperature Error Source Diagram - Gas Flow - T5

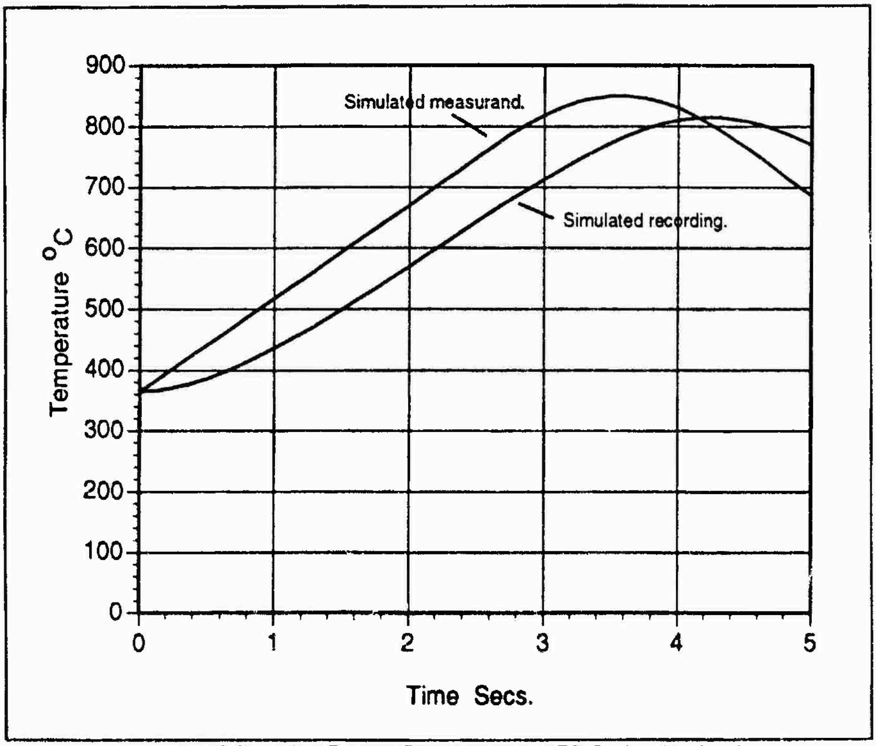

Figure 4.3-18 Simplified Exhaust Gas Temperature (T5) During Acceleration

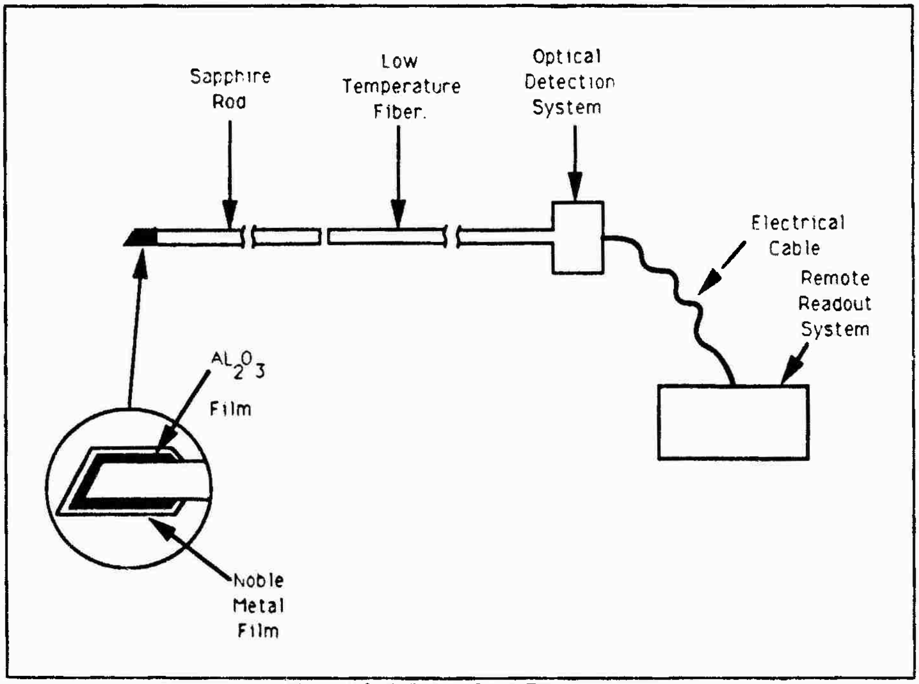

Figure 4.3-19 Optical Fibre Thermometer

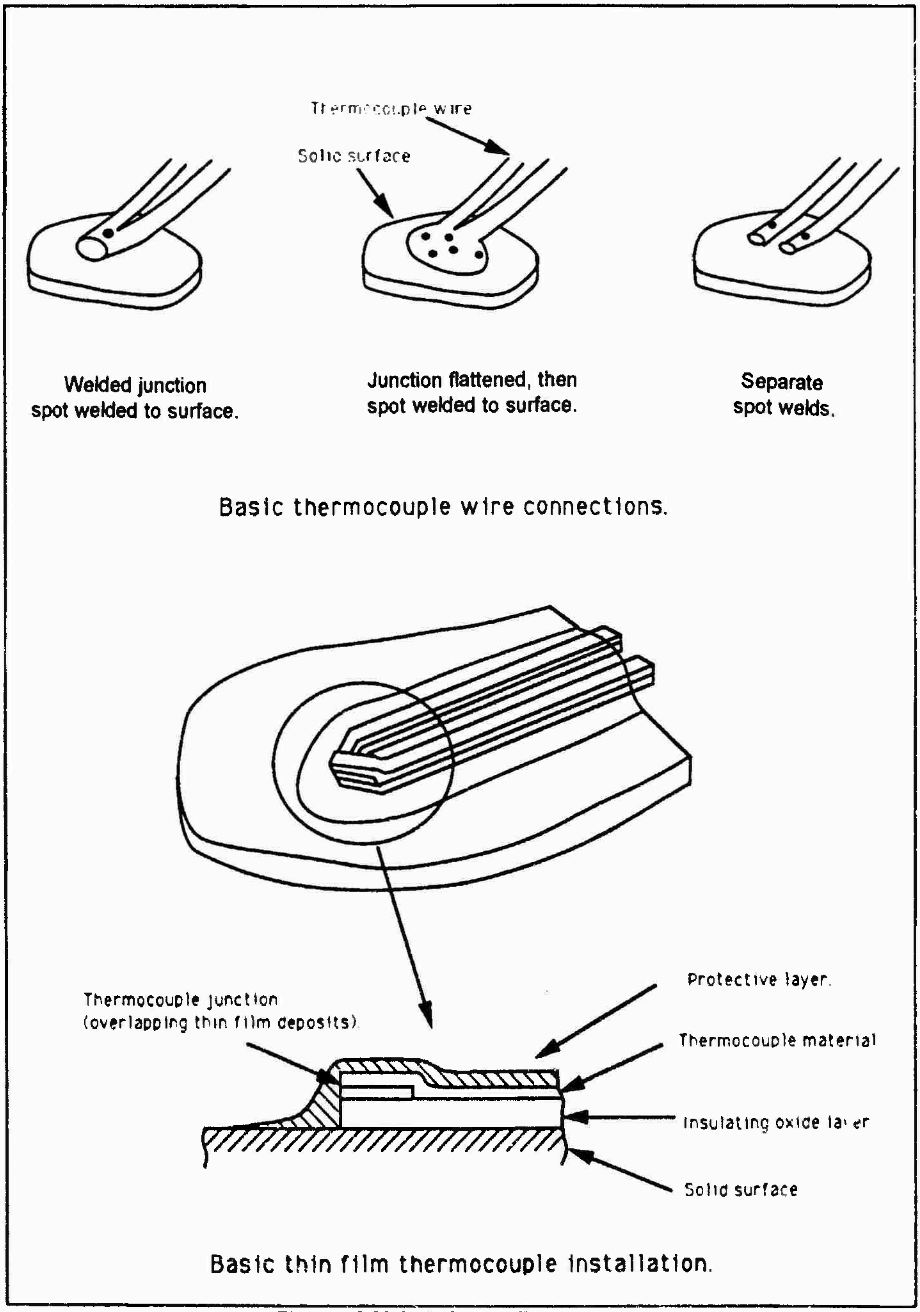

Figure 4.3-20 Solid Surface Thermocouples

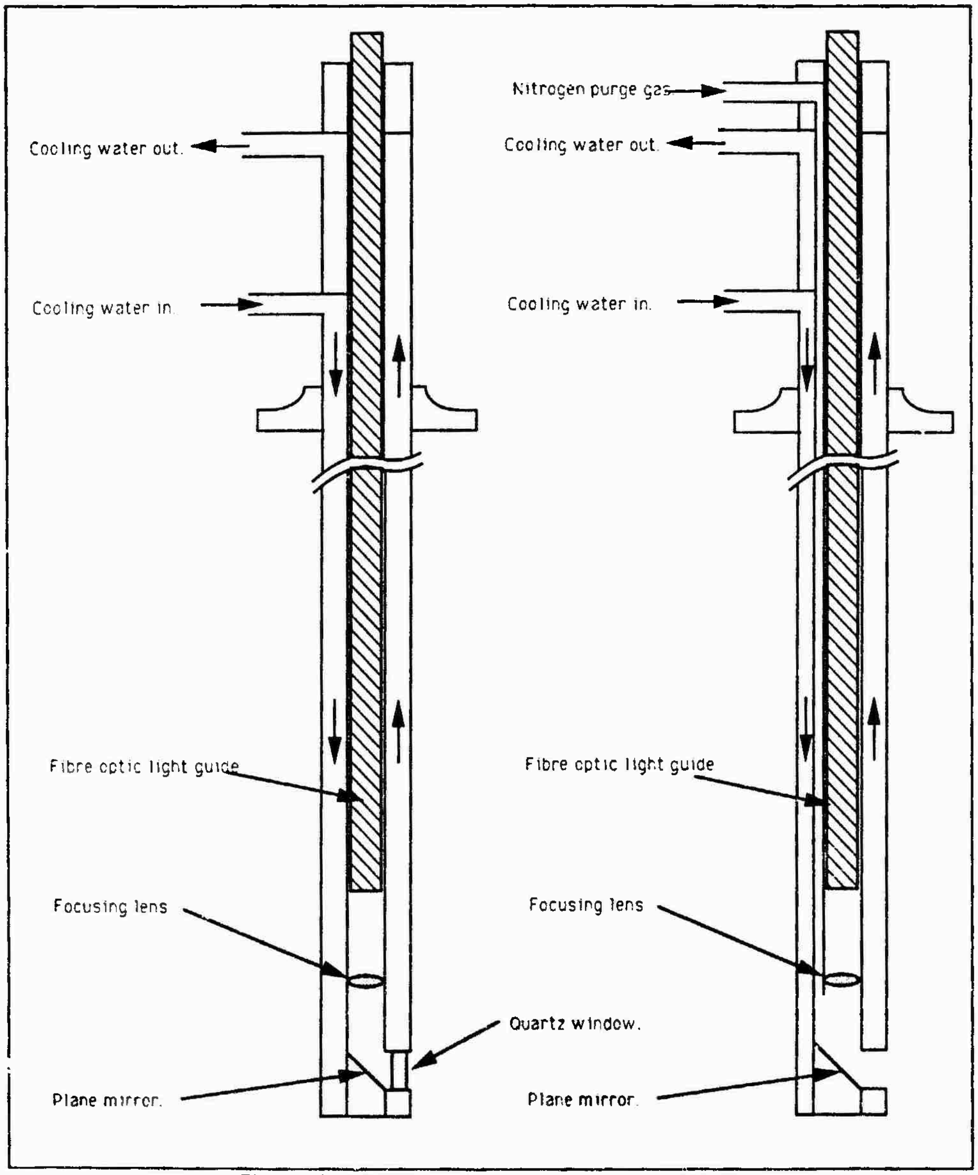

Figure 4.3-21 Examples of Optical Pyrometer Head Design

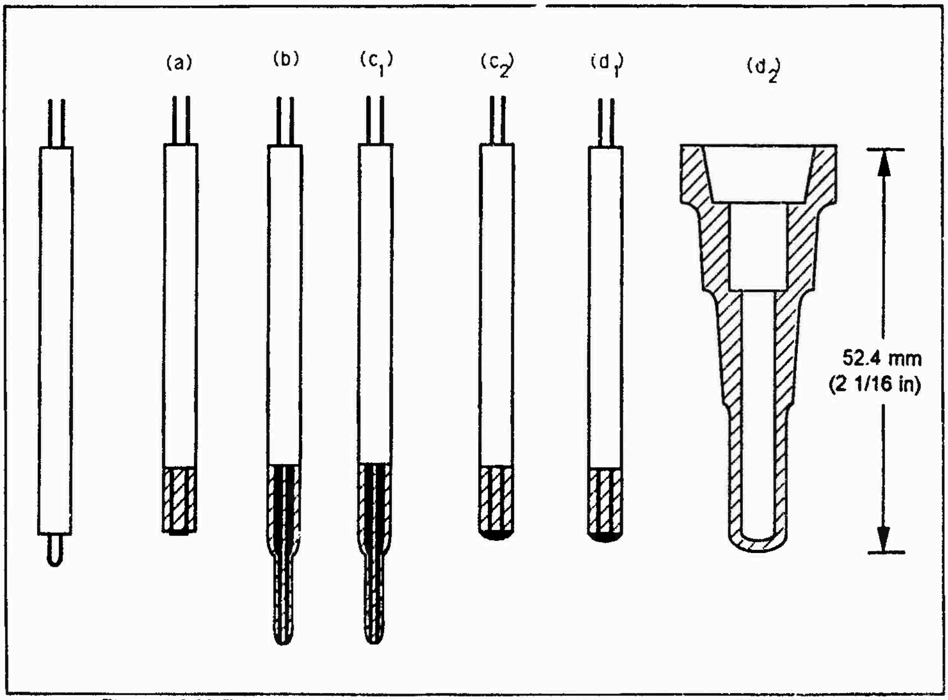

Figure 4.3-22 Thermocouple Sensors Used in Transient Fluid Temperature Measurement

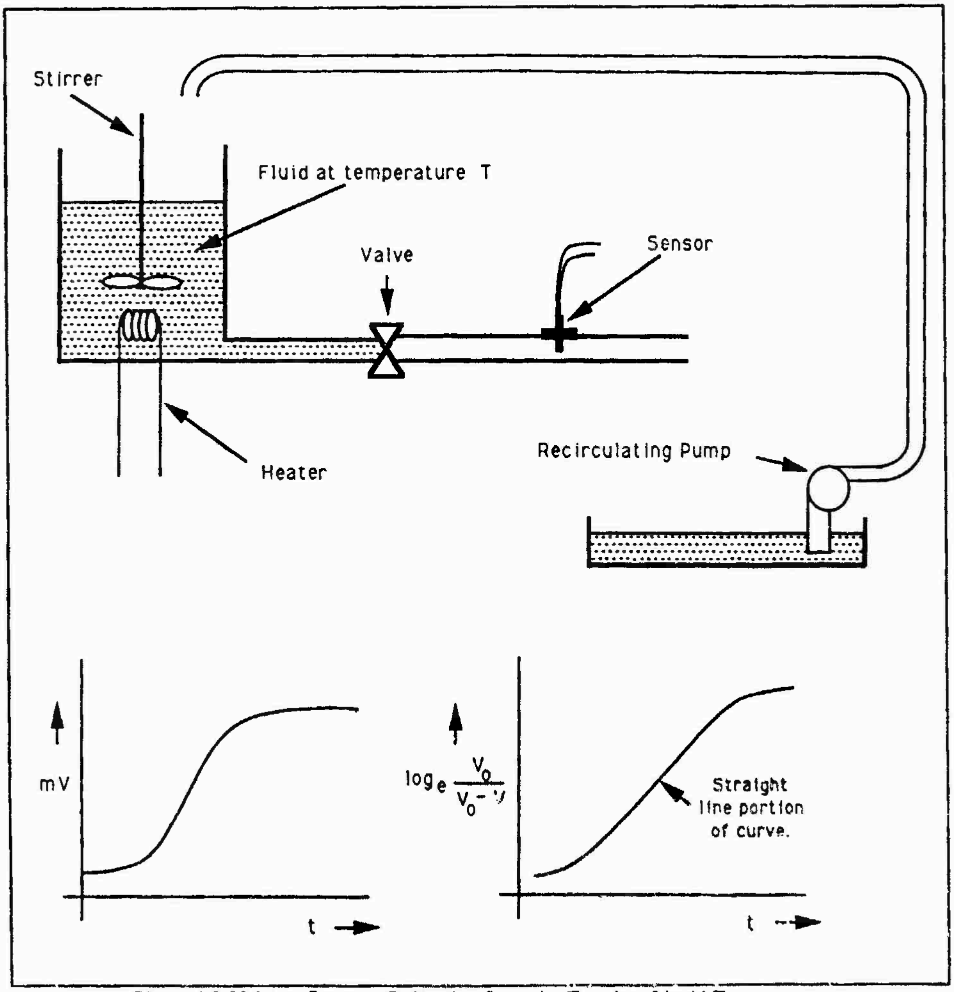

Figure 4.3-23 Time Constant Calibration Setup for Transient Liquid Temperatures

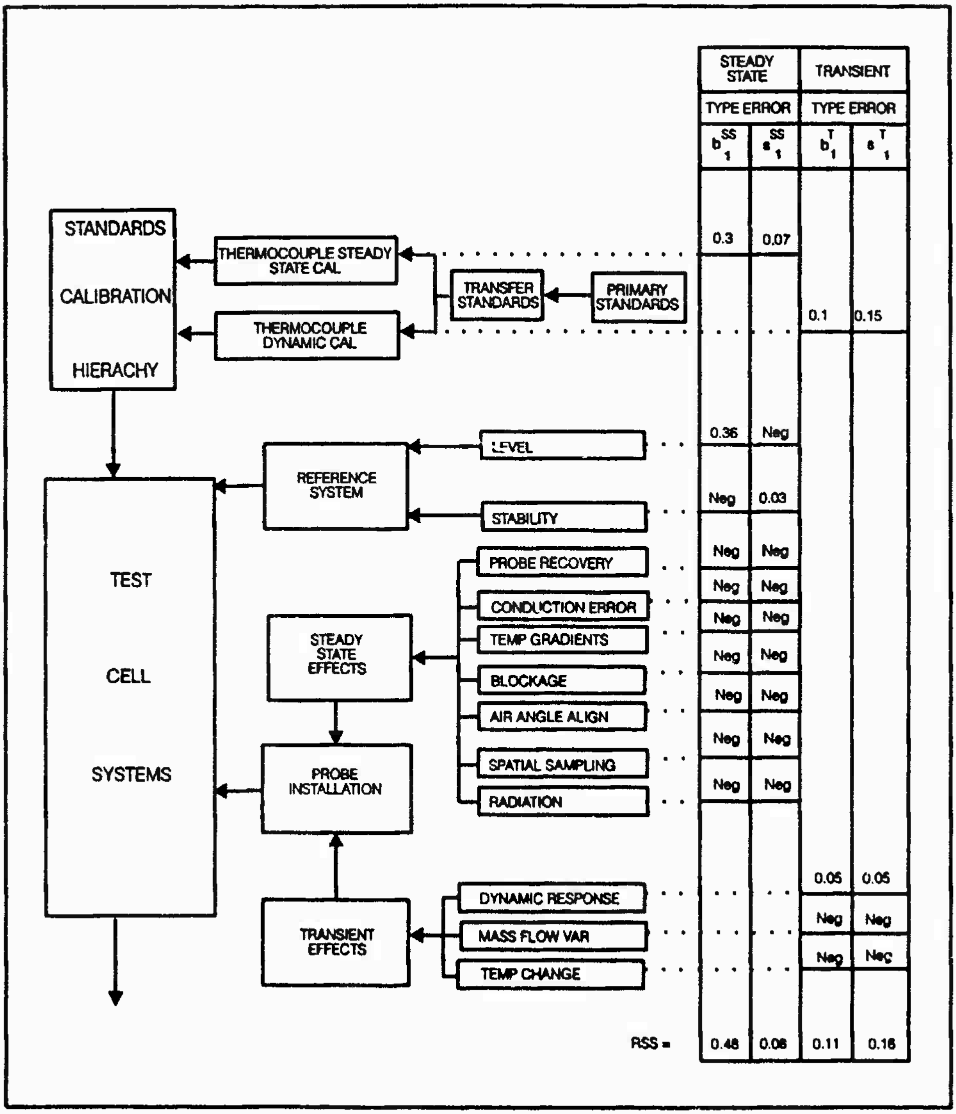

Figure 4.3-24 Transient Temperature Error Source Diagram - Liquid - Fuel Flow

4.4 FLOW[1]

4.4.1 Introduction & Definitions

Section 4.4 describes the transient flow measurement process used in turbine engine testing (fuel and air/gas path flow). Before the transient flow measurement process can be described, the reader must first understand the steady state measurement process. An attempt will be made here to describe briefly the basic concepts for each flow measurement system to be discussed. It is strongly recommended for the novice that an introductory course book or handbook on flow measurement be acquired for reference. A recommended reference is a Learning Module published by the Instrument Society of America (Reference 4.4.1).

National and international standards exist for the measurement of steady state flows in turbine engine testing. However, when time dependent or transient measurements are considered, standard practices do not exist. Steady state flow measurement practices will be deficient for transient flow measurement and result in serious errors. The purpose of this section is to provide transient flow measurement system design and application guidelines. Admittedly, the resources for experimental data on this subject are limited mainly due to the complexity of transient flow measurement. Some very good technical papers do exist and will be referenced in the particular flow measurement system sections.

For engine fuel and gas path flow measurement, numerous transient flow measurement systems are available. It is beyond the scope of this document to fully address all of these systems in detail. Therefore, the most commonly used types of transient flow measurement systems will be targeted for detailed description. They are as follows:

	Section
- Turbine flowmeter (fuel)	4.4.2
- Fuel injector differential pressure measurement system	4.4.3
- Fuel metering valve feedback system	4.4.4
- Venturis, nozzles, and bellmouths (air/gas)	4.4.5
- Fore-aft probe (air/gas)	4.4.6
- Airflow determination using thermodynamic engine models	4.4.7

Advanced systems will be described briefly in Section 4.4.8. The advanced instrumentation systems for flow measurement referenced in that section include:

- Hot-wire anemometer (air/gas)
- Laser anemometer (air/gas)
- Angular momentum flowmeter (fuel)
- Coriolis flowmeter (fuel)
- Target meter (fuel)
- Ultrasonic flowmeter (fuel or air/gas)
- Laser-induced fluorescence (air/gas)

Under the general heading of *Flow Measurement* a variety of properties may be measured. These include

- Velocity
- Mach Number
- Volumetric Flowrate
- Mass Flowrate

The flow measurement systems described may be specifically designed to measure or inferentially calculate one of these properties. Conversion from one to another of these properties (for example, from velocity to volumetric flowrate) will sometimes be provided as deemed necessary either in analytical or empirical form (calibrations).

A design example is provided for each of the most commonly used flow measurement systems described. A turbine flowmeter measurement system and an airflow determination using engine model examples will be described in detail as they will support Section 5, "Examples of A Measurement System Uncertainty Analysis for Two Test Cases." The other design examples will not include all aspects of the development of the particular measurement system but at least one aspect is presented in each case (design, calibration, and/or engine test results).

4.4.2 Turbine Flowmeter

4.4.2.1 *Description*

Turbine flowmeters can be used to measure either fuel or air flowrates. Only the application to fuel flow measurement is described in this section.

Turbine flowmeters are the most commonly used fuel flow measurement systems for steady state turbine engine test monitoring. Their application to transient engine monitoring is somewhat limited, mainly

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[1] Tables and Figures for Section 4.4 begin on page 4-138

by the effects of mainly inertial forces but also by bearing friction and fluid slippage. The use of close coupled low inertia turbine wheel flowmeters are a necessity for transient fuel flow monitoring in order to overcome some of these limitations. The smallest available turbine flowmeters still have some limitations and are useful for only specific transient applications as will be discussed in Section 4.4.2.3.

A typical flowmeter design is shown in Figure 4.4-1. Most turbine flowmeter designs incorporate a meter housing with standard flange or fittings. A miniature turbine, or rotor, is mounted axially in the flowmeter housing. Straightening vanes are included ahead of the turbine/rotor to minimize swirl. Also, upstream and downstream lengths of straight pipe are usually specified by the manufacturer for maintaining uniform flow profile and as a precaution against cavitation.

The rotor rotation is sensed by an external pickoff mounted directly above the flowmeter rotor. The pickoff senses the passage of the rotor blades. Fuel flow passage through the meter thus causes a train of electrical pulses. The frequency of these pulses is proportional to the fluid velocity and also volumetric flowrate since the passage of flow is fixed (area constant). The pulses are conditioned, transmitted, and finally converted to engineering units by a single, or combination of, electronic/computer processors. This volumetric flow can also be converted to mass flow with additional information provided from an independent density measurement system.

Typical fuel measurements using turbine flow meters for a fully configured engine include the following measurands:

- Combustor (primary, secondary, total main burner)
- Afterburner (core, pilot, bypass, total afterburner)
- Engine Total (main burner + afterburner)

Redundant metering is desirable, especially for situations where full range fuel flow cannot be accurately measured using a single flowmeter. Figure 4.4-2 presents an example of a complete fuel flow measurement system using turbine flowmeters.

4.4.2.2 *Basic Theory*

The turbine flowmeter is a transducer that measures average fluid velocity and also, because of fixed flow passage measures volumetric flowrate. When considering steady state flow only, viscosity effects must be accounted for in the calibration of the flowmeter. An increase in viscosity causes drag which in turn affects the rotor speed. A decrease in density reduces the power available to overcome bearing friction and causes a reduction in rotor speed. Calibration of these effects is necessary and standards exist for their correction (References 4.4.2 and 3). The correction of these steady state fluid effects can sometimes be incorporated in the calibrations for the range of temperature and flow that is anticipated. Sometimes the correction may be applied using a Universal Viscosity Curve which is a function of Hz/υ (output frequency/kinematic viscosity). The determination of viscosity (υ) in the Hz/υ term requires the measurement of fuel temperature. The above calibration techniques will be discussed in greater detail in the following sections.

When considering transient flow measurement, three additional effects are evident: moment-of-inertia, bearing friction, and effect of fluid slippage.

The effect of the moment-of-inertia is a rotor lag behind the actual flowrate. This effect is quantified by the equation for rotor motion:

$$T = I\frac{d^2\theta}{dt^2} \qquad 4.4\text{-}1$$

where
- T = Torque
- I = Moment of inertia of turbine flowmeter rotor about its axis
- θ = Angular displacement

The equation of motion is expanded by calculation of force per unit blade length (perpendicular to the effective velocity) and involves inclusion of a blade lift coefficient (Reference 4.4-4). The fully expanded formula in terms of known or measurable values is as follows (see Figure 4.4-3):

$$T = \frac{N_B\, \pi\, \rho\, \eta_A\, v^2 \sin\alpha_0\, L_C\, \bar{r}(r_2 - r_1)}{[1 + (2\, \eta_A/AR)]\cos\beta} = I\frac{d^2\theta}{dt^2} \qquad 4.4\text{-}2$$

where
- N_B = number of blades
- ρ = fluid density
- η_A = airfoil efficiency (Reference 4.4.4 recommends value of 0.9)
- v = fluid velocity

α_0 = blade effective angle of attack
L_C = blade mean chord
$\bar{r}$ = blade mean radius
r_2 = blade outer radius
r_1 = blade inner radius
AR = blade aspect ratio = $(r_2-r_1)^2$/(blade area)
β = $\tan^{-1} r/v(d\theta/dt)$

After trigonometric substitutions and integration the equation for system time constant is derived:

$$\tau = \frac{1}{A \cos \alpha_0} \qquad 4.4\text{-}3$$

where

$$A = \frac{N_B \, \pi \, \rho \, \eta_A \, v \, L_C \, \bar{r}^2 (r_2 - r_1)}{I[1+(2\eta_A/AR)]} \qquad 4.4\text{-}4$$

The bearing friction effect must not be confused with the steady-state friction effects (low density effects) as during transients the friction is due to the increased loading from inertial forces. If the measurement system is designed properly (high rotor speeds per flow range), bearing friction is usually small compared to the moment of inertia effect and can be absorbed into the calibration and/or treated as random error. Fluid slippage effects are also very small and can be treated similarly.

In general, the correction of fuel flow for transient effects is applied as a first order lag (simulates mainly the moment-of-inertia effect) (References 4.4.4, 5, and 6). The flowmeter can be calibrated against a high response measurement system used as a prover (Reference 4.4.5) with errors attributed to drag torques and fluid slippage. Section 4.4.2.5 will detail the recommended calibration procedures.

Mass Flowrate

Conversion of volumetric flowrate to mass flowrate requires the determination of density. Density (or specific gravity) can be determined by measurement or as a function of fuel temperature. Some schemes in fact measure density at the start of a test period using some type of measurement device (hydrometer for example) and correct for temperature effects as the test proceeds.

4.4.2.3 *Advantages and Disadvantages*

The advantages of turbine flowmeter systems, such as linearity, compactness and durability, have led to their widely accepted use for fuel flow measurement (almost exclusively for steady state measurement). The turbine flowmeter is inexpensive and easy to install. A large variety of signal conditioning circuitry (pickoff, amplifiers, filtering, etc.) for different applications are available as well as built-in corrections for viscosity and fuel specific gravity effects. Transient calibrations (presented in Section 4.4.2.5) are relatively simple and usually inexpensive to perform.

The major disadvantage of the turbine flowmeter is that inertial effects prevent its usage for very high response events. Uncertainty can sometimes be large given frequency count interval requirements (dynamics of interest are so fast that blade passage is not frequent enough in interval to make an accurate flow calculation).

Recommending usage of turbine flowmeter for transient fuel flow measurement requires knowledge of engine size (fuel flow capacity during transients), transient scheduling (snap accel/decel fuel flow range), and fuel hydro-mechanical limitation (slew rate). Taking these considerations into account, recommendations are as follows:

1) For best results, transient fuel flow measurements should be made using the high end of the turbine flowmeter range. This prevents the inertial effects from degrading significantly the response of the meter. For example, during surge testing by fuel pulsing, multiple meters can be used to cover the entire power range such that the low range of the meters are not used. However, for very fast fuel slew rates, it may become impossible to pick a flowmeter that will have insignificant lag. For these situations, some of the other fuel flow measurement systems should be considered.
2) Recommended for overall transient time investigations where the flowmeter error at initial pulsing will not be significant.
3) Recommended for control scheduling/optimization where flowmeter lag effect is not significant.
4) Recommended for blowout studies given the guidelines of number 1 above are followed.
5) Recommended for any testing where the fuel control transient scheduling has relatively constant levels of fuel flow (giving the meter time to catch up) or relatively slow slew rates such that time corrections can be applied or are not necessary. Start testing is an example where constant levels of fuel flow are scheduled.

Transient performance models (full thermodynamic plus control logic simulations) can be very beneficial in determining what size turbine flowmeter will be acceptable given a specific application. The models can be used to predict the influence of a given measurement device, with or without time correction, on other performance parameters of interest (horsepower profile, thrust profile, combustion velocity, combustion loading parameter, control scheduling, etc) and whether or not the error/uncertainty is acceptable. A model of the measurement device using formulae or calibration techniques described in this section must be included in the simulation.

Several breakthroughs in turbine flowmeter design have greatly benefitted its application for transient measurement and mainly pertain to its miniaturization (low moment-of-inertia). Other breakthroughs include development of flowmeters with tungsten carbide shafts and sapphire supports in vee jewel pivot bearing assemblies. Despite low life and low flow limitations, these type of meters do offer less starting and running friction than the ball bearing types. Flowmeter advancements are ongoing and many of the limitations detailed herein may eventually be overcome.

4.4.2.4 *Signal Conditioning*

For successful and accurate flow measurement using the turbine meter, a number of factors must be considered. One of the most important considerations is selection of signal conditioning equipment. This selection depends on flowrate, flow range, temperature range, pressure range, fluid properties, and numerous other factors. Manufacturers' handbooks are usually very helpful and straight forward in guiding the user to the proper selection of flowmeter and signal conditioning given steady state requirements. However, information is usually lacking for transient measurement considerations. It is important to contact directly the manufacturer and detail the specific "transient needs" before equipment is procured.

The frequency or pulse count conditioning can affect the transient response of a given flowmeter if not performed properly. The signal conditioning options available to the user are summarized in Figure 4.4-4 and detailed as follows:

> Two types of pickoffs, magnetic and RF, are available. The magnetic pickoff utilizes either a permanent magnet mounted within the pickoff body (inductive) or magnet mounted in the rotor body itself (reluctance). The electrical output of the magnetic pickoff is amplified through a pre-amplifier. The RF (modulated carrier) pickoff utilizes a 45 kHz carrier frequency which is amplitude-modulated by the passage of the turbine rotor blades. The RF amplification is inherently built into the carrier frequency. The magnetic pickoff causes drag and is difficult to characterize at low flows while the RF pickoff enhances low flow performance and allows for even higher accuracy by use of low flow offset signal conditioners (alters output frequency to enhance linearity of meter at low flow). At high flows, either type pickoff is acceptable for transient flow measurement. At low flows, the RF pickoff should be used and not the magnetic type because of the low flow drag limitations. It should be emphasized that "low flow" is only relative, as flowmeters of either type can be designed for the expected flow value. But as wide range flow measurement become necessary, the low flow end of the magnetic pickoff flowmeter is deficient because of the reasons stated.

> Amplification is necessary for signal transmission at great distances and/or when noisy environments exist (noisy environment would cause errors in a low level un-amplified signal). The pickoff and pre-amplifier are sometimes provided as a single unit built into the flowmeter itself. The delay or lag of the pickoff/amplification system depends on capacitance of input cable and frequency response of the amplifier itself. The calculation of the total frequency response of the pickoff/amplifier is complex and not recommended for the normal user. It is recommended that the total frequency response of the pickoff/amplifier be taken from the manufacturer's specifications with total flowmeter response verified through calibration methods which will be detailed in the following section. If properly selected, the pickoff/amplifier transient effect is generally insignificant relative to the moment-of-inertia effect.

> Count processing can be performed by pulse rate converters which are basically frequency to analogue conversion devices or by digital count processing schemes available inside the data reduction system itself. The frequency converter should match system requirements and of course the frequency

range of the flowmeter itself. Inadequate match can cause aliasing problems and signal distortion. Count processing guidelines are provided in Section 4.5.2.

Noise filtering may also be part of the signal conditioning circuitry. It is important to isolate the noise frequency and magnitude because inadequate filtering could provide additional lags and attenuate the total transient flow measurement system. It is also recommended that the filtering (if provided by in-line circuitry) be included in the system calibration as described in the following section. An important note is that the total response of the measurement system is only as fast as the noise filtering. For example, if 240 Hz noise (60 Hz harmonic) is evident and filtering necessary, flow response measurement or correction is only feasible below the filter response. Noise filtering is generally performed by low-pass filters on the order of 200 Hz which does not retard the flowmeter response.

4.4.2.5 *Calibration*

<u>*Steady State Calibration*</u>

Steady state uncertainty calculation guidelines are provided in References 4.4.2 and 3 (see also Section 3, above). Steady state fuel flow calculation (mass flow) using turbine flowmeters not only requires the measurement of turbine wheel frequency but additionally the measurement of temperature (for viscosity calculation) and the determination of specific gravity (either by measurement and/or as a function of fuel temperature). Separate uncertainty analyses are then required for each of these measurement systems with the total uncertainty for mass flow measurement being the combination of all the errors (see Section 3). All steady state calibrations should be traceable to a national standards laboratory. Error sources for fuel temperature measurements have been discussed in Section 4.3.3. Error sources in the determination of specific gravity are illustrated in Table 4.4-1. Figure 4.4-5 summarizes the error sources (including fuel temperature and specific gravity) to be considered in estimating the total uncertainty of the fuel flow measurement. The possible error introduced by the selected sampling rate is included here as part of the measurement system, rather than as part of the Data Processing System described in Section 4.9 below.

<u>*Transient Calibration*</u>

Two calibration procedures are recommended.

The first technique (Reference 4.4.5), involves experimentally determining the flowmeter transfer function by frequency response approach. This involves a calibration technique where a variable sinusoidal frequency is induced about an average fuel velocity. The breakpoint frequency can be determined by calculation of the magnitude ratio and phase angle of the actual flow meter reading to an orifice reading (which is designed to be "fast enough" to sense the actual flow) (see Figure 4.4-6). The transfer function is of first order form (see Equation 3-16).

$$W_{indicated} = \frac{W_{actual}}{1 + i(f/f_o)} \qquad 4.4\text{-}5$$

where

f_o = breakpoint frequency

The calibration requires variation of the frequency about the ranges expected in actual test conditions as well as variation of the average fuel flow since the time constant is directly proportional to this flow. The paper goes on to state that the breakpoint frequency can be found if the amplitude ratio and phase angle are plotted on frequency plots and a first order lag function fit made. This can more easily be accomplished by plotting the phase angle and amplitude ratio on Bode paper (see Figure 4.4-7a). The time constant (which is inversely proportional to the breakpoint frequency, i.e. $\tau = 1/(2\pi f_o)$ will be apparent as it is the point where the asymptotic lines intersect. The time constant or breakpoint frequency can be correlated as linearly proportional to the average fuel flow by variation of this average fuel flow. A calibration constant is then determined.

$$f_o = C_f W_{av} \qquad 4.4\text{-}6$$

or

$$\tau = C_\tau / W_{av} \qquad 4.4\text{-}7$$

where

$$C_\tau = 1/(2\pi C_f) \qquad 4.4\text{-}8$$

The actual flow can be determined from the indicated flow using the equation:

$$W_{actual} = \left[1 + i\frac{f}{C_f W_{av}}\right] W_{indicated} \qquad 4.4\text{-}9$$

or in Laplace form:

$$W_{actual} = (1 + \tau i \frac{f}{C_r C_f}) W_{indicated} \qquad 4.4\text{-}10$$

The noise filtering may be part of the measurement system and will show up in the calibration. By design, the filters should not interfere with the actual flowmeter signal at the frequency of interest. If it is necessary for the filter time constant to be close to the frequency being measured, it will show up in the frequency response calibration as a second asymptote (Figure 4.4-7b) unless the signal is measured before filtering (Figure 4.4-7c and d). Noise filtering guidelines are provided in Section 4.1.

In fact, the true signal transfer function is much more complex because of the combination of inertial lags, filter lags, line capacitance, amplification effects, fluid slippage, bearing forces, etc. This calibration technique is acceptable when the inertial lag is dominant and the other effects (higher harmonics) can be treated as random errors in the calibration process.

A second method is described (Reference 4.4.6) where a calibration constant is determined (similar to the method of Reference 4.4.5 in that it is proportional to the flowrate). The difference lies in the determination of the time constant experimentally (uses time domain versus frequency domain of the first method). For this test the flowmeter is modified to include a spring loaded pin which releases the turbine wheel upon activation. The test basically simulates a step change from zero rpm to a steady rpm at a known steady state flow. Another unique feature of this technique is that the transient response is measured by oscillation amplitude instead of the traditional frequency method (see Figure 4.4-8). The time constant is determined by introducing the amplitude increase into a first order lag function and varying the time constant until the test profile is matched. This is done for several magnitudes of flow to determine the calibration constant for the particular meter.

From these two methods several conclusions are made. The first method has the advantage that the calibration technique measures the response in actual conditions which more realistically represent actual flow conditions in turbine engine transients. This method also enables isolation of other effects (filters etc.,) by use of Bode diagrams. The second method has the advantage of being simpler and less expensive to perform and measurements may be more exact by the fact that the fuel flows are determined by magnitude, not frequency, in the count interval.

Both methods require actual fuel flow values for the time constant determination. Since fuel flow is the value being determined/measured, derivative guesses of flow based on the previous digital time sample calculation are necessary. The error in the derivative guess can be reduced to almost negligible amount by ensuring very small sample rates in the digital recording system.

4.4.2.6 *Design Considerations*

This section involves the general assessment of turbine meters for the measurement of fuel flow during transient engine tests. The section includes discussion on:

1) Laboratory dynamic calibration of a turbine flowmeter using methodology similar to that demonstrated in Reference 4.4.5.
2) Measurement of fuel flow during actual engine transient events using a turbine flowmeter with the dynamic calibrations applied.
3) Final assessment of a turbine meter measurement for specific transient events.

A high response differential-pressure-producing class measurement system should be used as the reference system for both the laboratory bench calibration and the on-engine testing. An orifice measurement system is used as the reference measurement system during the bench calibration while a fuel injector measurement system (described in Section 4.4.3) can be used during the on-engine testing. The orifice and fuel injector flow measurement systems should be selected to be "fast enough" for measurement of the specific transient events and not require dynamic corrections. Uncertainty estimates will not be shown for this discussion, but are always recommended and should be performed using the guidelines provided previously.

The bench calibration setup is slightly different than that presented in Figure 4.4-6. A pure fuel flow step (instead of sinusoidal) is activated by installation of a shut-off valve behind a slave fuel control unit. During valve shut-off, the slave fuel control is in re-circulation mode. Fuel steps are performed in both directions (closing/opening valve) and at target values from min to max expected fuel flows. Fuel temperatures are monitored transiently and used in the mass flow calculation (see Figure 4.4-9) because the fuel control re-circulation causes fuel temperature fluctuations (fuel heats up).

The dynamic calibration procedure involves variation of the time constant in a first order transfer function such that the turbine meter fuel flow reading matches the orifice fuel flow reading (Equation 4.4-10):

$$W_{actual} = (1 + \tau\, i\frac{f}{C_\tau C_f})W_{meter}$$

Figure 4.4-10 presents typical calibration results for a turbine meter in terms of time constant and breakpoint frequency. Reference 4.4.5 demonstrates a linear fit of the breakpoint frequency which passes through the zero flow, zero frequency point. Figure 4.4-10 shows more scatter (fuel step increases at high flow have the highest scatter) and does not show a truly linear characteristic. Regardless, a linear fit passing through the zero flow, zero frequency point is applied in keeping with Reference 4.4.5 methodology.

The dynamic calibration is applied to actual on-engine turbine flowmeter measurements. Figure 4.4-11 shows records for the preliminary portion of an engine snap acceleration with uncorrected turbine meter, corrected turbine meter, and fuel injector fuel flow readings. Part A of the figure shows un-filtered data with high frequency noise which makes it difficult to interpret. Part B of the figure shows results after the high frequency noise is filtered. During the initial pulse, the turbine meter reading is successfully time corrected to match the true value as represented by the fuel injector reading. After the initial pulse, the turbine meter is attenuated such that it is unable to keep up with the differential-pressure measurement system. There appears to be a high frequency fuel oscillation which causes the turbine meter error. It is reasoned that the oscillation is induced by the resonant frequency of the fuel control flapper valve inherent to this particular engine configuration. When the transient is in the pulse portion though, the flapper valve is fully extended in one direction (max slew rate) and does not have significant error.

Figure 4.4-12 part A demonstrates the accuracy of the turbine meter for measurement of overall acceleration fuel flow profiles. Figure 4.4-12 part B demonstrates the accuracy during the initial fuel spike region as discussed previously. If this setup was used for surge testing by way of fuel spike testing (at max slew rate), the results would have satisfactory accuracy. If the surge testing involved surges during transients while on the acceleration schedule (post-pulse), the results would not obtain the required accuracy because of the control flapper valve resonant frequency. Figure 4.4-13 demonstrates an example of the potential error. In this figure the surge occurs at one of the peaks caused by the flapper valve oscillations where the turbine meter does not respond, resulting in an error of approximately 4%.

The final assessment of this particular turbine meter on this engine configuration shows that it can provide accurate measurement for evaluations which involve overall acceleration and some fuel spike events. However, because of the fuel control flapper valve hysteresis, surge investigation while on the control acceleration schedule will not be accurate enough An example would be a pass-off test where fuel control trim setting is determined during acceleration such that surge is cleared by a specified margin.

These design results are particular to the specific engine configuration used. Other engines may and do have tighter tolerance on fuel control hysteresis. For these engines, the turbine fuel flow meter will have a wider range of applications.

4.4.2.7 ***Design Example (see also Section 5.2)***

Detailed information on the fuel flow measurement system used in the design example presented in Section 5.2 is provided here. The design example in Section 5.2 is for a fuel spike (surge test). The fuel flow sensor used in this example is a turbine flowmeter. The sensor chosen here is not necessarily the most suitable system for the particular task, but the primary objective is to provide the reader with an example of an uncertainty estimate of a transient fuel flow measurement device. The turbine flowmeter is one of the more common transient fuel flow measurement devices used in the industry today, mainly because of its low cost, and can be used for applications similar to that presented in Section 5.2. (A more general review of the use of turbine flowmeters for transient tests is given above (Section 4.4.2.6)).

The test in Section 5.2 involves a fuel spike starting at approximately .265 kg/sec (2100 PPH), pulsing up to 1.64 kg/sec (13000 PPH) in 10 ms, and then returning to .265 kg/sec (2100 PPH) in 70 ms. For this example, the main interest in the fuel flow measurement is to assure repeatability of the fuel pulse. A target uncertainty for this system would be on the order of ±10% error.

The fuel flow measurement sensor chosen is described as follows:

Dual Axial Turbine Flowmeter
Extended Flow Range: $.022 \times 10^{-3}$ to 2.2×10^{-3} m^3/sec (.35 to 35 USGPM)
Approximate Frequency Output of 2000 Hz at max fuel flow. (K factor of approx. 900,000 pulses per m^3)

Design Considerations

1) Turbine flowmeters are selected which do not exceed ±0.2 percent nonlinearity. The nonlinearity is that of the K factor curve. The objective here is to start with a small nonlinearity in order to reduce the K-factor correction error.
2) Turbine flowmeters are calibrated using JP-4. Calibrations are traceable to the national standards institute.
3) Fuel temperature is controlled to ± .5 C° (5 F°).
4) Fuel is deaerated and filtered with a 5 micron filter. The purpose is to conserve the accuracy of the precision flowmeters.
5) The data reduction system corrects for changes in specific gravity and also corrects K-factor shift due to fuel temperature changes.
6) Two flow meters are installed in series and measurements are compared and averaged.
7) The flowmeters are recalibrated after 100 hours of engine operation; recalibrations are also performed when the difference in reading between the two meters exceeds ±0.3 percent of 1.3 kg/sec (10000 lb/hr) when below that flow rate. Another option would be to use a reference system in series with the main system occasionally to verify performance.
8) The dual precision flowmeters are bypassed through a less precise flowmeter when performance data are not being recorded. The purpose is to conserve the accuracy of the precision flowmeters.
9) The flowmeters are mounted as close as possible to the flowdivider (within 5 feet) in order to optimize time and amplitude response.
10) Straight pipe is mounted before and after the flowmeter according to the manufacturer's specification which is usually 10 diameters before and 5 diameters after. It is recommended that longer lengths of pipe than that specified by manufacturer's specification be used wherever possible in order to ensure adequate flow straightening. Straight pipe should also be augmented by flow straightening sections.
11) The flowmeters should be calibrated on a ballistic calibrator. Typical calibrations should contain approximately 20 points between min and max fuel flow. The curve fit is by table lookup with linear interpolation between points. A residual error of ± 0.1 percent error remains and is the nonlinearity left over after table lookup and linear interpolation between points.
12) A pulse rate converter with multiple settings is used. The fastest setting is used and has a 10 to 90 percent response to a step change of 10 ms. This equates to a 3db cutoff frequency limit of about 35 Hz.

Flowmeter Dynamic Calibration/Error

Dynamic calibrations using the technique described abve showed the frequency response characterization for this flowmeter to be $f_0=40\times W$, (W in kgm/sec). The transient error without applying a time correction is estimated by simulating the transient profile (either through transient models or previous experience) and applying the flowmeter 1st order lag (time constant = $1/(2\pi f_0)$).

Figure 4.4-14 presents the simulation for the fuel pulse example with an error of approximately .08 kg/sec (635 PPH) or 4.88 percent when surge occurs. The meter response will be treated as a bias error with no time correction applied (see also Figure 4.4-5).

Also note that a 200 Hz low-pass filter is included inline before the data acquisition system for the design example. The filter does not significantly affect the response of the flowmeter in the frequency range of interest.

Uncertainty Calculation Notes

The determinations of the steady-state measurement uncertainties for fuel temperature, fuel specific gravity, and fuel flow for this example are not detailed here but the technique is similar to that presented earlier and that given in References 4.4.2 and 4.4.7. The final steady-state fuel flow error sources are summarized in Figure 4.4-5 which includes the propagated effects of fuel specific gravity and temperature.

The uncertainties associated with the pulse rate converter are estimated by applying a known frequency and frequency rate increase and using the methodology described in Section 3 to calculate the bias and precision.

Final Assessment

Although the total uncertainty of the instantaneous fuel flow at the surge point is large (approximately ±7.8 percent), it is assumed that the fuel pulse rate or time profile is consistent from pulse to pulse. The surge condition is primarily a function of the total excess fuel flow during the spike up to the surge point.

If more stringent accuracy requirements for fuel flow measurement during fuel pulse testing are required, other measurement options must be sought. A recommended measurement system would be the fuel metering valve feedback system which is also discussed in this report.

4.4.3 Fuel Injector

Fuel flow measurement can be accomplished by installation of a nozzle or orifice with a delta pressure transducer somewhere in the engine inlet fuel line. The problem that arises is that installation of a single nozzle/orifice will either have non-linear characterization over the required range of delta pressures encountered (adding to uncertainty) or will limit the flow at the high fuel flow demand conditions (choke conditions). The measurement system then requires installation of multiple nozzles/orifices with flow division schemes incorporated to maintain linear delta pressure to fuel flow characterization and unrestricted flow. These are the same problems that arise in the design of the fuel injector system inherently built into the engine fuel delivery system. It is the "best practice" to take advantage of the engine fuel injector system orifice/nozzle to provide the delta pressure required to measure fuel flow instead of designing a completely independent differential-pressure measurement system. The use of fully characterized nozzles/orifices are still recommended during the bench calibration stage and will be described.

4.4.3.1 *Description*

Liquid fuel injected into combustion zones (main or afterburning) of gas turbines must first be atomized. Atomization is the process which converts the fuel liquid into small droplets such that evaporation can occur. The atomization is accomplished by spreading the fuel into a thin sheet so that it will more easily disintegrate into droplets. This sheet of fuel is formed by various atomizer designs as shown in Figure 4.4-15. All of these atomizers employ an orifice or nozzle of some type to increase the fuel velocity. Thus, fuel flow can be calculated from pressure drop across the fuel injector.

The convenience of this differential-pressure-producing class of measurement system is that the orifice/nozzle is part of the engine hardware itself. The fuel injector system consists of multiple atomizers (the number required is dependent on the combustor design). Determination of fuel flow only requires the introduction of transducers to measure the delta pressure across the fuel injector system. The inlet side or fuel pressure can be sensed at the engine external fuel lines while the exit side or combustor pressure can be sensed through available locations in the outer annulus plenum (boroscope holes for example) or special instrumentation taps in the primary zone (see Figure 4.4-16).

For the main burner, the fuel injector types consist mainly of single fuel circuit and dual fuel circuit designs. Dual fuel circuit design is sometimes necessary to accommodate large ranges of fuel flow which are difficult to achieve using a single fuel circuit given conflicting pump design limits and atomization requirements. Dual fuel circuits have various configurations. They may include two individual atomizers (orifice, simplex, spill-return, air-assist) each designed for a specific range of fuel flow. The dual fuel circuit may also be an integral part of the atomizer itself (duplex, dual orifice, pilot-airblast as shown in Figure 4.4-15).

The dual fuel circuit involves the use of a flow divider valve activated by either fuel pressure, flow, or electric solenoid. For starting and sometimes for near idle power conditions, only the primary (or pilot) circuit is active. For higher power settings, the secondary circuit becomes active (at the flow divider crack-point) along with the primary. More than two fuel circuits are sometimes used and are activated by similar schemes.

The determination of the fuel flow for a dual fuel circuit injector system can be by either of two methods. The first method involves individual fuel circuit pressure measurement and the calculation of fuel flow using the two delta pressures (primary minus combustor pressure and secondary minus combustor pressure). This first method is not always possible as the flow divider may be an integral part of the fuel injector system, thus preventing individual circuit pressure measurement. The second method then becomes necessary and involves single fuel pressure measurement before the split to primary and secondary fuel. The fuel flow calculation by this method requires calibrations curves that include correlation of a single delta pressure to total fuel flow. These two methods of calibration will be discussed further in Section 4.4.3.5.

For afterburning, the fuel injector type is usually that of plain-orifice design. Afterburners involve multiple zones of burning generally categorized as pilot, core, and bypass (or fan). The distribution of fuel to these zones can also be accomplished by pressure, flow, or electrically activated flow dividers. Each zone of fuel flow measurement in the afterburning requires its own pressure transducer system to measure the respective delta pressures.

Transient fuel flow measurement using the fuel injector measurement system is usually treated as quasi-steady state. That is, transiently the fuel injector is assumed to react the same (hydraulically and mechanically) as it does steady state. This statement is true only if the pressure measurement system does not have significant lag. Transient mechanical bysteresis effects are sometimes significant and should be accounted for. Hysteresis accommodation will be further discussed in Section 4.4.3.5.

As the fuel injector is an inferential measurement system using pressure as the primary measurement, the reader is referred to Section 4.2 for specifics on pressure measurement systems including calibration and signal conditioning. What will be described in this section are details which pertain only to the determination of fuel flow.

4.4.3.2 *Basic Theory*

Using Bernoulli's equation and the principle of conservation of mass, the mass flowrate through the fuel injector is given by:

$$W = \frac{\pi}{4} D_o^2 C_w \sqrt{2\rho \Delta P} \qquad 4.4\text{-}11$$

Discharge coefficients can be analytically calculated for the various fuel injector types. Reference 4.4.8, for example, gives a formula for the calculation of discharge coefficient for a simplex type atomizer as:

$$C_w^2 = 0.0616 \frac{D_s}{D_o} \frac{A_p}{D_s D_o} \qquad 4.4\text{-}12$$

where D_s = swirl chamber diameter
D_o = orifice diameter
A_p = swirl chamber inlet port area.

Fuel injector production tolerances are usually such that accurate fuel flow calculations cannot be made using design specification values. Also, accurate orifice dimension measurements for the specific fuel injector unit to be used are extremely difficult to make. It therefore becomes necessary to determine fuel flow by calibration. The flow coefficient for an orifice is a function of the fuel condition and orifice geometry (see Reference 4.4.1). Since the orifice dimensions are fixed and if fuel flow temperature effects are insignificant, fuel flow calibrations can be made using only fuel injector delta pressures. A typical calibration curve profile is shown in Figure 4.4-17 for single and dual fuel circuit design (no temperature compensation).

If fuel temperature effects are significant, fuel temperature compensation will be necessary. Fuel temperature effects for constant tank temperatures test facilities are mainly due to temperature rise across the fuel pump or because of in-line heat exchanger devices. This temperature rise affects fuel density and can sometime be significant from min to max power conditions. Other fuel temperature effects include Reynolds Number and orifice thermal growth effects. Altitude facility testing will have wide variations in tank temperature and must include some type of fuel temperature compensation. These issues and other calibration procedures will be discussed further in Section 4.4.3.5.

The calculation of fuel flow requires the use of individual transducer measurements for fuel pressure and combustor pressure, or the use of a single delta pressure transducer. Close coupling of the combustor gas pressure is absolutely necessary for transient fuel flow calculation. Guidelines as presented in Section 4.2 should be maintained. Fuel pressure coupling requirements are not as stringent since the dynamics of a liquid are of much less magnitude per lengtb of transducer feed tubing than that of a gas. It is apparent that phase shifts will be evident between the fuel pressure and the combustor gas pressure measurement and will be discussed further in Section 4.4.3.4.

4.4.3.3 *Advantages and Disadvantages*

The major advantage of the fuel injector flow measurement system is the fact that it generally has a higher rate of response than the turbine flowmeter if higb response transducers and close coupling guidelines are maintained. The fuel injector flow measurement system requires only the incorporation of pressure transducers (if fuel temperature effects are insignificant) as the actual measurement hardware (the orifice/nozzle) is inherently built into the fuel delivery system. Calibrations are relatively easy and can be performed during engine steady state calibrations, as will be discussed in Section 4.4.3.5.

The major disadvantage to the fuel injector measurement system is that uncertainty may become unreasonably bigb at low flows where the calibration curve is sometimes steep (extremely sensitive to pressure error as shown in Figure 4.4-17). Fuel injector clogging can also cause problems as the calibration curve will have an evident shift because less flow is passed for a given pressure. This problem can be remedied if frequent steady state calibrations are performed such that nozzle clogging is recognized and compensated for in the calibration curves. Phase shifts will be evident because of the differing dynamics of fuel versus gas pressure but can be maintained at a minimum with extremely close coupling and high response transducer usage. If fuel tank temperatures are not maintained at relatively constant levels or if the fuel temperature variation due to fuel pump or heat exchanger device energy transfer is significant, fuel temperature compensation will be necessary. Finally, some internal dual fuel circuit systems will have hysteresis which can cause uncertainty in the calibration curve but may also be remedied if dual calibration curves are generated (one for increasing fuel flow and one for decreasing fuel flow as will be discussed in Section 4.4.3.5).

For high frequency events where the turbine flowmeter may be too slow responding, the fuel injector measurement system should be considered.

4.4.3.4 *Signal Conditioning*

As a fuel flow calculation using the fuel injector measurement system is inferential, the reader is referred to Section 4.2 for pressure measurement signal conditioning specifics which include transducer excitation, signal amplification, and filtering. Techniques for frequency response and phase shift determination are provided there.

4.4.3.5 *Calibration*

For engine testing where the fuel is stored at ambient conditions or maintained at a constant temperature, ambient bench calibrations as a function of only delta pressure across the fuel injector may be reasonably accurate if effects from fuel pump or in-line heat exchange devices are insignificant. Fuel injector bench calibrations performed in a fuel component test stand involve determination of fuel flowrate using a reference flow measurement system. This reference system has quality limits checked and maintained by frequent calibrations with master orifices that are certified by a quality control organization. Since the transient operation of the fuel injector can be viewed as quasi-steady state, the bench calibrations involve setting steady state fuel flow at values between min and max expected from transient engine testing. More calibrations points will be necessary in areas where the calibration curve becomes steep (for example on dual circuit design where flow divider valve switches from primary to primary plus secondary flow as shown in Figure 4.4-17). Typical bench calibration data is presented in Figure 4.4-18.

When possible, bench calibrations should include the actual engine test hardware (fuel injector engine-set, fuel pump, fuel pump-to-injector plumbing, fuel pressure instrumentation, etc.) and fuel type to be used. This will minimize calibration adjustments due to variations between bench and on-engine configuration.

Performing bench calibrations for every fuel injector unit to be used for transient testing can become expensive and time consuming. On-engine steady state calibrations using an accurate reference system (turbine flowmeter for example) is possible and would reduce cost and time. The problem that will be encountered with this calibration technique is that on-engine steady state performance calibrations will not cover the full range of transient engine operation. Extrapolations of the fuel injector calibration curve will become necessary with a potential for large errors, especially at the low power where the curve is steep. A compromise calibration procedure to maintain reasonable accuracy is recommended when lower cost and pre-test preparation time are necessary:

1) Calibrate only one fuel injector engine-set which is representative of production hardware on the ambient fuel bench from min to max expected transient fuel flows.
2) Calibrate the specific fuel injector engine-set that will be used for the transient testing during on-engine steady state testing (from idle to max power).
3) Extend the on-engine calibration curve relative to the bench calibration profiles to extremes that will be evident during transient testing.

In this recommended calibration procedure, production tolerances are accounted for by individual fuel injector unit calibrations done for on-engine steady state testing. Also, if the combustor outer annulus pressure instead of combustor primary pressure is measured, the on-engine calibration will account for the evident pressure loss (combustor primary to outer annulus). An example of application of this calibration procedure will be presented in Section 4.4.3.6.

When a single calibration curve is used for a dual fuel circuit system (primary + secondary), hysteresis in the flow divider valve can sometimes cause large uncertainties, especially in pressure regulated valves (see Figure 4.4-19). It may become necessary to develop two calibration curves, one for fuel increase (accel) and one for fuel decrease (decel). The hysteresis effects should always be determined by fuelbench calibrations because on-engine steady state calibrations may not experience the full effect of the hysteresis. This is especially true when steady state engine fuel control is closed loop with another engine parameter (spool speed for example). For closed loop control types, the fuel flow oscillates about a value which holds the specified engine parameter constant. Hysteresis effects will then be diminished at steady state on-engine calibrations (see Figure 4.4-20).

The hysteresis investigation is simple and demands only performing bench calibrations in both directions (incr asing fuel from min to max then decreasing from max to min as shown in Figure 4.4-19). When the on-engine steady state calibration is performed, the bench calibration curves must still be used but shifted such that the on-engine data are exactly centered (see Figure 4.4-20). Note that these calibration curves should only be used for either snap accel or snap decel transients. For transient testing where oscillations between fuel increases and fuel decreases are necessary (e.g. throtle reversal or turnaround), double hysteresis calibration curve usage may give incorrect results.

Because flow divider valve hysteresis is such a large contributor to the error in fuel injector measurement systems, dual calibration curves (one for primary and one for secondary) should be used if at all possible.

If fuel temperature compensation is necessary, the technique used is dependant on source of the temperature effect. If the fuel temperature effect is due only to tank temperature changes (in an altitude facility for example), temperature effects can be compensated by an independent steady state calibration at the given tank temperature before each actual transient is performed. Temperature compensation can also be in the form of a correction algorithm developed during bench calibrations as a function of fuel temperature. Of course, this scheme requires an additional instrument in the form of a fuel temperature probe. If the fuel temperature effect is due to fuel pump energy transfer or an in-line heat exchanger device, the compensation schemes can become more complicated. Because the energy transfer is time dependent (metal to fluid heat transfer time constant), steady state engine calibrations will not suffice for transient operation. Temperature compensation through actual fuel temperature measurement and use of a correction algorithm developed through bench calibrations may be the only solution.

Uncertainty Considerations

Uncertainty in the fuel injector measurement system may be reasonable when fuel temperature effects, flow divider valve hysteresis, and pressure measurement uncertainty are negligible. However, these effects should be fully analyzed and not simply ignored, especially the temperature effect errors as they can propagate to fuel physical property changes and thermal growth effects. Uncertainty due to fuel temperature effects can be minimized through compensation techniques which may require fuel temperature measurement.

Another important uncertainty consideration in the fuel injector flow measurement system is that fuel injector clogging may occur causing a shift in the calibration curve (higher flow at a given delta pressure). Fuel injector clogging can usually be compensated by frequent on-engine calibration of the fuel injector system.

Uncertainty due to the effect of different fuel usage (physical property effects) should also be accounted for. Different fuel types will have slightly different calibration curves . calibrations for specific fuel types can be ned. However, if the recommended calibration procedure is followed, on-engine calibrations will automatically compensate for fuel type effect.

A final uncertainty consideration is due to the sensitivity of the differential pressure to the fuel flow calibration curve. Fuel injectors will always be most sensitive at the low end of the calibration curve where the slope is steep. Pressure errors are greatly amplified in this region and operation in this region should be avoided if at all possible.

For the recommended calibration procedure, given that all the considerations mentioned above are examined, the fuel injector measurement accuracy can be as good as the turbine flowmeter.

4.4.3.6 *Design Example*

The design example presented involves a combination of a fuel bench calibration and an on-engine steady state calibration as described in the previous section. Fuel bench calibration is performed using a typical production fuel injector engine-set (see Figure 4.4-21). From this bench calibration, a characteristic calibration profile is developed (solid line). Note that no fuel flow divider hysteresis effects exist (flow regulated crack-point). Transient testing is to be performed on a specific engine, not necessarily using the same fuel injectors, but of similar specification. Steady state calibrations are performed and comparison made between the fuel injector delta pressure reading and a high accuracy turbine flowmeter with increments from idle to max power. The representative bench calibration curve is overlaid on top of the on-engine calibration and the shape is used to extend its range so that it can be applied during transient operation (see Figure 4.4-21). Shifts in the calibration curve due to production tolerances, combustor primary zone to outer annulus pressure loss, and fuel type are all automatically accounted for. Also, for this example, fuel temperature effects are determined to be insignificant.

This final calibration curve is then used to convert the transient fuel injector delta pressure measurement into actual fuel flow, given that high response transducer and close coupling guidelines are followed. An example of application of this system will be presented in the next section where fuel metering valve feedback measurements are compared to other measurement techniques during actual turbine engine transient testing.

4.4.4 Fuel Metering Valve Feedback

4.4.4.1 *Description*

There are a variety of fuel control schemes used in the turbine engine industry today. The type discussed in this section is that which closes the loop on fuel flow by use of a fuel metering valve feedback system. Fuel metering valve feedback can be accomplished by various methods including hydraulic, pneumatic, mechanical, and/or electrical means. The feedback system to be described is that which uses the linear or rotary variable differential transformer (LVDT or RVDT). The LVDT or RVDT, which converts valve stroke to voltage, is one of the most commonly used feedback systems because it integrates easily into the engine controller (Full Authority Digital Electronic Control--FADEC).

The typical fuel control unit (FCU) and engine controller arrangement are shown in functional form in Figure 4.4-22. The gear pump delivers the fuel flowrate at constant pressure maintained by a relief valve. The fuel flowrate is determined by the fuel flow command received from the analogue circuitry within the controller and commands a metering valve driver (torque motor in this example). Pressure drop across the metering valve is maintained by a pressure regulator. The fuel metering valve position is fed back into both the analog and digital part of the controller. Direct loop closure is usually handled by the analogue circuitry while the feedback into the digital software is for monitoring and/or control logic synthesis.

4.4.4.2 *Basic Theory*

FCU metering valves have a variety of designs including spool, flapper, jet pipe, slide, and plate. Descriptions of the various types of valves will not be made here. The technique for converting the movement (opening/closing) of these valves, measured by linear or rotational translation (stroke), to actual fuel flow units will be the subject of discussion.

The valve port shape defines the gain of the system as well as the stroke to flow area relationship. Square-shaped ports have constant stroke to flow area relationship while various curved shape ports have non-linear relationships. Logarithmic shaped ports (exponentially contoured) have constant gain resulting in constant percent error regardless of valve position. Conversion of stroke to flow area can be made by either geometric calculations or incorporated as table lookup in the controller digital software (see Figure 4.4-23).

Using Bernoulli's equation and the principle of conservation of mass, the mass flowrate is calculated by:

$$W = C_w A\sqrt{2\rho\Delta P} \qquad \text{(See also 4.4-11)}$$

If constant fuel temperature is assumed, the fuel density becomes a constant. Because of the pressure regulation scheme, the delta pressure also becomes a constant. The equation can then be reduced to:

$$W = CA \qquad 4.4\text{-}13$$

The value for C then includes the discharge coefficient effects, the delta pressure constant, and the fuel density constant. Since area is a direct function of stroke, the fuel flow can be correlated directly with stroke and can be determined through bench calibrations.

Discharge coefficients for orifices in incompressible flow are usually correlated with both Reynolds Number and Beta (ratio of orifice diameter to inlet flow diameter). If the flow conditions are constant (temperature and pressure), the only variables that will influence discharge coefficient are the valve dimensions. The discharge coefficient then correlates very well with valve area or stroke. The assumption of constant fuel flow temperature at the metering valve is not always reasonable as energy transfer from the fuel pump or in-line heat exchange devices will cause a fuel temperature rise over the range of fuel flows experienced. Fuel temperature effects must be investigated and accounted for if they prove significant. The flow calculation is somewhat insensitive to error in constant delta pressure regulation because of its square root influence. Other potential error sources in this calibration technique will be discussed in Section 4.4.4.5.

LVDT circuits are discussed in more detail in Section 4.5.3.2. Instead of converting separately from LVDT voltage to valve stroke, and then valve stroke to fuel flow, calibration curves usually involve a direct conversion (LVDT voltage to fuel flow as seen in Figure 4.4-24). Ideally the LVDT should be positioned such that zero volts is equivalent to zero flow but this is not absolutely necessary as zero offsets can be accounted for in the calibration curve (see Figure 4.4-24). The demodulator function is handled through electronic circuitry in the analogue portion of the controller (see Figure 4.4-22) but for monitoring purposes can also be handled in the digital portion.

The transient capabilities of the fuel control unit are usually very good. If the raw LVDT signal is used, no measurement lag exists except for insignificant lag/delays associated with frequency demodulation and signal transmission. The raw LVDT measurement is faster than the other fuel measurement systems presented (turbine flowmeter and fuel injector delta pressure). If the fuel flow signal is taken from the controller (development controllers can have output or recording capability) it may be slower due to the existence of sampling delays and signal filtering. This signal should still have excellent response because it must be fast enough to maintain and/or monitor closed loop control stability.

4.4.4.3 *Advantages and Disadvantages*

The major advantage of the FCU metering valve feedback measurement is that it is a built-in feature (for closed loop fuel controls only). Since it is always present, it is extremely useful for comparison purposes or as a secondary reading. Fuel metering valve feedback measurements have extremely fast response and are usually faster than the other fuel measurement systems presented (dependant on whether raw signal or post-controller signal is used with its built-in signal conditioning, as discussed previously). It then can be used to evaluate the response capability of available primary measurement systems during transient engine tests, for example, that of a turbine flowmeter. An example of this will be presented in Section 4.4.4.6.

The major disadvantage to the FCU metering valve measurement is that the typical data user cannot dictate accuracy requirement in its design. Engine control stability and accuracy requirements dictate the FCU metering valve feedback design. Because the control systems may be closed loop with engine speed measurement, accuracy of the FCU closed loop (fuel flow) may be of secondary importance. The result may be metering valve production tolerances and/or feedback system design with unacceptable fuel flow measurement accuracy for the data user. For these situations, acceptable accuracy may be gained if bench calibrations are conducted for a specific FCU to be used for engine transient tests. This calibration will eliminate the production tolerance influence. The reader is cautioned that this calibration may not be enough to bring the accuracy within their requirements as feedback system accuracy and fuel temperature effects may still be significant.

The two options of extracting the metering valve feedback (LVDT signal) each have their associated disadvantages. If LVDT signal is obtained from the engine controller, built-in input/output signal conditioning circuitry may be unacceptable or even unknown unless inquiries are made with the controller manufacturer. If pre-controller pickoff of the LVDT signal is made, these problems can be avoided but new ones might be introduced due to influences of the pick-off on the signal fed to the engine controller (noise, bias, etc.). Proper isolation must be exercised when this method is used.

4.4.4.4 *Signal Conditioning*

LVDT conditioning circuitry varies depending on application and specific engine controller requirements. LVDT conditioning circuitry generally has three distinct arrangements described as follows:

1) Conditioning circuitry, including demodulator, carrier frequency, DC amplifier, and filtering, is included in a hybrid microcircuit module as part of the LVDT.
2) Conditioning circuitry, including demodulator, carrier frequency, DC amplifier, and filtering, is included in the hybrid circuitry as part of the analogue portion of controller.
3) Conditioning circuitry including only carrier frequency, AC amplifier, and filtering is included in the hybrid circuitry of the analogue portion of the controller while the demodulation is handled in the digital portion.

LVDT signal conditioning may further include a buffer to establish isolation of the electronics from the environment insuring that shorts and open circuits within are detected and do not affect the operation of the conditioning circuitry. Filtering usually consists of a 2-pole Butterworth low pass filter. The filter's cutoff frequency is chosen to minimize passband ripple while maintaining adequate response.

As mentioned previously, there are two methods of obtaining the metering valve feedback. The first method is to extract the feedback from the controller and the second is to pick the signal from the LVDT directly. If the first method is used, inquiries as to the specifics of signal conditioning techniques from the FCU manufacturer are necessary. They may or may not be exactly as presented in the above paragraphs. If the second method is used, conditioning similar to that presented in the above paragraphs may be used but it is entirely dependent on data user needs.

4.4.4.5 *Calibration*

Calibration of the metering valve stroke or LVDT output to fuel flow is simple and may be performed by bench calibrations or provided by FCU manufacturer (see Figure 4.4-24). Because of production tolerance uncertainties, it is usually better to calibrate per specific FCU. The calibrations performed in a fuel bench involve flowing fuel at set intervals from min to max range and measuring the LVDT feedback signal. The driver control and feedback measurement of the FCU in the fuel bench calibration can be made by independently designed systems (torque motor current driver and LVDT demodulator) or preferably by use of the actual engine controller itself (FADEC). Use of the engine controller for calibration eliminates any signal drift/offset that may be built inherently into the controller/FCU combination. Calibrations are made at steady state fuel flow conditions thus allowing for use of high accuracy turbine flowmeters as the reference measurement system.

Fuel temperature variations over the range of fuel flow experienced as discussed previously may be significant (fuel pump or heat exchanger device energy transfer) even though the tank fuel temperature is constant (ambient conditions). Fuel temperature effects should be quantified during bench calibrations as they may prove to be significant causing unacceptable uncertainty during actual application. These effects include fuel density change and valve thermal growth. Temperature compensation techniques similar to those presented in Section 4.4.3 can be applied but require the inclusion of temperature measurement and correction algorithms. Fuel temperature can also affect the coil winding resistance in the LVDT or RVDT which in turn will affect the calibration. Correction for this effect is more thoroughly discussed in Section 4.5.3.

Calibration of the metering valve feedback can also be performed during actual steady state engine testing but is not recommended because full range fuel flow will not be possible. Accel and decel ranges will exceed that of the on engine steady state calibration, thus forcing extrapolations.

Uncertainty of the fuel flow feedback system is mostly influenced by the inaccuracies of the stroke to flow relationship. This relationship is affected mainly by production tolerances. LVDT measurement errors can also be significant. High accuracy LVDTs are available (.3% full stroke) but are extremely expensive and not standard on FCUs. Typical LVDT accuracies are on the order of 1% of stroke which, for a logarithmic valve, translates to approximately 2% of flow. A major influence on the system accuracy can also be fuel temperature effects experienced from storage tank temperature variations (altitude facility). For altitude facilities, where the fuel temperature can range from -55° to +180°C (-65 to 350°F), system errors can result in up to 4 percent in fuel flow if temperature compensation is not made. Temperature compensation is generally not applied in practice. For transient testing where fuel temperature remains at a relatively constant value (fuel tanks at ambient conditions for example), the uncertainty may not be significant but nevertheless should be investigated. Constant pressure regulation errors, as previously mentioned, are small (square root function of delta pressure in the fuel flow calculation) but also should be investigated.

The total metering valve feedback accuracy can usually be obtained from the FCU manufacturer. It is highly recommended that this accuracy be ascertained before the FCU metering valve feedback is considered as a fuel flow measurement system. As mentioned previously, the errors due to production tolerances can be eliminated by calibration of a specific FCU to be used for transient testing. The effectiveness of these calibrations in reducing measurement uncertainty should be considered before ruling out usage of a FCU feedback system with too high of an uncertainty.

4.4.4.6 *Design Example*

The FCU metering valve feedback is generally not used as a primary fuel flow measurement device because of the uncertainties due to production tolerances, LVDT accuracy, and stroke to flow calibrations. However, because of its extremely fast response, it can be very useful in assessing the transient response of other fuel flow measurement systems.

In this design example, two fuel flow measurement systems are transiently evaluated by comparison to the fuel flow signal from the FCU metering valve feedback. The two fuel measurement systems are a low inertia turbine fuel flow meter and a fuel injector measurement system. Figure 4.4-25 presents the comparison of the three traces for a typical engine deceleration. From this plot it can be seen that the fuel injector measurement (unfiltered) and the FCU metering valve feedback measurement are very similar in response. The magnitude difference is also very small and possibly within accuracy requirements. The turbine fuel flow meter trace, however, does not show as quick a response since it has a slight lag. Its transient measurement capability will be limited depending on application.

For this application the FCU metering valve feedback measurement provided valuable information in assessing the transient measurement capabilities of the other fuel flow measurement systems. In this example, the FCU metering valve feedback also showed good agreement based on magnitude comparisons. It is important to note that the feedback system presented here had more stringent accuracy requirements than the typical FCU system and that magnitude comparison in general will not likely be as good on other FCU designs.

A final comment on FCU feedback systems - with its evolution and the increased importance of engine monitoring capabilities, the accuracy of the FCU feedback systems should improve and become a viable option for many transient test applications.

4.4.5 Venturis and Flow Nozzles

4.4.5.1 *Description*

Transient engine inlet airflow measurement, though difficult to achieve, is one of the most important parameters to be measured for engine performance and stability limit investigations. Many technical papers and handbooks have been written that describe the use of venturis and flow nozzles and define standards for steady state engine testing (ISO and ASME are well recognized). This is not true for their use as transient measurement systems, as very limited information and no standards exist. There is however one technical report written by AEDC (Reference 4.4.9) which does investigate the performance of venturis (sonic and subsonic) and a flow nozzle (or bellmouth) using an airflow simulator with known uncertainty. This report defines a standard for which transient airflow measurements in engine inlets can be judged. A majority of the recommendations given here for transient flow measurement using venturis and nozzles are based directly on the findings of this report. It is strongly recommended that this report be reviewed before an engine inlet transient airflow measurement system is designed.

The most important point made by this report is that the determination of transient airflow is possible by the assumption that the airflow is quasi-steady state. This statement is true only if the system is properly designed. That is, high response temperature and pressure measurement system design guidelines are maintained and rigorous calibration procedures are followed. Preferred transducers for pressure measurements are piezoresistive close-coupled type, and for temperature, thin wire design with time corrections applied. This report recommends pressure and temperature responses to be an order of magnitude greater than which is desired for final calculated airflow. The transient response and calibration requirements will be further discussed in the following sections.

4.4.5.2 *Basic Theory*

Airflow measurement by use of venturis and nozzles are inferential calculations which involve primary measured values of venturi or nozzle inlet pressure, inlet temperature, throat pressure, wall temperature, wet bulb temperature, dry bulb temperature, upstream diameter, and throat diameter. The ASME and, more recently, ISO have been the authorities on the proper use of flowmeters (References 4.4.10 and 11). The ASME handbook, for example, provides all the necessary equations and guidelines for the calculation of airflow using nozzles and venturis. Table 4.4-2 presents all of the equations necessary to calculate airflow from primary measured parameters with exact reference to location (figure, equation, or table number) in Reference 4.4.10. Also presented in Table 4.4-2 are alternate references which contain the same information or variations based on specific applications.

Subsonic Venturis and Flow Nozzles

Figure 4.4-26 presents a schematic of a typical venturi and nozzle with measuring stations identified.

The most commonly used venturis are the classical (or Herschel) venturi tube and the venturi nozzle. The venturi tube is mostly used in North America while the venturi nozzle is preferred in Europe. The venturi nozzle has an advantage over the venturi tube in that it is of much shorter design resulting in less cost due to storage and installation.

The most commonly used systems of flow nozzle measurement, which are also distinguished by their usage in either North America and Europe, are the ASME long-radius flow nozzle and the ISA 1932 nozzle. The advantage that the nozzle has over the venturi is its shorter overall length and lower cost. The nozzle does also share the advantage of lower pressure loss that the venturi has with respect to orifices, but is not quite as good as the venturi. (Reference 4.4.1 shows overall pressure losses for the venturi on the order of 20 to 50 % lower than the nozzle). Discharge coefficients are also much more complex for the nozzle than for the venturi, as detailed by the references noted in Table 4.4-2. It is not the intent of this report to fully describe the design considerations for the flow nozzles and venturis as they are already detailed sufficiently in the references (sections II-III-20 through II-III-48 in Reference 4.4.10, for example, details guidelines for flow nozzles and venturi tubes). The references detail fabrication guidelines which include material selection, nozzle form, pressure tap configurations, pressure loss calculation, and airflow calculation. The venturis and nozzles do share the same basic equation for calculation of airflow as shown by Table 4.4-2.

Sonic Venturis

Figure 4.4-26 also presents a schematic of a sonic venturi with measuring stations identified. The sonic venturi is sometimes called the critical-flow venturi by the fact that, ideally, it should operate at critical flow conditions (choked).

The advantage of the sonic venturi is that when it operates at its critical pressure ratio, the flow is a function of upstream conditions only. Critical flow venturis, when choked, result in a very accurate flow calculation and, therefore, sonic venturis are sometimes used as primary standards when calibrating other airflow measurement devices. The sonic flowmeter does require measurement of upstream total pressure, therefore approach velocity corrections must be made if wall static pressure measurements are used. Sonic flowmeters have definite disadvantages when considering transients over the full operating range and are related to the difficulty in maintaining choke flow and exit flow conditioning requirements. These subjects will be discussed further in Section 4.4.5.3.

Reference 4.4.10 provides the equations for calculating airflow from sonic nozzles (see Table 4.4-2) but Reference 4.4.12 is preferred because of its thoroughness and the additional information provided for calculating discharge coefficient.

When the sonic venturi becomes unchoked the calculation of flow is identical to that of the subsonic venturi and flow nozzles as provided in Table 4.4-2.

Discharge Coefficient

The discharge coefficient can be determined by one of three methods:

1) Discharge coefficients can be determined by matching fabrication guidelines and using empirically developed values (see References 4.4.10 and 4.4.11 for example). Fabrication guidelines include nozzle/venturi dimensions, instrument location, probe design, fabrication materials, and flow conditioning. The requirement for no external work by the fluid and no heat transfer between fluid and pipe must also be met.
2) Discharge coefficients can be determined by using theoretically developed relationships (References 4.4.12, 13,14, 15, and 16). The real flow process must be consistent with the assumptions that go along with the theoretical relationships and usually include two-dimensional, adiabatic, and undisturbed flow.
3) Discharge coefficients can be determined by calibration. Most common calibration procedures involve comparison with a critical flow standard. Other methods include calibration by use of traversing measurement systems or by liquid calibration. These calibration procedures will be further described in Section 4.4.5.4.

The advantages of determining discharge coefficients either by meeting fabrication guidelines or by calculations using theoretically derived relationships are reduced cost and development time. Obviously, meeting fabrication guidelines offers the highest accuracy, but theoretically derived discharge coefficients can achieve accuracies on the order of ± 0.1 percent within that determined by calibration (Reference 4.4.9).

Transient Relationships

Before a transient airflow measurement can be realized, special care must be taken to ensure responsive primary measurement systems. Pressure and temperature frequency response relationships are covered in other sections (4.2 and 4.3). It is essential that the highest response measurement systems be used (miniature piezoresistive transducers and thin-wire thermocouples, for example) and guidelines be maintained for close-coupling and filtering to ensure adequate response. The requirements for high response temperature may be relaxed if engine <u>inlet</u> airflow is the measurand (versus interstage).

As mentioned previously, an AEDC report (Reference 4.4.9) presents a comparison of several inlet airflow measurement systems and evaluates their effectiveness with regard to given transient measurement accuracy requirements. These systems will be described further in the following sections.

Reference 4.4.9 states that determination of transient airflow is possible by the assumption that the airflow is quasi-steady state. This report points out that this assumption is justified for pressure measurement because pressure waves travel at acoustic speeds which are much greater than the pressure time transients encountered. Air temperature transients are controlled by heat transfer processes which require much longer times to reach equilibrium. However, engine testing is generally for constant air temperatures which have transients of less than 1 to 2%/sec. With time correction applied, temperature measurement can be realized as quasi-steady state with minimum uncertainty relative to steady state. Measured wall or skin temperatures are of course quasi-steady state by the fact that metal temperature gradients are usually an order of magnitude slower than the air temperature gradient and thus do not require time correction.

If flows are evaluated that do have larger temperature or pressure gradients than normal in short time periods, time correction and its uncertainty must be added to total uncertainty. Uncertainty requirements will be difficult to meet for these cases.

A final time correction that must be discussed is the volumetric dynamic correction which is usually necessary when the measurement system requires exit flow conditioning (sonic nozzle, for example, Reference 4.4.9). This correction requires additional probes at the engine face for static pressure and total temperature. This dynamic flow correction is calculated is by:

$$\Delta W = \frac{V_i}{R\,T2^2}\left[T2\,\frac{\Delta PS2}{\Delta t} - PS2\,\frac{\Delta T2}{\Delta t}\right] \qquad 4.4\text{-}14$$

where V_i = volume between measurement device and engine inlet

2 = engine inlet face location

All other notation is consistent with that described in the nomenclature list.

4.4.5.3 *Advantages and Disadvantages*

The assessments made in this section on sonic venturis, flow nozzles, and subsonic venturis are based on information from Reference 4.4.9.

Flow Nozzles (Bellmouths)

Flow nozzles offer low pressure drop characteristics and do not limit flow capability (choking/flow throttling) which is extremely important during transient testing. The subsonic venturi may offer slightly better pressure drop characteristics but the flow nozzle is cheaper to fabricate and maintain by its inherently short design.

The nozzle has drawbacks when uncertainty considerations are important. Though it may be acceptable for measurement in high Mach number conditions (>0.25), the uncertainty can become relatively high because of airflow calculation sensitivity to pressure error at low Mach numbers. This uncertainty can be reduced by maintaining rigorous calibration procedures which include frequent and online calibrations which will be discussed in section 4.4.5.5. Still, the low Mach number uncertainties are high relative to the subsonic venturi. Reference 4.4.9 shows that uncertainty levels of 1 percent are obtainable for engine face flow Mach numbers greater than 0.25 to 0.3 but on the order of 4 to 8 percent for lower Mach numbers.

Sonic/Critical Flow Venturi

The sonic venturi is simple, durable, and requires minimum maintenance. Sonic venturis have always been highly regarded for their steady state flow measurement accuracy.

However, sonic venturis have major drawbacks when used as transient airflow measurement systems. A major disadvantage is their inability to operate at critical flow levels for transients from idle to max power. The sonic venturi must be operated unchoked if it is to realize the full range. If it doesn't, it acts as a flow throttling system, which results in reduced flow control for simulation of transient engine operation. Once the sonic venturi operates unchoked it is identical to and no-better than the subsonic venturi. Wall contours designs for the sonic venturi are not optimum for subcritical operation, but effects can be overcome by calibration at subcritical operation. The sonic venturi has an additional drawback in that it requires exit flow conditioning which puts the measurement system far away from the engine inlet face. Dynamic flow corrections are then necessary. The transient flow calculation then requires additional measurement of engine inlet face temperature and pressure for the dynamic flow calculation which adds to the total uncertainty relative to that of a subsonic nozzle. Reference 4.4.9 shows that uncertainty levels are obtainable from 1 to 2 percent.

Subsonic Venturi

A subsonic venturi has the advantage similar to the bellmouth in that it has low pressure drop characteristics and does not limit flow control. Additionally, it has a reduced flow area resulting in higher Mach number at the measurement plane and thus lower uncertainty due to low sensitivity to pressure measurement accuracy. Also, because of the increased Mach number, the flow coefficient range is small (between .99 and unity) resulting in reduced uncertainty when theoretically calculated flow coefficients are used (Figure 4.4-27). This is possible only if flow conditioning guidelines are met (Reference 4.4.10 and 4.4.11). A definite advantage over the sonic venturi, as mentioned previously, is that exit flow conditioning requirements are reduced, thus close-coupling with the engine inlet and avoiding flow dynamic corrections.

A disadvantage is the cost which is related to the long length of the measurement system (materials and installation costs). Another disadvantage is that the flow contours must be evaluated (inlet, throat, exit); if fabrication guidelines are adhered to, this disadvantage is minimal.

The subsonic venturi is the system of choice for airflow measurement because of its low uncertainties. Reference 4.4.9 demonstrate that uncertainty levels of 0.7 to 1.0 percent are obtainable for engine face flow Mach number variations of 0.15 to 0.5, respectively.

4.4.5.4 *Signal Conditioning*

Airflow determination using venturis and flow nozzles is inferential and involves measured primary parameters of air pressure, air temperature, and metal temperature. Signal conditioning for these parameter measurements are covered in Sections 4.2 and 4.3.

Of primary concern in airflow measurement is the phase relationship of the primary measured parameters involved and its effect on inferential flow calculation. Phase relationships between measured parameters are affected by both the aerodynamic design and the associated signal conditioning/recording equipment. It is the intention of this discussion to address only the aerodynamic concerns (recording system concerns are addressed in Section 4.9). The phase relationships can be handled by either of two methods.

The first methods assumes that no phase correction is necessary because the primary measurements are designed or deemed fast enough that the phase effect is negligible. This is a definite possibility when considering inlet/throat static pressure measurement systems that are of close-coupled design, and temperature measurement where gradients experienced are slow. This is generally the case for engine inlet airflow measurement.

The second method involves designing the system such that primary measurements have the same phase. An example is by matching pressure line volumes which is discussed in Reference 4.4.9.

4.4.5.5 *Calibration*

Uncertainty requirements are often difficult to meet for steady-state processes, and even more so for transients. Rigorous calibration procedures are critical and must be maintained to keep the uncertainty levels reasonable.

Discharge Coefficient Calibration

Calibration of venturi or nozzle discharge coefficients can be accomplished by either of three methods (Reference 4.4.13). That is by comparison to a standard flowmeter where the discharge coefficient is known, by traversing the meter throat with a pitot static probe to define the flow profile, or by translation of the flow measured for a known volume of liquid to that of a compressible fluid by dynamic similarity.

When calibration by comparison to a standard flowmeter technique is used, the sonic or critical flowmeter is the most popular, because of its reduced uncertainty levels. Reference 4.4.2 provides the necessary criteria for critical flowmeter installation and airflow calculation. Reference 4.4.2 also presents an example and guidelines for calculating the discharge coefficient uncertainty of an independent flowmeter.

If the discharge coefficient is determined by the traverse method, guidelines are given in Reference 4.4.2 for traverse system radial and circumferential positioning (see Figure 4.4-28) as well as for the discharge coefficient uncertainty calculation.

The method of calibration by liquid flow is also detailed in Reference 4.4.2. Reference 4.4.2 cautions that published data on expansion factors must be used, with the associated errors which will be reflected in the discharge coefficient. Also, an appeal to dynamic similarity through the Reynolds analogy is required, and quantitative assessment of the uncertainty of the similarity is unavoidable.

Pressure Calibration

Pressure calibration guidelines are provided in Section 4.2. Additional pressure calibration guidelines, relative to flow calculation, are available in Reference 4.4.9 which is briefly summarized:

- o The airflow measurement system uncertainty was greatly reduced by frequent online calibrations. Absolute pressure transducers were calibrated by applying the full range of expected pressures and matched to a pressure-measuring device calibrated in a Standards Laboratory. This calibration was performed at 15 minute intervals. The online calibrations were performed to compensate for transducer drift and to limit bias between the different transducers.

- o Differential transducers were initially used to determine venturi or flow nozzle delta pressures. But because of unacceptable accuracy due to nonrepeatability and signal drift, the differential transducers were used as low-range absolute transducers. This was accomplished by connecting one side of the transducer to a constant reference pressure system (similar to the ZOC system described in Section 4.2). This system was also calibrated at short time intervals.
- o The pressure response characteristics were estimated by the method as described in Section 4.2. The frequency response was then verified by experimental means using the proposed plumbing for the close-coupled pressure transducer system and a pressure pulse generator. The results did not agree with the calculated and this was attributed to mass-transfer lag or capacitance influences neglected in the calculated values. Precise response characteristics of a given pressure system are difficult to predict analytically and should always be backed up with experimental evaluation.

Temperature Calibration

Temperature calibration guidelines are presented in Section 4.3. Reference 4.4.9 also presents an example of calibration procedures where frequent and online calibrations were performed using known millivolt levels as input. The corresponding temperature equivalents were obtained from reference tables from the national standards organization. Temperature time corrections were also applied as detailed in Section 4.3.

Inferential Airflow Uncertainty Calculation

Airflow uncertainty calculations during steady state are provided in Reference 4.4.17. Transient uncertainty calculation guidelines are provided in Section 3.6 and involve the combination of the steady state and transient uncertainties as shown in Figure 3-7.

Reference 4.4.9 presents uncertainty evaluation by comparison to an airflow simulator which has a calculated uncertainty of 0.5 percent at max flow and 1.0 percent at min flows. The airflow simulator consist of a bullet-nose, support struts, translating plug, and two outer shroud assemblies for two different flow ranges. The simulator is calibrated by correlating plug position with air flowrate using a sonic venturi. The subsonic venturi uncertainty which is the system of choice for transient engine inlet airflow measurement is demonstrated by comparison to the airflow simulator values (see Figure 4.4-29).

4.4.5.6 *Design Example*

A detailed design example will not be presented formally, instead the reader is referred to Reference 4.4.9 where details on the development and evaluation of several types of inlet airflow measurement systems are available. The system of choice (one with lowest uncertainty) was the subsonic flowmeter. Its design is briefly summarized.

The direct-connected subsonic venturi design was that of the ASME low beta inlet wall contour design including short cylindrical throat, a conical diffuser, and inlet/exit flow-straightener section (see Figure 4.4-30). Subsonic venturi sizing procedure, inlet flow-conditioning requirements, and exit flow-conditioning requirements are presented in detail in the Appendices of Reference 4.4.9. Venturi instrumentation includes eight close-coupled wall static pressure probes (to evaluate stagnation pressure at engine plenum), six-probe total temperature rakes (to evaluate stagnation temperature at engine plenum), eight close-coupled wall static pressure probes (to evaluate throat Mach number), and two wall surface temperature probes (to evaluate thermal changes in the throat flow area).

Calibrations were performed frequently for temperature and pressure using on-line calibration procedures as previously described. Both experimental and theoretically derived flow coefficients were used to calculated airflow with references noted. Airflow calculation can be made using equations presented in Table 4.4-2. Results show that the subsonic venturi system uncertainty approached that of the airflow simulator (see Figure 4.4-29).

4.4.6 Fore-Aft Probes

4.4.6.1 *Description*

Venturi and nozzle airflow measurement systems described in Section 4.4.5, although having the advantage of low uncertainty, have one major disadvantage. Nozzles and venturis cannot be used for internal engine airflow measurements. A uniquely designed probe which allows for compressor inlet/exit Mach number and airflow measurement is the fore-aft probe. This probe is sometimes called a Mach probe or airflow rake.

References 4.4.18 and 19 present examples of the fore-aft probe usage for post-stall compressor characteristic investigations. Reference 4.4.18 gives specific details on a fore-aft probe design, signal conditioning, and calibration. The examples referenced are for rig testing but the fore-aft probes can be used for full engine testing as long as access ports are available to accommodate the probe configuration and the calibration guidelines are satisfied. The fore-aft probe examples referenced are specialized for compressor section measurements, but, in principle, the usage of fore-aft probes may be applicable to hot section (turbines) if probe internal cooling schemes are adequate. However, no literature is currently available on their usage in turbine engine hot sections. The focus of this section will then be on their use in investigations of fan/compressor transient performance, surge, stall, rotating stall, and recovery investigations where measurement of forward and reverse flow is important.

Figure 4.4-31 presents a schematic of the fore-aft probe showing internal placement of the primary measuring devices of miniature piezoresistive pressure transducers and a thin-wire aspirated thermocouple. This fore-aft probe includes a maximum of 25.4 mm (1 inch) of feed tubing to the in-line miniature transducers. Frequency response capability of a fore-aft probe is mainly dependent on the particular transducer chosen and feed tube geometry. The frequency response for fore-aft probes are well known and can be on the order of 5 kHz. The transducers presented in Reference 4.4.18 are on the order of 100 to 400 kHz frequency response, but with the added dynamics of the feed tube, are reduced to approximately 400 Hz. The fore-aft probe design includes cooling fluid circulation (for example common tap water) to eliminate thermal drift of the transducers. The probe also includes adjacent fore-aft steady state measurement paths for remotely located transducers that are used for calibration purposes. Reference 4.4.18 describes an alternate scheme where the high response transducers allow for a leakage path for steady state pressure measurement and calibration.

Aerodynamic design considerations are important since the fore-aft probe is an intrusive probe. Flow disturbances presented by the probe in the flowpath must be minimized wherever possible.

4.4.6.2 *Basic Theory*

Mach number and airflow are inferentially calculated using primary measurements of gas path total pressure, static pressure, and temperature.

Mach number can be calculated by the relationship:

$$Ma_{calc} = \left[\frac{2}{\gamma-1}\left[\left(\frac{P_T}{P_S}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right]^{0.5} \qquad 4.4\text{-}15$$

For Mach numbers less than 0.5 this equation can be reduced to (by Maclaurin series expansion and elimination of higher order terms):

$$Ma_{calc} = \sqrt{\frac{2}{\gamma}\,\frac{P_T - P_S}{P_T}} \qquad 4.4\text{-}16$$

This equation then shows a linear relationship with $\sqrt{\frac{dP}{P}}$ if γ is assumed to be constant.

As the aft pressure measurement is not truly a static pressure but a wake pressure, the Mach number must be corrected. This Mach number effect must be determined by wind tunnel calibrations. The method as presented by Reference 4.4.18 is to apply the correction as a simple slope offset adjustment.

$$Ma_{true} = a\,Ma_{calc} + b \qquad 4.4\text{-}17$$

This method corrects for temperature and pressure recovery by adjustment to the calculated Mach number.

Yaw angle effects on measured Mach number must also be investigated during wind tunnel testing. Fore-aft probes are designed such that the variation in total pressure recovery is insignificant within the expected flow angle variation (see Figure 4.4-32).

Corrected airflow can then be calculated by the relationship:

$$Wcor = \frac{A}{P_t}\sqrt{\frac{T_t\gamma}{R}}\;\frac{Ma_{true}}{1+\frac{\gamma-1}{2}Ma_{true}^2}\;\frac{\gamma+1}{2}(\gamma-1) \qquad 4.4\text{-}18$$

From this, local airflow can then be calculated by

$$\text{Wabs} = \text{Wcor}\ \frac{P_T}{P_t}\sqrt{\frac{T_t}{T_T}} \qquad 4.4\text{-}19$$

Average airflow is determined by calibration, where several methods are available and will be presented in Section 4.4.6.5.

Corrections for temperature and pressure readings are presented in Sections 4.2 and 4.3 respectively, including lags due to feed tube volume and wire diameter. References 4.4.18 and 19 present examples where pressure and temperature measurements are designed such that no lag corrections are necessary (fast enough).

For reverse flow measurement during surge and stall testing, the equations are the same but the forward and aft readings are reversed. Flow direction sensing is obvious as flow travels in direction from higher pressure (stagnation) to lower pressure (wake).

4.4.6.3 *Advantages and Disadvantages*

The major advantage of the fore-aft probe as mentioned previously is that it can be used for inter-engine airflow measurement, specifically inlet or exit fan/compressor flow. The fore-aft probe is considerably less expensive to fabricate, develop, and install as compared to the venturi and nozzle measurement ystems. Because of its specialized design, it can measure either forward or reverse flow which makes it ideal for surge and stall investigations. Because of the simplistic design and the thorough understanding of the equations used to calculate Mach number and flow, the fore-aft probe is currently the "best practice" for measurement of full engine fan/compressor transient airflows. As the thermal and laser anemometry measurement systems evolve (covered in Section 4.4.7) this statement may no longer be true because of the unavoidable disadvantages of fore-aft probes.

The major disadvantage of the Mach probe is that it is an intrusive probe and may create flow disturbances which affect the overall flow profile and the measurement process itself. The fore-aft probe is not a true airflow measurement system, as it is inferential requiring primary parameter measurements of total pressure, wake pressure, and temperature. The probe actually measures only local airflow and must be calibrated against a reference measurement system to obtain average Mach number and airflow readings. Larger uncertainties than that of the venturi and nozzle measurement systems described in Section 4.4.5 should be expected for full engine measurements using the Mach probe because of limitations on the number of probes that typically can be installed. Access to the flow profile may be difficult depending on the engine configuration, size, and placement of the probes. As is the case for any intrusive measurement system, recovery effects must be considered and investigated through wind-tunnel testing. Finally, the flow angles may vary at different engine locations and should be considered in the probe design.

It must be realized that, in many cases, the achievable uncertainty for the fore-aft probe measurement system may be so large that the test results can be viewed only on a qualitative rather than quantitative basis. This may be acceptable for specific applications. Examples would include investigations involving location of surge relative to other engine parameters (rotor speed or fuel flow) or in investigations of the surge recovery capability.

4.4.6.4 *Signal Conditioning*

The measurement of airflow using the fore-aft probe, as mentioned previously, is inferential involving primary parameters of total pressure, wake pressure, and temperature. Signal conditioning for these parameters is covered in Sections 4.2 and 4.3.

As is also the case for venturi and nozzle measurement systems, the phase relationship between the primary measured parameters involved is of concern. As discussed in Section 4.4.5.4, there are two ways to handle the phase relationships. The first is to design the system such that no phase correction is necessary (fast enough). The second is to match the individual parameter response such that no phase difference exists (pressure line matching).

Reference 4.4.18 presents an example where the fore-alt measurement system is designed fast-enough such that phase relationships are not of concern. This is generally the case, as very high-response transducers (miniature piezoresistive) are employed with very close coupling (25 mm (1 inch) or less feed tubing). In this arrangement, transient fan/compressor flows during snap transients and surge are of lower frequencies relative to the response of the fore-aft probe. However, when higher frequency events (i.e., rotating stall effects such as flow separation) are to be considered, the phase relationships of the primary parameters are important and should be investigated.

Correcting for phase relationships, or the matching of response by pressure line sizing, becomes difficult when high frequencies are of interest. Phase shifts can occur because of a multitude of factors including feed tube dynamics, transducer dynamics, filtering, and digital sampling. It may be more feasible in most situations to determine phase relationships from full system calibrations.

Pressure Signal versus Calculated Airflow Filtering

It sometimes becomes necessary to filter out very high-frequency events from the lower frequency events of interest. Reference 4.4.18 presents an example where the air flowrates during surges are of interest but flow disturbances caused by rotating stall cells are not. Distortion of the data from the rotating stalls is evident and interferes with data analysis and interpretation. It then becomes necessary to filter out the high frequency pressure fluctuations. Reference 4.4.18 has assessed filtering by two methods: filtering of the individual pressure signals themselves or filtering of the calculated airflow. The filtering system employed were 3rd and 5th order Butterworth filters with 47.7 Hz cutoff frequency. The results showed that some low frequency amplitude was lost when using the calculated airflow filtering scheme and was attributed to the non-linearity of the flow calculation itself. For this particular study, it was recommended that filtering be performed on the raw primary signals for the fore-aft probe measurement systems. Determination of whether to filter the raw data or the calculated results is generally dependent on the application and how the results are going to be used.

4.4.6.5 *Calibration*

Uncertainty requirements are difficult to meet for any transient airflow measurement system. Rigorous calibration procedures are critical and must be maintained to keep the uncertainty levels reasonable.

One of the drawbacks of the fore-aft probe as mentioned previously is that it measures only local airflow. Calibration with a reference system must be performed in order to determine average airflow. The calibrations may be performed on a rig if the inlet configuration and boundary layer growth effects are the same as that in an actual full engine installation (effective area). If the measurement is to be performed on a rig, the calibration can be performed on-line with an orifice, venturi, nozzle, or traverse system. However, full engine calibrations are preferred (effective areas from rig to engine are usually difficult to resolve), and may be performed using steady state traverse or fully instrumented (circumferential and radial) flow measurement systems. On-engine steady state calibrations may be impossible. If rig calibrations are not acceptable, calibrations must be performed in conjunction with full engine thermodynamic performance models.

The correction from local to total airflow can be performed by various techniques. Reference 4.4.18 employs a technique where the high-response total pressure probes are biased to match the more-accurate steady state pressure probes (pressure taken from identical location from fore-aft probe). The wake pressures are then biased such that the calculated airflow matches the total airflow which is measured by an upstream venturi. This technique, of course, can only be performed on rig testing where inclusion of the upstream venturi is possible. In Reference 4.4.18, calibration is performed for steady state operation only but could be applied for transients if a high response venturi measurement system as presented in Section 4.4.5 was included.

For full engine testing, a correlation must be developed (rig or on-engine as discussed previously) and applied to the local Mach number to obtain the average airflow. Figure 4.4-33 shows an example of local Mach number to average airflow correlation.

Multiple immersion fore-aft probes are always an advantage and should be employed whenever possible as averaging will decrease uncertainty. Reference 4.4.18 presents examples of multi-immersion probes at both inlet and exit of a compressor.

Pressure Calibration

Pressure calibration guidelines are provided in Section 4.2. The method most common to the fore-aft measurement systems is that using differential pressure transducers. This system, as discussed previously in Section 4.4.5.5, improves accuracy of the pressure measurement by introducing a constant, accurately measured pressure to the reference side of the transducers. Its advantage is that it allows for on-line and frequent calibrations.

Reference 4.4.18 presents a ZOC (zero, operate, and calibrate) system. The zero mode is used to couple each side of the transducer to force zero output so that zero shift and electrical bias can be determined. The calibrate mode involves applying a known pressure to the reference side and is used to determine any changes in transducer sensitivity during the testing, for example, for thermal sensitivity. The operate mode is that used for actual transient test measurement. The ZOC system is described in more detail in Section 4.2.2.3.3 of this report.

A final calibration performed during steady state operation is by comparison to the high accuracy steady state remotely mounted transducers. As mentioned previously, these measurements are made using an adjacent or leak airpath included in the fore-aft probe design.

Temperature Calibration
Temperature calibration and time correction guidelines are presented in Section 4.3. Reference 4.4.18 presents an example where time correction was not necessary because of the adequate response of the probe relative to the test events to be investigated.
Probe Cooling Effects Investigation
The transducers mounted inside the fore-aft probe must be maintained at temperatures within those limits specified by the manufacturer. Cooling effectiveness must be investigated through some sort of bench calibration arrangement (oven for example). Figure 4.4-34 presents typical results of this type of investigation.
Uncertainty Calculation
Transient uncertainty calculation guidelines are provide in Section 3.6 and involve the combination of the steady state and transient uncertainties as shown in Figure 3-7. Overall uncertainty estimates are not provided in References 4.4.18 and 19, but are expected to be similar to those presented for venturis and nozzles in Section 4.4.5. However, if fore-aft probe measurement is used in full engine testing, the uncertainty is certain to be higher. This is because a high accuracy reference system (orifice, venturi, or nozzle) for calibration cannot be included on full engine testing and the usage of rig calibrations is generally inaccurate as discussed previously.

4.4.6.6 *Design Example*
Design examples for usage of a fore-aft probe are provided in References 4.4.18 and 4.4.19. The probes described were specifically developed for the flowpaths of the compressors being investigated. These systems are briefly described. It is recommended that the reader acquire these reports if more information is required.

Reference 4.4.18 testing included two probes at the inlet and exit of the compressor to measure the hub and tip airflows. The transducers at the inlet have a range of ±207 kPa (30 psi) and frequency response of 275 KHz. The transducers at the exit have a range of ±414 kPa (60 psi) and frequency response of 275 KHz. The thermocouples were of type E (chromel-constantan) for both inlet and exit rakes. The probes included leakage pressure paths for remote steady state calibration of each high response transducer. Calibration of airflow (local to average) was performed steady state using an upstream venturi.

Reference 4.4.19 presents a similar setup in that two fore-aft probes each at inlet and exit are included. Detail probe design information is not provided for the fore-aft probe used in Reference 4.4.19. The probe does include a separate but adjacent tubing for a remote steady state pressure measurement to be used for pressure calibration. The local to average flowpath calibration is performed using an upstream orifice.

General recommendations for the design of the fore-aft probes are difficult because they are highly dependent on the various flow profiles (normal/surge) of a specific compressor or fan. In general, a background in fluid mechanics, internal flows, and boundary layer theory is necessary to decide what pressures are to be measured. It is the responsibility of the end user of the data to determine how to sense various flow regimes and to decide on location using their understanding of the flow and the analysis techniques to be employed.

4.4.7 Airflow Determination Using Engine Models
4.4.7.1 *Description*
Transient airflow measurement systems, as stated repeatedly in this section, are complex and take considerable time to set up relative to transient temperature, pressure, and fuel flow measurement systems. The cost and time for development of these airflow systems are frequently beyond that available for most testing. It may also be very difficult or impossible to gain access to an adequate airflow measurement location. This is especially true for the engine certifier and aircraft users. It then becomes necessary to use an indirect approach for determining airflow. This approach involves the use of a thermodynamic engine model complete with component maps, bleed circuitry, power loading, and transient algorithms.

Once an adequate model is acquired, the determination of a particular station airflow is achieved by matching it to a single measurement which determines engine power with time. In some cases multiple measured parameters may be necessary depending on the degrees of freedom of the engine control. For example, an engine with fuel flow and compressor guide vane control will require an engine model match to two parameters.

4.4.7.2 *Basic Theory*
The thermodynamic model consists of component maps usually defined through rig testing (see Figure 4.4-35). These component maps are good only for steady state operation and do not account for transient effects. The transient effects which must also be included in the model are clearance effects (due to thermal growth,

pressure deflection, and inertial growth), component metal heat storage effects, and volume dynamics (mass storage). Algorithms that simulate these effects are documented by various methods (References 4.4.20, 21, and 22). These algorithms are usually analytical in nature but can be calibrated through actual engine or rig testing. These calibrations involve measurement systems for tip clearances, metal temperatures, air temperatures, and pressures which are all described in other sections of this document.

Determination of a specific engine location airflow is performed by matching the transient model to an available measured parameter which determines engine power level with time. The most commonly used being pressure, fuel flow, and/or spool speeds. The extent of the model is dependent on the specific measurement to be matched and the location of the airflow of interest. For example, if compressor airflow is desired and compressor pressure ratio and speed are measured, only a compressor model is necessary. This compressor model could be as simple as a compressor map, defined by compressor rig testing, and associated transient algorithms for clearance, mass storage, and heat storage effects (such effects are usually translated to component map scalars). However, if other measurements are to be used, for example fuel flow or engine spool speed, a full thermodynamic engine model will be required. This full engine model must, of course, include all engine component maps (compressor, inlet, burner, turbine, nozzle, etc.) with their associated bleed circuitry, power connections/extractions, and transient algorithms.

4.4.7.3 *Advantages and Disadvantages*

As mentioned previously, the main advantage of using this airflow measurement process is that it is less costly and generally less time consuming than alternatives. This statement is true only if the appropriate model is available. The provided model may require the transient algorithms, as specified above, depending on their significance.

This measurement technique also provides the engine certifier and aircraft user a means for determining station airflows where access on a production engine may be difficult or even impossible.

Another major advantage is that this airflow measurement technique can be applied given a multitude of instrumentation arrangements, as long as the particular measurements used will determine engine power with time (spool speeds, fuel flows, component pressures, etc.).

The disadvantage of this measurement process is that it usually results in higher uncertainty than those systems which directly measure station airflows. The thermodynamic model used may consist of purely analytical transient algorithms or may be more rigorously defined through actual engine/rig calibrations depending on the stage of the engine development. The model with purely analytical transient algorithms will of course have the highest uncertainty, but in either case it is very difficult to assess the total uncertainty mainly because of the complexity of the entire calculation process and propagation of errors. The total uncertainty calculated may, therefore, be based mostly on engineering judgement. For the engine certifier and aircraft user, it is important to provide all pertinent information to the model developer (usually engine manufacturer) on specifically how it will be used in order to properly assess the uncertainty. This is very important because the user may inadvertently apply the model beyond its limitations. The uncertainty must be estimated for the particular application before it can be considered for a particular station airflow measurement.

Even though the uncertainty of this method is generally high relative to that of other measurement systems, it is a method frequently used because of its reduced development time and cost. Also, as mentioned previously, it may be the only option available to the engine certifiers and aircraft users who do not have access to interstage component airflows on production engines.

4.4.7.4 *Signal Conditioning*

The airflow determination by the use of a thermodynamic model is purely an inferential measurement process and thus is dependent on primary parameters whose signal conditioning is defined elsewhere in this document. Refer to the appropriate section for conditioning information. In general, the primary measurement systems mostly used in this airflow measurement process are fuel flow, pressure, spool speeds, and geometries (variable guide vanes and/or nozzle areas).

4.4.7.5 *Calibration*

The calibration of the thermodynamic model is left to the engine manufacturer. The engine certifier and aircraft user are responsible only for calibrating the specific primary measurement device which will be used to determine engine power level with time via model matches. The model calibration process is described only briefly here as it is a complex subject of its own. It will be left to the reader to acquire more detailed information.

The model may in some cases be generated using purely analytical transient algorithms with no calibration being performed. The uncertainty is largest for these types of models. More accurate models are developed by actual transient engine calibrations using all the measurement processes described in this document. The calibration is usually performed in two parts, steady state effects, then transient. The steady state calibration of the model may involve particular component scaling to account for engine deterioration, engine production tolerances, or even specific engine problems such as excess leakage or hardware damage. The transient calibration of the model is then performed after the steady state calibration is completed. Some transient calibrations may be quite extensive and involve measurement systems including metal temperature and clearance probes. However, in many cases, the extensive measurement schemes are not possible for calibrations. Calibrations are then performed simply by adjusting transient algorithm correlation coefficients to match standard measurements (air temperature, pressure, combustor fuel flow, and spool speeds).

4.4.7.6 *Design Example*

The most widespread system for the measurement of transient engine airflow utilizes the engine compressor and/or the fan as the flow sensor. The necessary calibrations of the compressor or fan are obtained either from steady-state rig tests of the component or from steady-state tests of a specifically instrumented component installed in an engine. The use of the compressor or fan as the flow sensor offers major advantages in measurement system simplicity and reliability, and generally provides results with acceptable uncertainties. Use of this method does require careful attention to ensure little or no phase shift in the several simultaneous measurements required. Further, the validity of the estimates of measurement uncertainty is strongly dependent on test data to establish the matrix of influence coefficents for the ranges of compressor inlet profiles and turbulence and for the expected range of off-schedule positions of the variable vanes which will occur during transient operation. In this sub-section, (4.4.7.6) detailed information will be given on airflow measurement for the design example presented in Section 5.2, viz., compressor surge point characterization by a fuel spike. Airflow will be deduced using the compressor model, measured total pressure at HPC entrance (P25), measured total temperature at HPC entrance (T25), total pressure at HPC discharge (P3 inferred from measured PS31), measured high rotor speed (N_H), and measured compressor vane position, if variable. The estimated uncertainty of the flow so obtained will be determined.

Section 5.2 indicates that the compressor inlet airflow to be calculated will be on the order of 16.8 to 18.6 kg/sec (37 to 41 lbm/s). The target uncertainty of the airflow measurement at the surge point is on the order of 4 percent. The frequency criterion is satisfied through design of the primary measurement systems which are discussed in their respective sections of this report.

a) Air Flow Determination

For this case, the model used will be a fully calibrated steady-state airflow and pressure ratio map for the particular compressor build being tested. Pressure ratio and corrected speed at the surge point are calculated using measured parameters:

$$P_R = P3/P25$$

$$N_{Hcor} = N_H \sqrt{\frac{T_{ref}}{T25}}$$

These values fix a point on the map (see Figure 5.2-1). Corrected airflow can then be extracted and absolute airflow calculated using measured parameters and Equation 4.4-19.

b) Uncertainty Determination

The uncertainty of the airflow is the uncertainty of the model (or map) plus the uncertainty of the primary measurement systems propagated through the model on airflow calculation.

The uncertainty of the model is due to the error in the map's characterization of steady state as well as transient operation. The transient errors may be attributed to:

1) Tip clearance effects
2) Heat storage effects
3) Volume dynamic effects
4) Vane Angle lag effects
5) Interstage rematch due to all above.

Because of the quickness of the fuel pulse for the design example presented, many of the transient effects will be insignificant. However, detailed discussion of each is still included in an effort to inform the reader of the uncertainty estimate process which may be necessary for other transient events. The estimated uncertainty factors for each error source are summarized in Figure 4.4-36.

Steady-State Map Errors

The compressor maps are defined through steady-state rig testing. The maps are calibrated after engine installation by steady-state engine runs using available on-engine high accuracy instrumentation. The uncertainty calculation of the steady-state component maps is in itself rather complex and the estimated accuracy should be treated with caution. Reference 4.4.17 should be consulted for estimation of typical steady-state airflow errors.

Transient Tip Clearance Error

The clearance corrections can be included in the model. Calibration of the clearance effects is also possible through the use of rig or on-engine capacitance probes. The clearance correction may include all component growths that directly affect component performance (blade, disk, attachments, case, and outer seals). The uncertainty of the corrections is dependent on the dynamics of the transient of interest. Because the duration of the pulse up to surge is no more that 50 ms, the thermal growth correction errors can be ignored. Also, since the absolute speed change during the pulse is negligible, the centrifugal growth correction errors can also be ignored. The remaining clearance effect is that due to the pressure deflection. This is the clearance change due to rotor shift in axial direction caused by rotor group loading. Because this example is for an axial compressor, the pressure deflections will be small. Other types of compressors like centrifugal may experience greater pressure deflections. Because all the transient clearance effects are small, their correction will not be applied and error treated as insignificant.

Transient Heat Storage Error

The heat storage correction involves the calculation of energy loss or gain through heat transfer with component metals. This correction can be applied in the model by methods previously described in this section. Calibration of the heat storage corrections can be performed by actual transient testing with transient instrumentation. This can be achieved by sizing of the analytically derived heat sink mass and time constants to match actual transient data such as compressor pressures, temperatures, speed, and sometimes metal temperatures. However, for this design example, the heat storage effects are treated primarily as bias errors.

Volume Dynamic Error

Volume dynamic effects can be applied to the model through the laws of conservation of mass and energy (Reference 4.4.20):

$$\frac{dP}{dt} = \frac{\gamma RT}{V}(\dot{m}_{in} - \dot{m}_{out})$$

$$\frac{dT}{dt} = \frac{RT}{PVc_p}(H_{in} - H_{out} + \dot{q}) - \frac{RT^2}{PV}(\dot{m}_{in} - \dot{m}_{out}) \qquad 4.4\text{-}20$$

These effects are difficult to calibrate without interstage dynamic pressure and temperature instrumentation. The correction is usually applied using purely analytical means. However, the error is usually small. For the Section 5.2 design example, the volume dynamic correction is not applied and is treated as an error.

Vane Angle Effects

Blade row guide vanes are usually scheduled as a function of N_H. When a transient pulse is performed, the blade row guide vanes will not respond immediately to the corrected speed because of the actuation lag. As it has been assumed that the speed change is negligible during this fuel spike, the vane angle effects will be negligible.

Interstage Rematch Error

This error is caused by all of the above errors. Because of the described errors, transient stage-by-stage rematch will not be truly represented by the overall compressor map. A model with individual stage maps would correct this error. However, for the design example provided, the error is treated as a bias error. Since this error is due to the previously described transient errors, in each case the interstage bias has been added to their individual bias values. Accurate estimates of these errors must be achieved by use of a multi-stage model. However, these models may not always be available. It may therefore be necessary to estimate this error based on engineering judgement.

Total Uncertainty

Typical values for the individual errors described above are summarized in Figure 4.4-36. The total bias and precision errors for the airflow can then be caluculated using a Taylor's series expansion including the individual errors of each of the contributing factors as described in Reference 4.4.2 (see also Section 3 of this report).

For the purposes of this example, the integrated errors in the engine model have been based on engineering judgment and the uncertainty in the model has been assumed to equivalent to a bias of approxi mately 3% of the air flow at the surge point. It is shown in Section 5.2.3.6 that this uncertainty is the dominate one in the calculation of air flow.

4.4.8 Advanced Sensors

4.4.8.1 *Hot-Wire Anemometry*

The hot-wire anemometer is generally a velocity measurement device and is used mainly where pulsations in velocity or turbulence detection are of interest. Rotating, traversing, and/or stationary hot wire probes have been used to investigate the flow properties inside a blade passage. Hot wire anemometry has also been used in the measurement of turbulent fluctuations in hypersonic flow fields and of inlet-distortion generated compressor aerodynamic unsteadiness.

Hot-wire anemometry has not been widely accepted in the past because of high uncertainty levels due to inaccurate probe thermal properties definition and probe flow disturbances. Installation concerns were also a factor. Over the past decade, the hot-wire probes have been accepted more widely due to their evolution which included enhancement in sensor construction and solid-state circuitry. The current state-of-the-art hot-wire probe has many advantages. A major advantage of the hot-wire anemometer is its capability of measuring flow independent of direction as long as flow is normal to the wire. Other advantages include high level voltages or current output, very low pressure drop, sensitivity to low flows, and ability to take measurements close to pipe/shroud walls. Hot-wire anemometry will be more predominant in the future and should definitely be considered depending on system requirements.

4.4.8.2 *Laser Anemometry*

Laser anemometry has become popular in recent years and is becoming widely accepted as a dependable airflow velocity measurement device. Laser anemometry has been demonstrated for flow measurement near and between rotating components including investigations of turbulent flow regions, blade wakes, boundary layers, and distorted flows. This includes both compressor and turbine components. Burner velocity investigations are also documented using a laser anemometry measurement system.

There are two basic types of laser anemometers, the Laser-Doppler anemometer (LDA) and the Laser-Two-Focus (L2F) anemometer. The L2F is referred by various other names including spot method, dual focus, and transit-time method.

As compared to other measurement systems, the laser anemometer has many advantages. The laser anemometry signals are naturally linearized. The lack of a physical probe in the flow field is a major advantage especially on small engines where flow disturbances are critical. Measurements can also be made close to the component surfaces which aids in investigations of boundary layers and flow separation.

Disadvantages include the necessity for flow seeding, particle velocity rather than actual flow velocity is measured, accessibility is sometimes difficult (access windows), and systems are usually very specialized resulting in long setup times and expense. Flow seeding can cause additional disadvantages due to the agglomeration of solid particles. Access window contamination can also pose problems. Because of the current limitations of laser anemometry it is generally used only in rig development tests.

With the evolution of laser anemometry, extension to a wider range of applications will be evident. This evolution may include improved signal-to--noise ratio, optics, access window cleaning, particle seeding, electronics, and data evaluation techniques.

4.4.8.3 *Angular Momentum*

Angular momentum flowmeters have recently become popular by the fact that they are true mass flow measuring devices (versus inferential, for example, the turbine flowmeter). The angular momentum flowmeters are immune to the effects of variations in the specific gravity of fuels. While the turbine flowmeter must account for the specific gravity changes due to fuel temp change, the angular momentum flowmeter does not. Angular momentum flowmeters are becoming very popular in flight test as they claim greater reliability and less total user cost than a compensated volumetric flowmeter over the same flow range.

Though angular momentum flowmeters are becoming more widely used for steady state flow measurement, they are not currently used as high response measurement devices, mainly because of drawbacks related to inertial lags. They are mentioned in this report because of their popularity and of the expectation that the transient problems will be overcome in the future. Improvement might include miniaturization similar to the evolution that developed for turbine flowmeters to allow its application to transient measurements.

4.4.8.4 *Coriolis*

Flowmeters based on the Coriolis principle are similar to the angular momentum flowmeters in that they are true mass flow measuring devices. There are a variety of flowmeters based on the Coriolis principle (mainly used for liquid measurement) and include Coriolis type, Gyroscopic type, Oscillating type, Oscillating Gyroscopic type, and the U-shaped type.

The flowmeters using the Coriolis principle have many additional advantages other than just being a true mass flow measuring device. These advantages, depending on specific design, may include low pressure loss characteristics, non-intrusiveness, and no requirements for flow conditioning. Disadvantages, also dependant on specific design, include pipe strain, vibration sensitivity, and need for rotating seals and parts.

4.4.8.5 *Target Meters*
Target meters are know by a variety of other names such as vane, gate, drag, and force meters. Target meters have generally been used in the past for difficult applications such as dirty, sediment-laden, and high-melting point or corrosive liquid measurement. With proper installation and calibration, the target meter can provide accuracies comparable to other head-class flowmeters. Target meters have just recently extended their applications to include turbine engine fuel flow measurements.

The primary advantage of the target meter is that it does not require pressure taps and lead lines. In turn it will have extremely high frequency response. In fact, manufacturer specifications warn the user that due to extremely high frequency response of these flowmeters, flow fluctuations and transients may be seen which cannot be detected by other systems of flow measurement and that apparent instabilities sensed may actually exist in the fluid system.

With its evolution, which will include a larger experience base related to transient/dynamic measurements, the target meter should become a very useful and accurate transient fuel flow measurement device.

4.4.8.6 *Ultrasonic Flowmeters*
Ultrasonic meters are mostly used for liquid flow measurement but can be applied to gas flows. Some gas flow measurement systems employ sound waves to measure the flow by the Doppler principle.

There are many advantages to using ultrasonic flowmeters versus other volumetric/velocity measurement systems. They allow for measurement without disturbing the flow, are generally less expensive due to initial cost and maintenance (especially an externally mounted transducer type), and they do not cause pressure drop inside the pipe.

Disadvantages include frequent pipe ID and OD diameter measurements to compensate for thermal effects or mineral deposits. They also require fully developed, undistorted flow profiles when one measurement (plane/slice) is taken. This disadvantage can be remedied by using multipath units. A final disadvantage is that if mass flow measurement is desired, an additional measurement of specific gravity is required.

Ultrasonic meters are relatively new. With their evolution and experience, improvements will be gained to allow for a wider range of application and lower uncertainty.

4.4.8.7 *Laser-Induced Fluorescence*
Flow measurement using the laser-induced fluorescence technique is also relatively new. This measurement technique is non-intrusive and is extremely useful flow visualization for several specific applications. It has been used to study time resolved three-dimensional flow in transonic compressor rotors and wind tunnel diagnostics. It is also a possible measurement system for combustion investigations including 3-dimensional instantaneous flame mapping, species concentration investigations, and flow visualization.

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Table 4.4-1 Specific Gravity Measurement Errors

Elemental Error Source	Est. Bias ±S.G.	Est. Precision ±S.G.	Notes
Calibration Hierarchy	0.0011	-	±0.14% of Rdg.
Hydrometer Resolution	0.0005	-	0.001/Div.
Temperature Indicator Resolution	0.0004	-	±0.5 K
Temperature Indicator Linearity	0.0004	-	±0.5 K
Temperature Correction Chart for S.G.	0.0005	-	0.001/Div.
RSS	0.0014	0	
0.0014/0.763 = 0.18 percent			
Based on Fan Test Cell Hydrometer and Temperature Correction JP-4 Fuel, S.G. Nominal = 0.763			

Table 4.4-2 Calculation of Air Flow Using Venturis and Nozzles

Description	Calculation	Ref. 4.4.10	Other Ref.
Subsonic Venturi or Nozzle Flow	$W = \frac{\pi d^2}{4} \frac{C_w}{\sqrt{1-\beta^4}} Ya\ Fa \sqrt{2\rho_1(P_1-P_2)}$	Eqn I-5-29	4.4.11 4.4.23
Sonic Venturi Flow	$W = \frac{\pi d^2}{4} C_w\ \phi_i \left(\frac{\phi}{\phi_i}\right)\left(\frac{P_1}{\sqrt{T_1}}\right)$	Eqn I-5-129	4.4.12
Discharge Coefficient	C_w for nozzle = ƒ(Reynolds No., β, pressure tap configuration C_w for subsonic venturi = ƒ(entrance cone config.) C_w for sonic venturi	Table II-III-5 page 232	4.4.11 4.4.13 4.4.16 4.4.23
Adiabatic Expansion Factor	$Ya = \left[P_r^{\frac{2}{\gamma}}\left(\frac{\gamma}{\gamma-1}\right)\left(\frac{1-P_r^{\frac{\gamma-1}{\gamma}}}{1-P_r}\right)\left(\frac{1-\beta^4}{1-\beta^4 P_r^{\frac{2}{\gamma}}}\right)\right]^{\frac{1}{2}}$	Eqn I-5-26 Table II-III-6 and 7. Fig.II-III-20 and 21	4.4.11 4.4.23
Thermal Expansion Factor	Fa = ƒ(metal type, metal temperature)	Fig.II-I-3	4.4.11 4.4.23
Density (moist gas)	$\rho = 2.6991(1+SH)\frac{P-P_v}{TZ}$	Eqn I-3-40	4.4.24
Reynolds Number	$R_d = \frac{4W}{\pi\ d\ \mu}$	Eqn I-5-57	4.4.11 4.4.23
Absolute Viscosity	μ = ƒ(gas temperature, gas type)	Fig.II-I-9	4.4.25
Compressibility Factor	Z = ƒ(critical temperature and pressure)	Fig.II-III-31 Table II-I-5	4.4.24
Sonic-flow-function (Ideal gas)	$\phi_i = \sqrt{\frac{\gamma(m_w)}{R}\left(\frac{1+\gamma}{2}\right)^{-\left(\frac{\gamma+1}{\gamma-1}\right)}}$	Eqn I-5-103	4.4.12
Ratio Real to Ideal Gas Sonic-flow-function	$\frac{\phi}{\phi_i}$ = ƒ(inlet stagnation press & temp)	Table II-III-8 through 20	4.4.12
Specific Humidity	SH = 0.622 Pv/(P-Pv)	Eqn I-3-38	4.4.26
Vapour Pressure	Pv = ƒ(wet and dry bulb temperatures)	Not provided	4.4.26

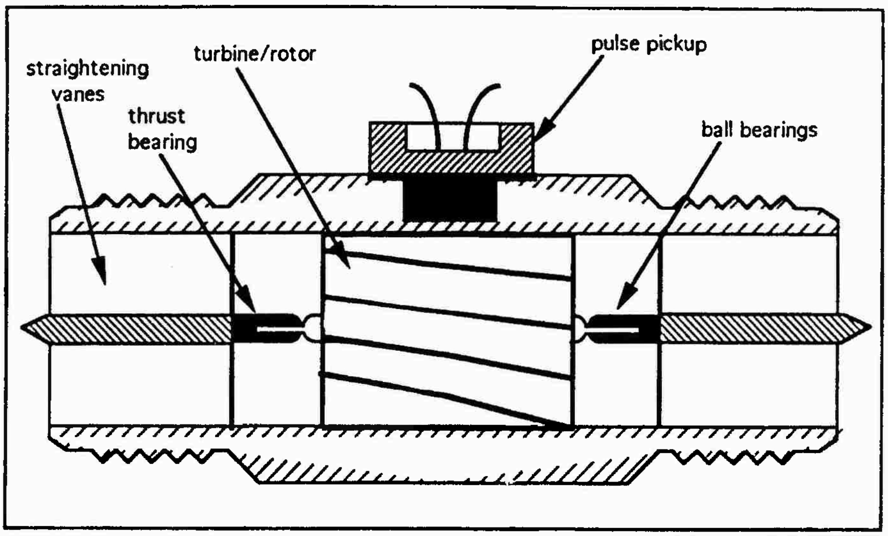


Figure 4.4-1 Turbine Flowmeter Design

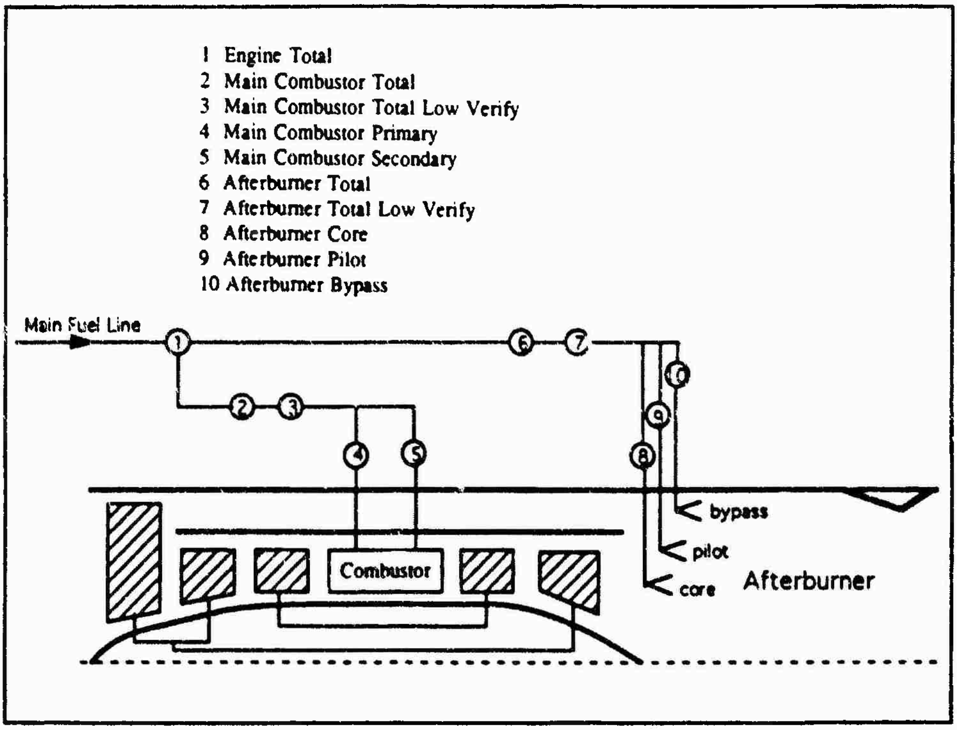


Figure 4.4-2 Complete Turbine Fuel Measurement System

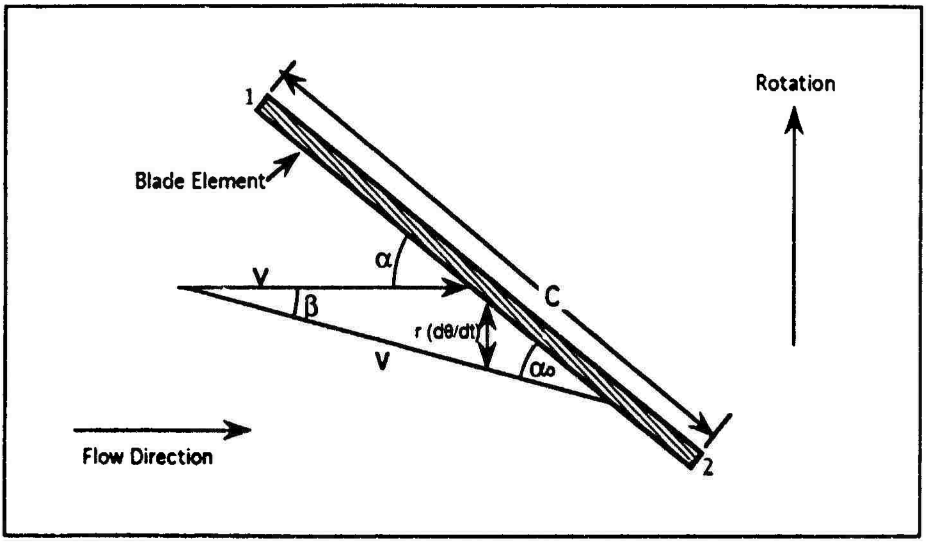


Figure 4.4-3 Blade Dimensions Necessary for Time Constant Measurement
(Reference 4.4.5)

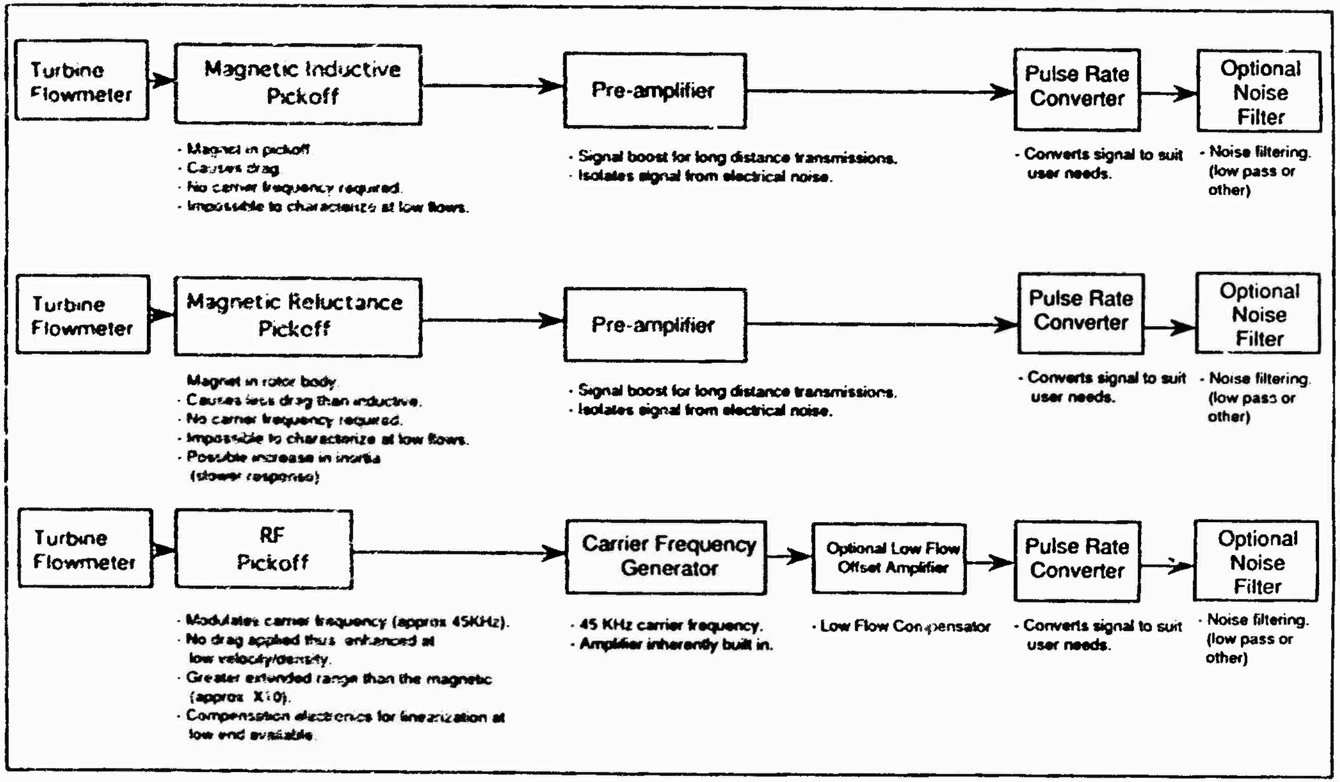
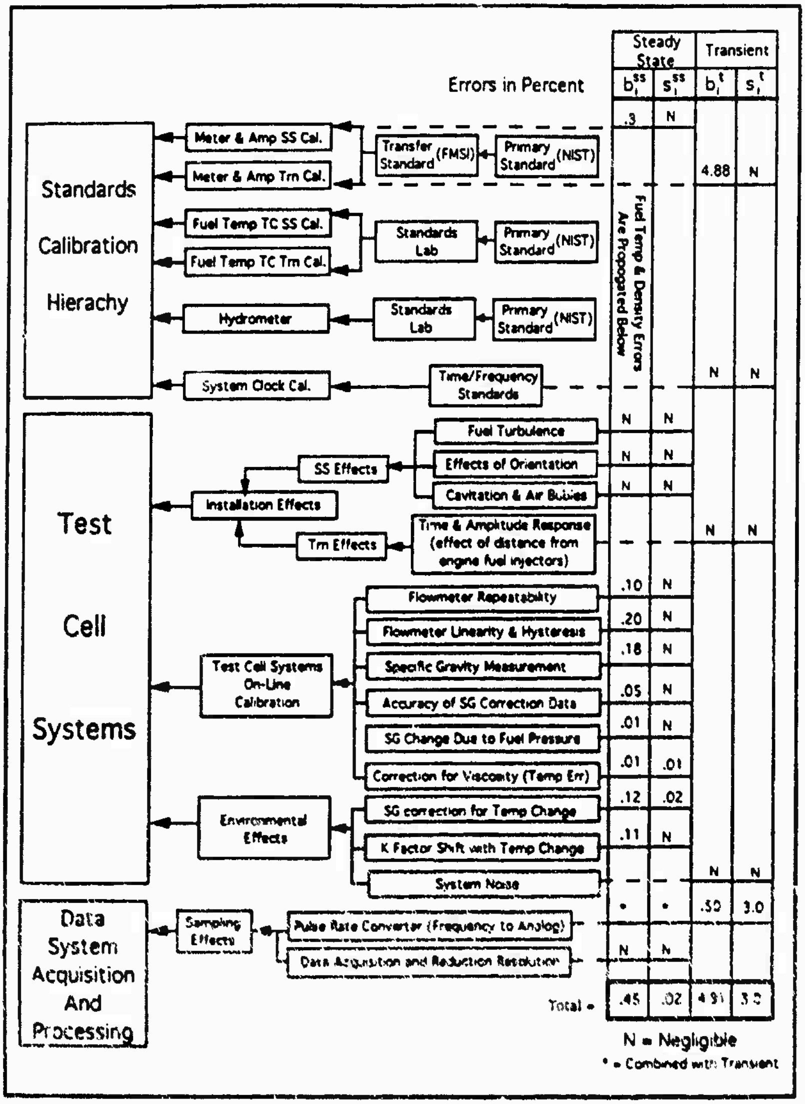


Figure 4.4-4 Turbine Flowmeter Signal Conditioning Options



Error source	b_i^{ss}	s_i^{ss}	b_i^t	s_i^t
Meter & Amp SS Cal.	.3	N		
Meter & Amp Trn Cal.			4.88	N
System Clock Cal.			N	N
Fuel Turbulence	N	N		
Effects of Orientation	N	N		
Cavitation & Air Bubles	N	N		
Time & Amplitude Response			N	N
Flowmeter Repeatability	.10	N		
Flowmeter Linearity & Hysteresis	.20	N		
Specific Gravity Measurement	.18	N		
Accuracy of SG Correction Data	.05	N		
SG Change Due to Fuel Pressure	.01	N		
Correction for Viscosity (Temp Err)	.01	.01		
SG correction for Temp Change	.12	.02		
K Factor Shift with Temp Change	.11	N		
System Noise			N	N
Pulse Rate Converter (Frequency to Analog)	*	*	.50	3.0
Data Acquisition and Reduction Resolution	N	N		
Total =	.45	.02	4.91	3.0

Figure 4.4-5 Fuel Flow Error Source Diagram for Fuel Spike Test

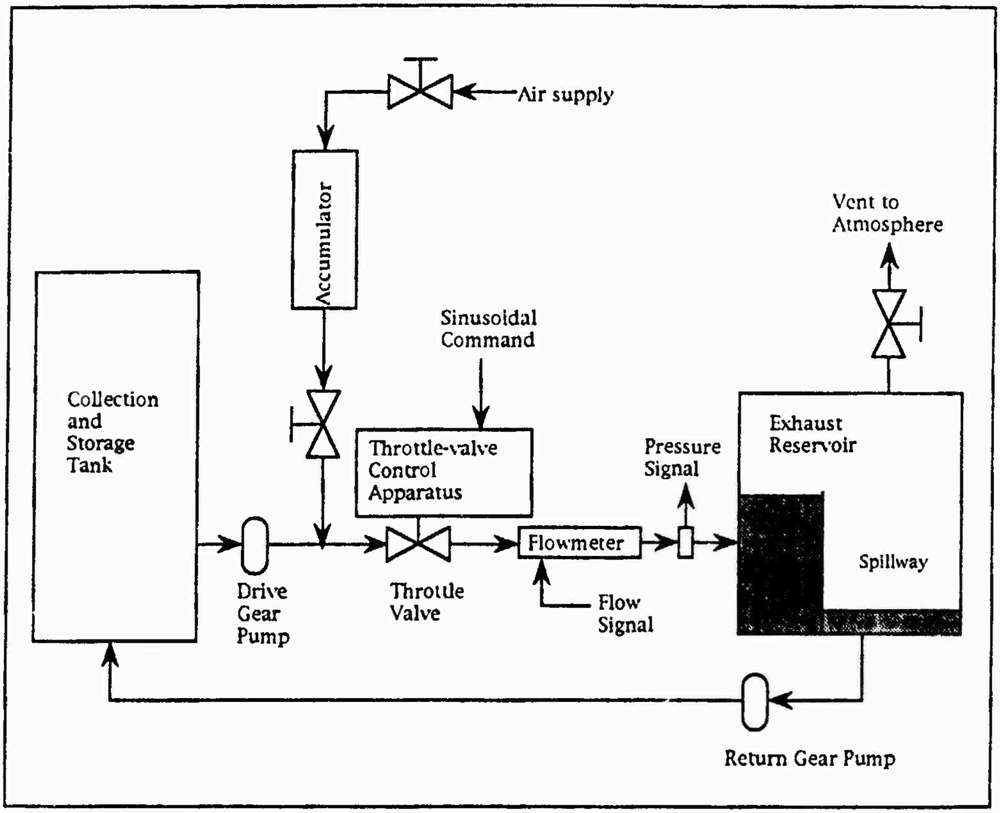


Figure 4.4-6 Frequency Response Calibration Setup
(Reference 4.4-6)

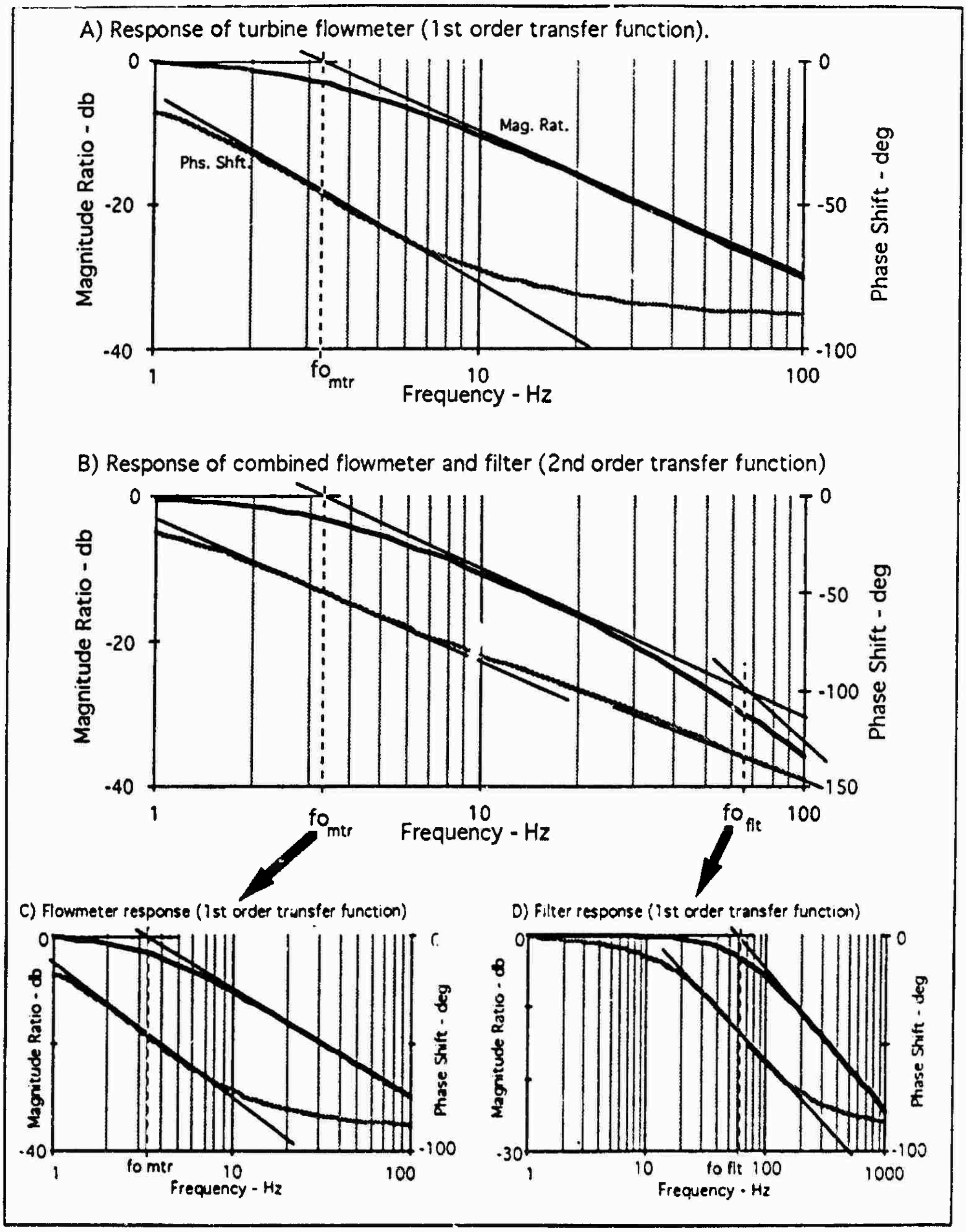


Figure 4.4-7 System Response Determination Using Bode Diagrams

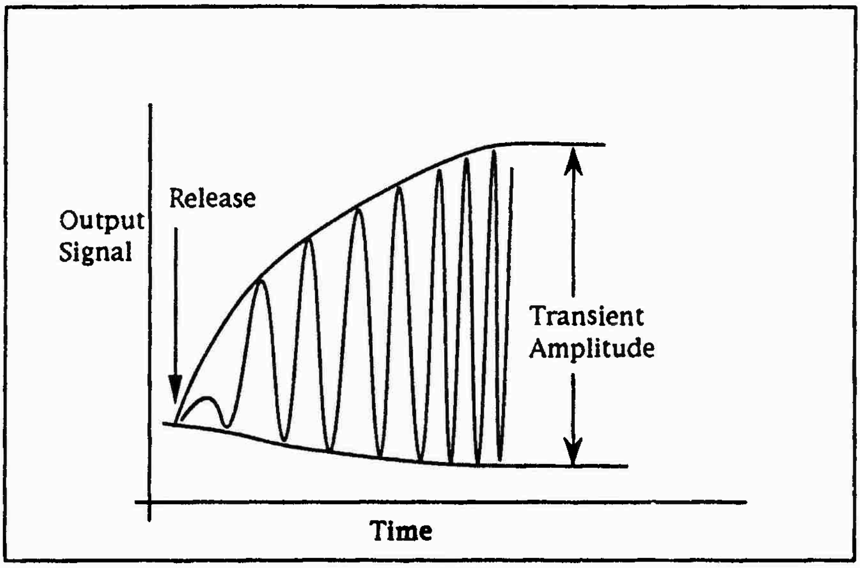


Figure 4.4-8 Amplitude Response Interpretation
(Reference 4.4-7)

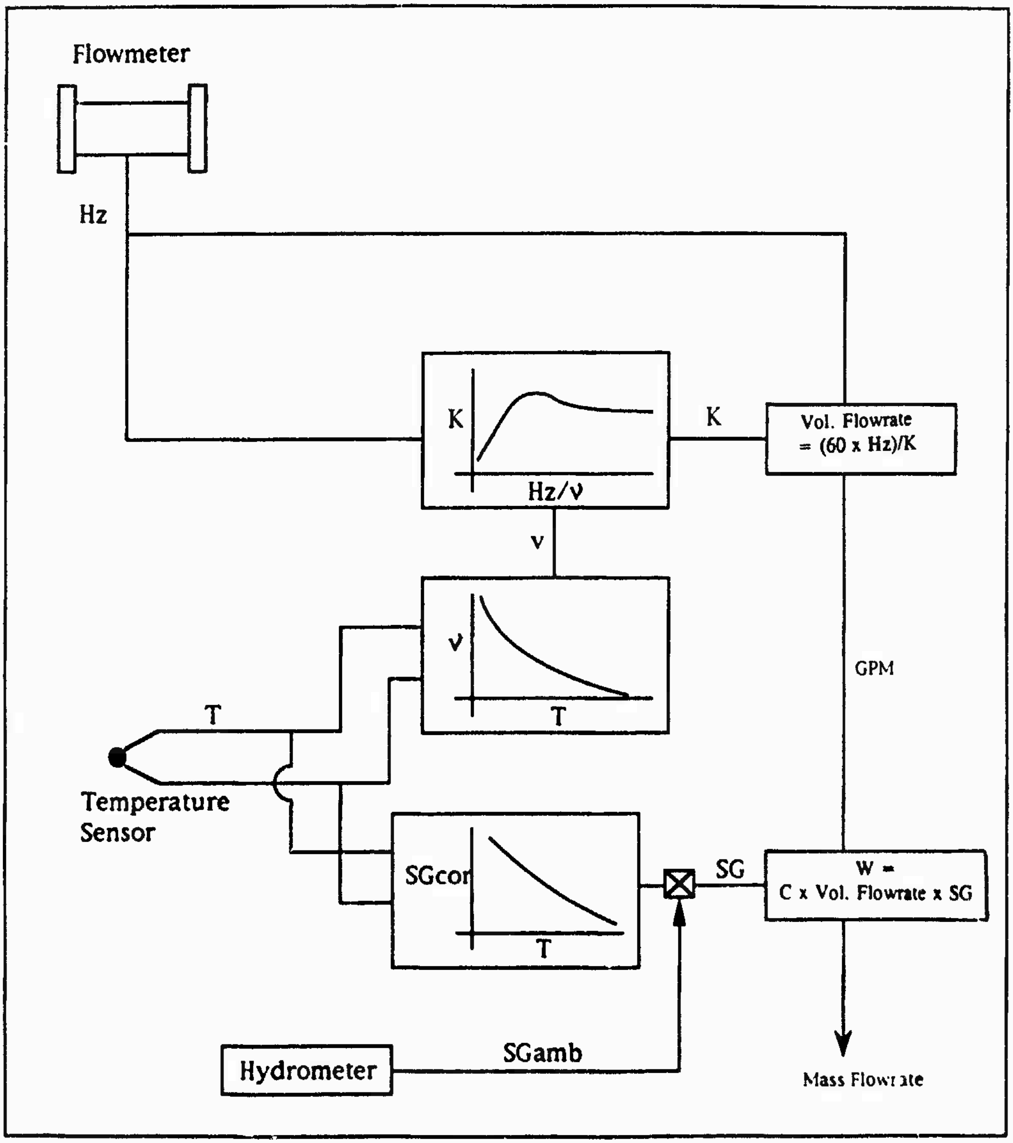


Figure 4.4-9 Mass Flowrate Calibration

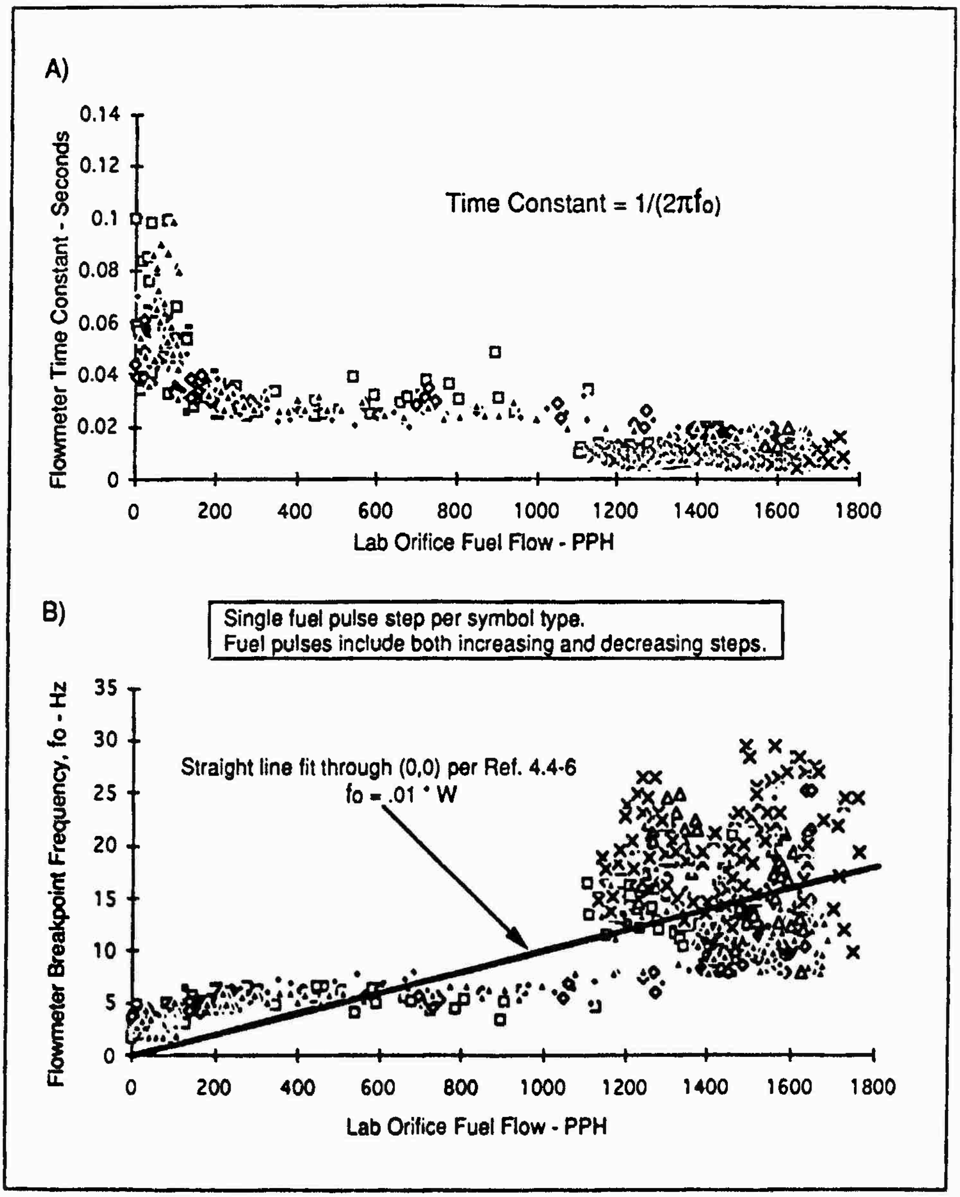


Figure 4.4-10 Turbine Flowmeter Bench Calibration Results

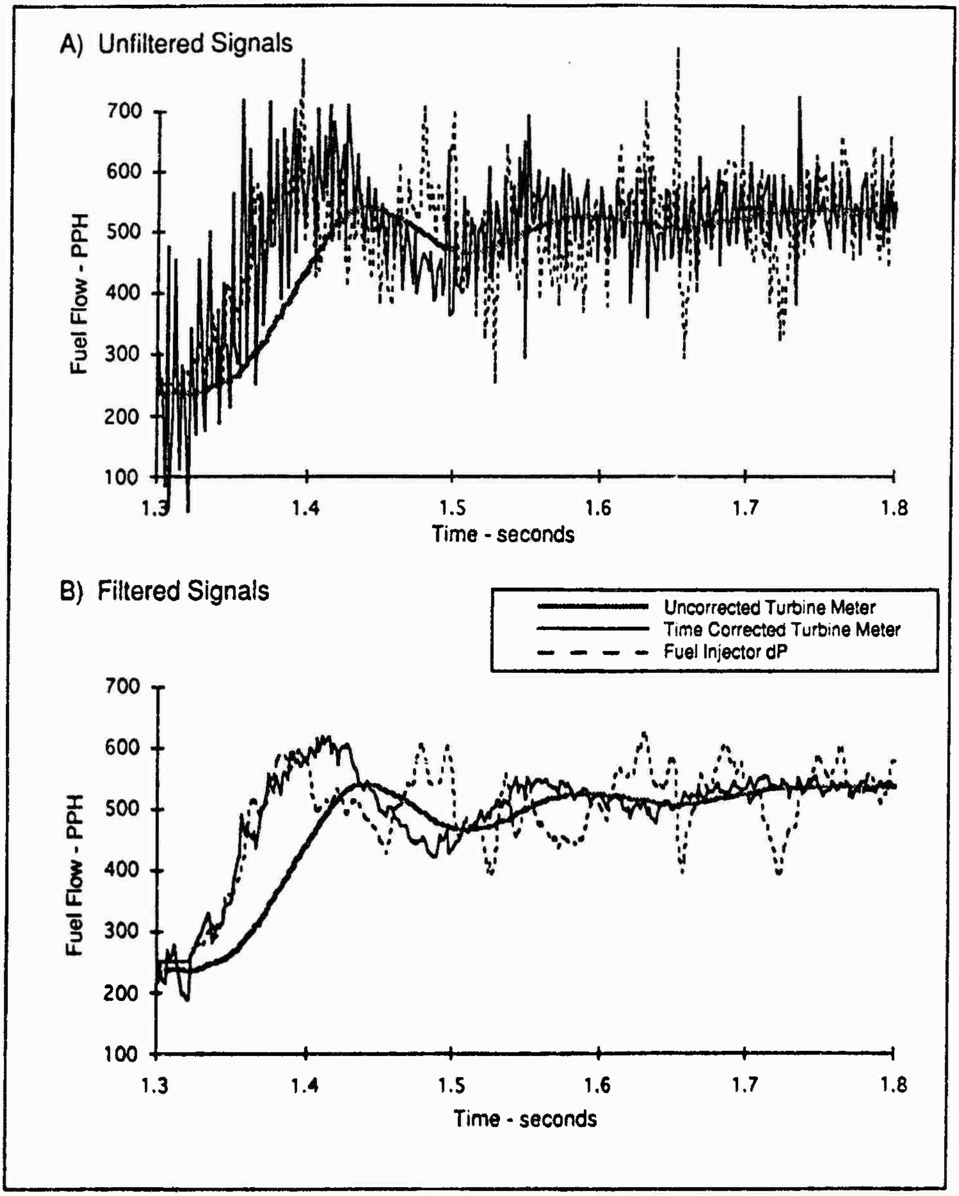


Figure 4.4-11 On-Engine Turbine Flowmeter Time Correction Results

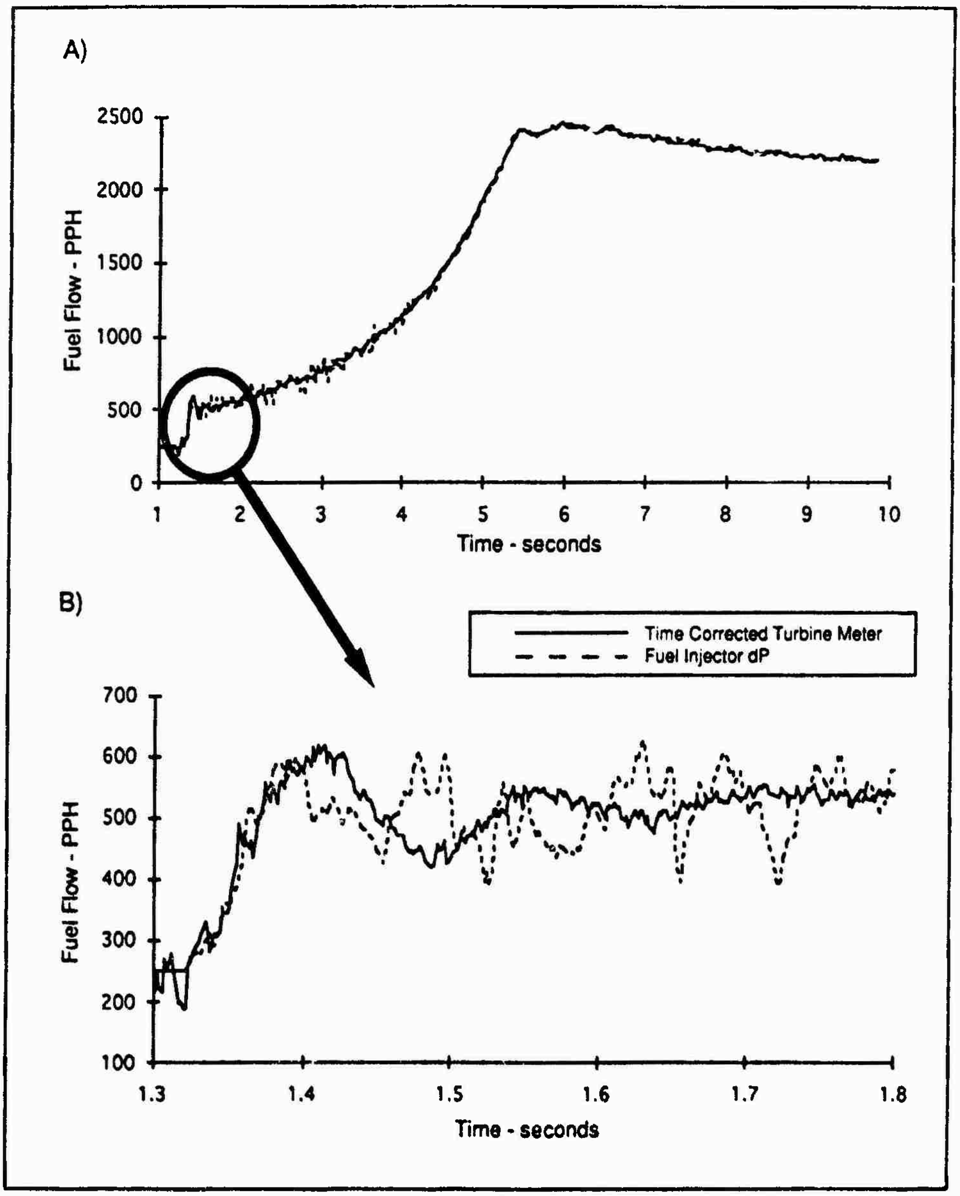


Figure 4.4-12 Turbine Meter Measurement During Snap Accel

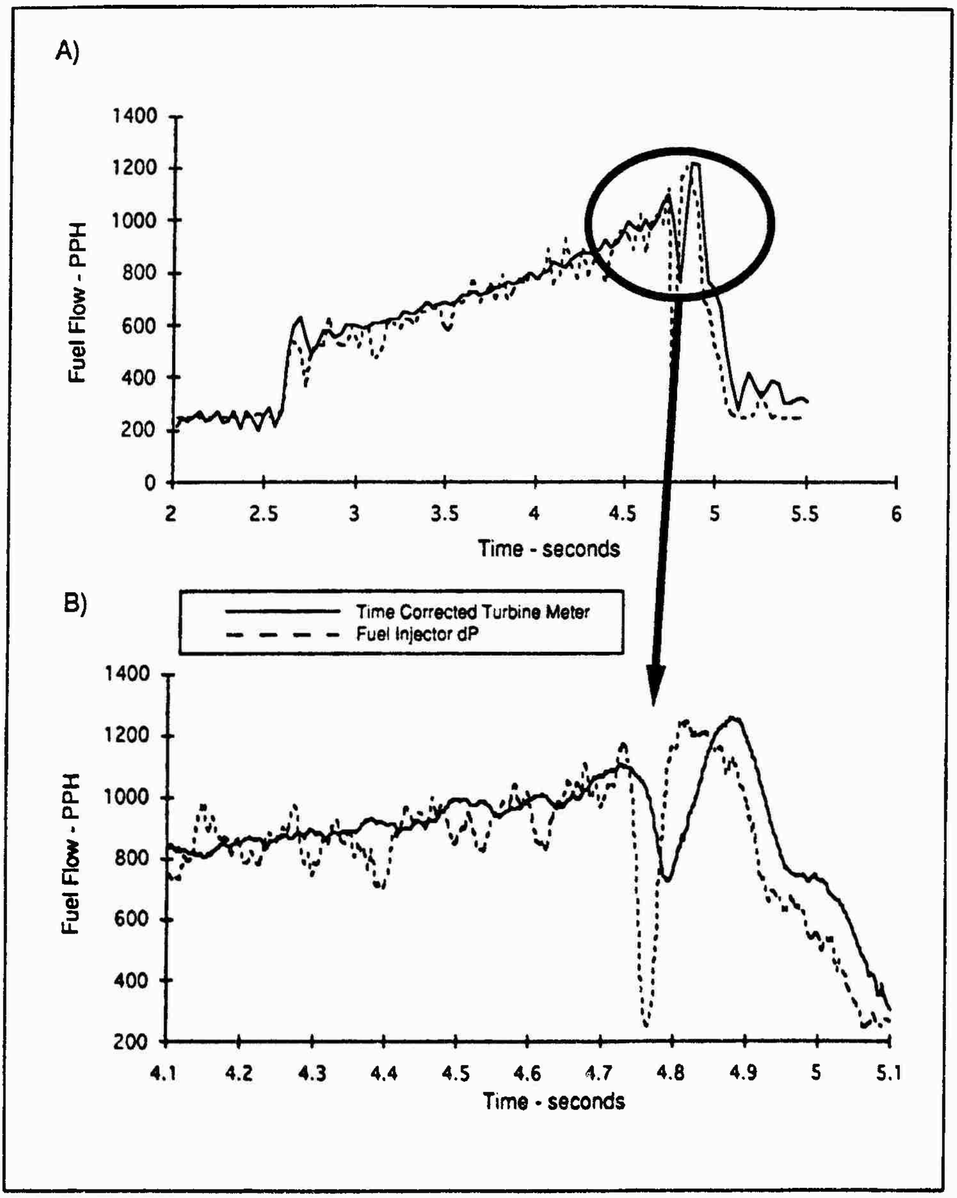


Figure 4.4-13 Turbine Meter Measurement During Engine Surge

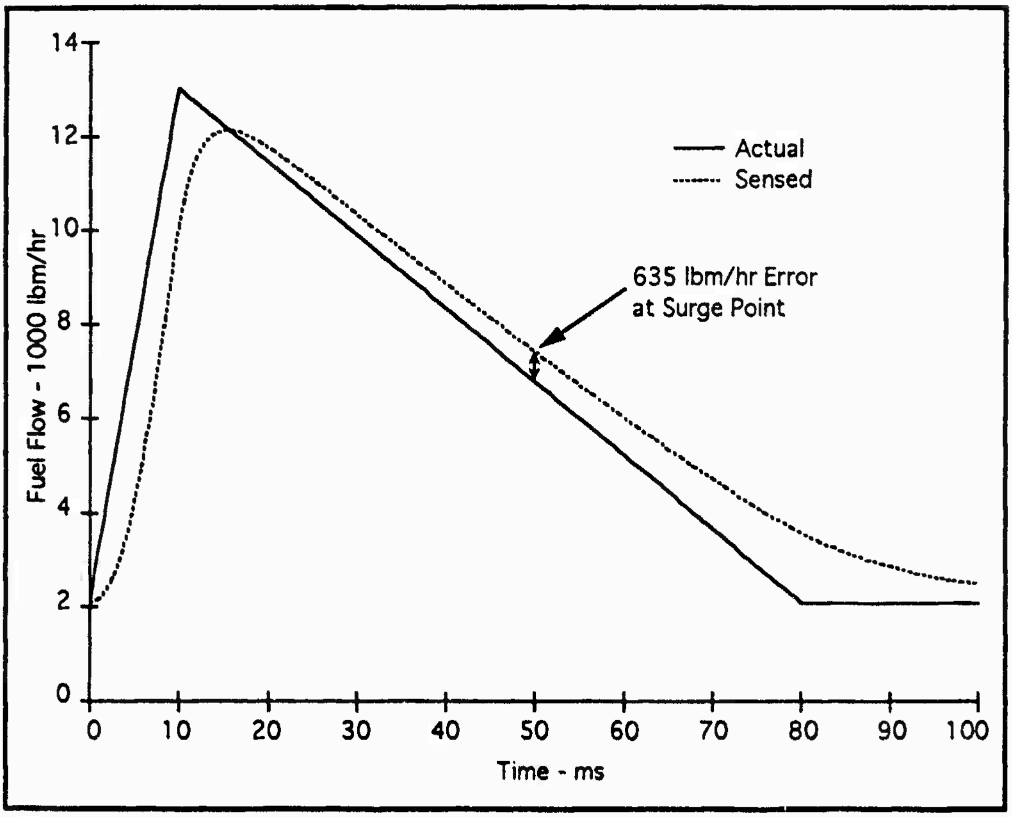


Figure 4.4-14 Flowmeter Response for Fuel Pulse Test

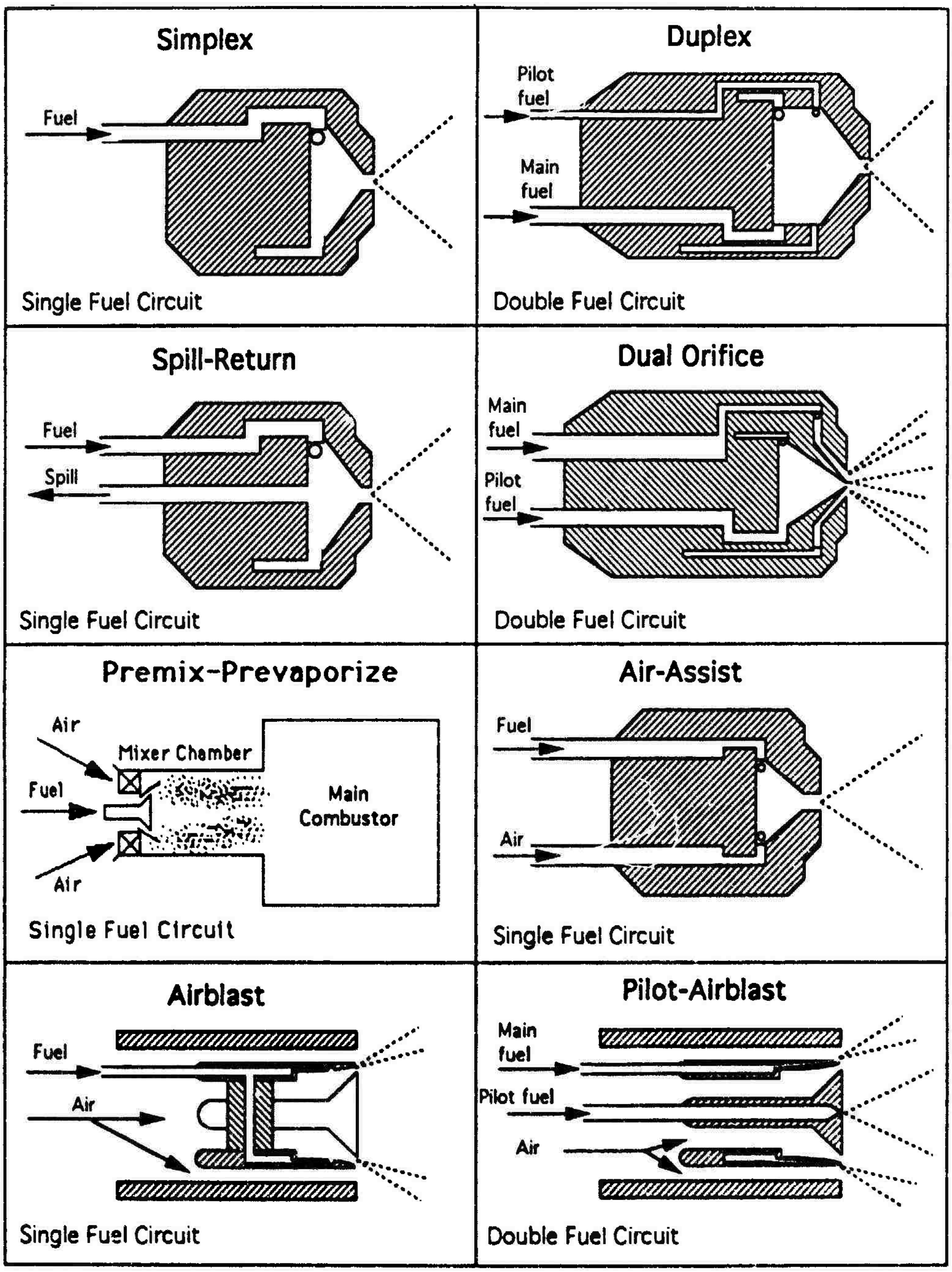


Figure 4.4-15 Fuel Injector Atomizer Designs
(Reference 4.4-8)

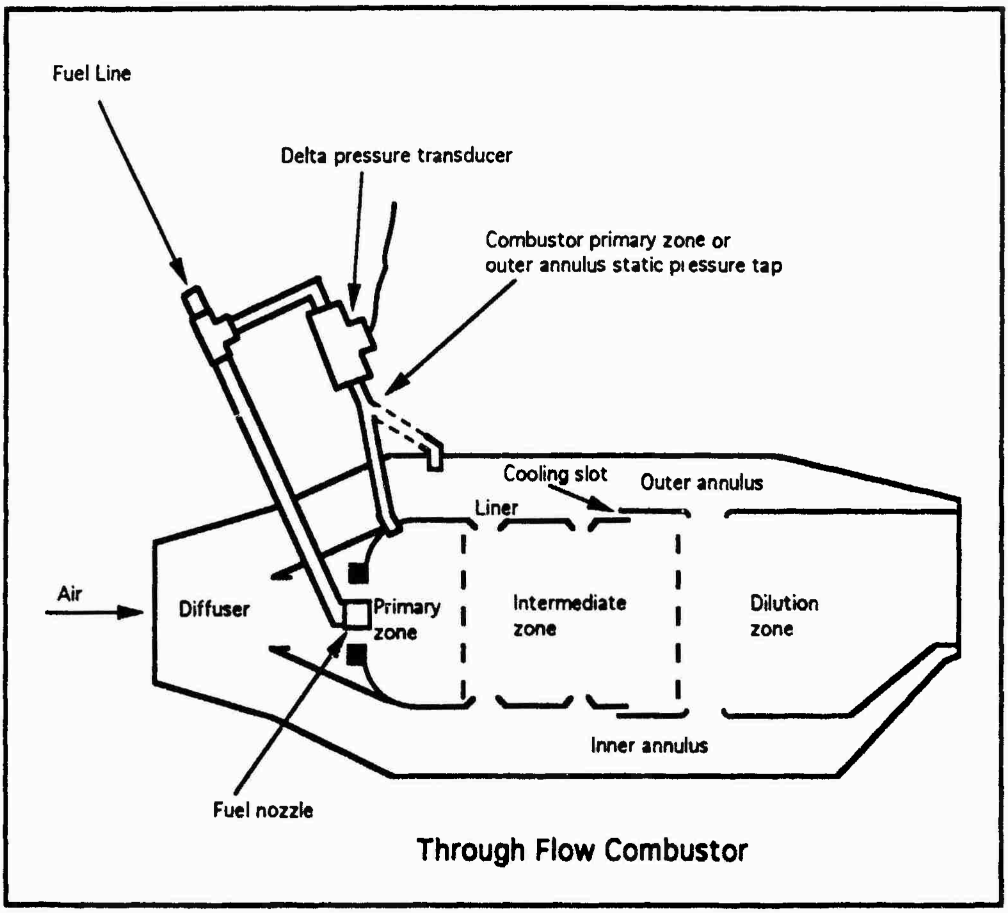


Figure 4.4-16 Fuel Injector Delta Pressure Measurement

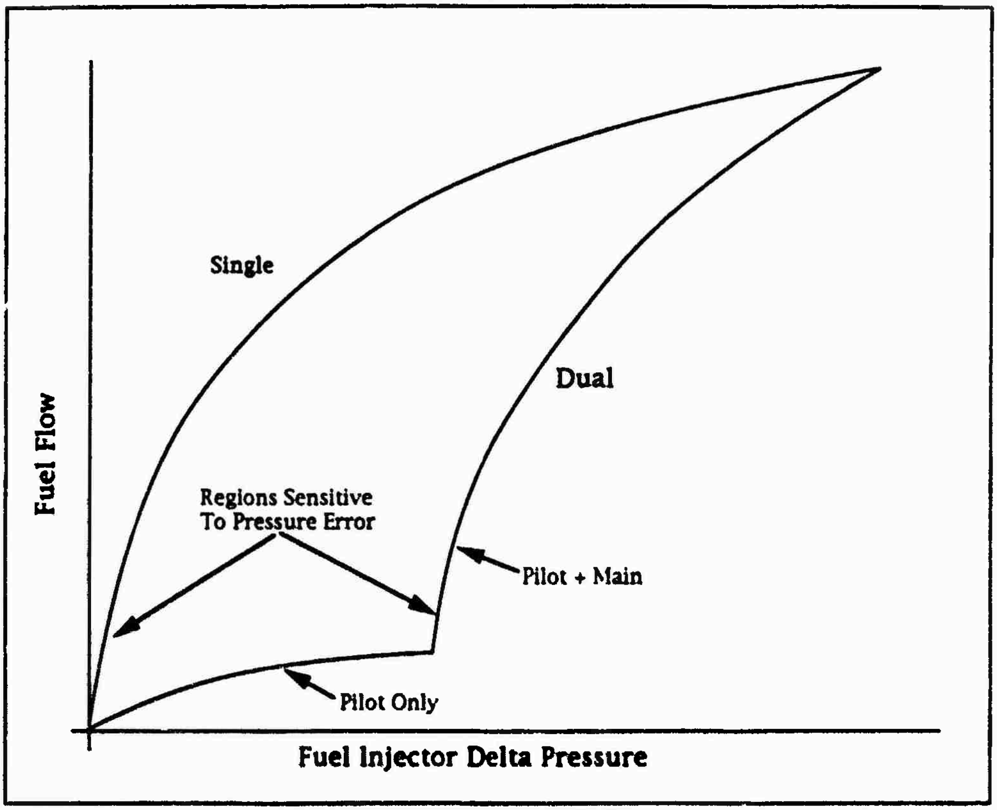


Figure 4.4-17 Fuel Injector Calibration for Single and Dual Fuel Circuit

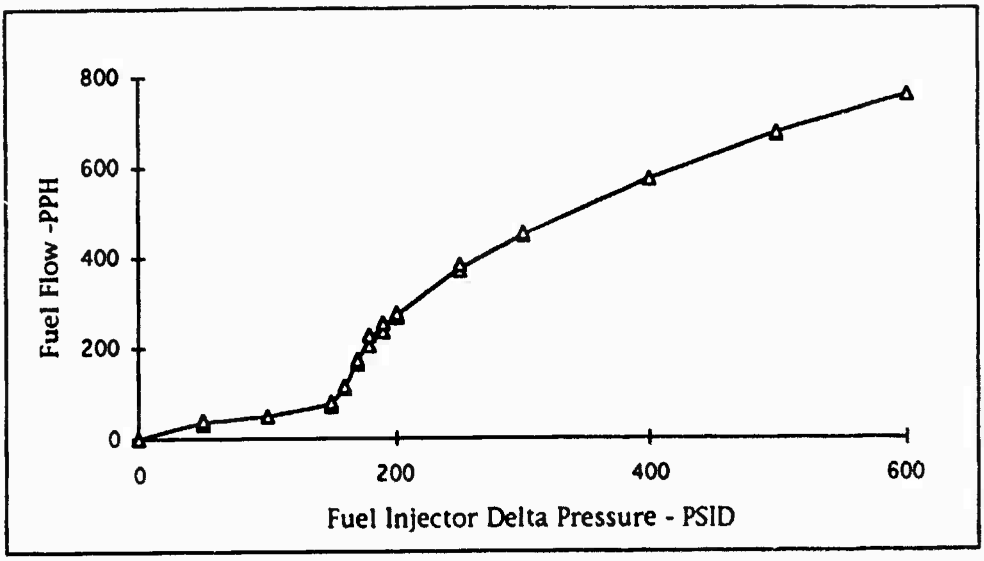


Figure 4.4-18 Fuel Injector Bench Calibration

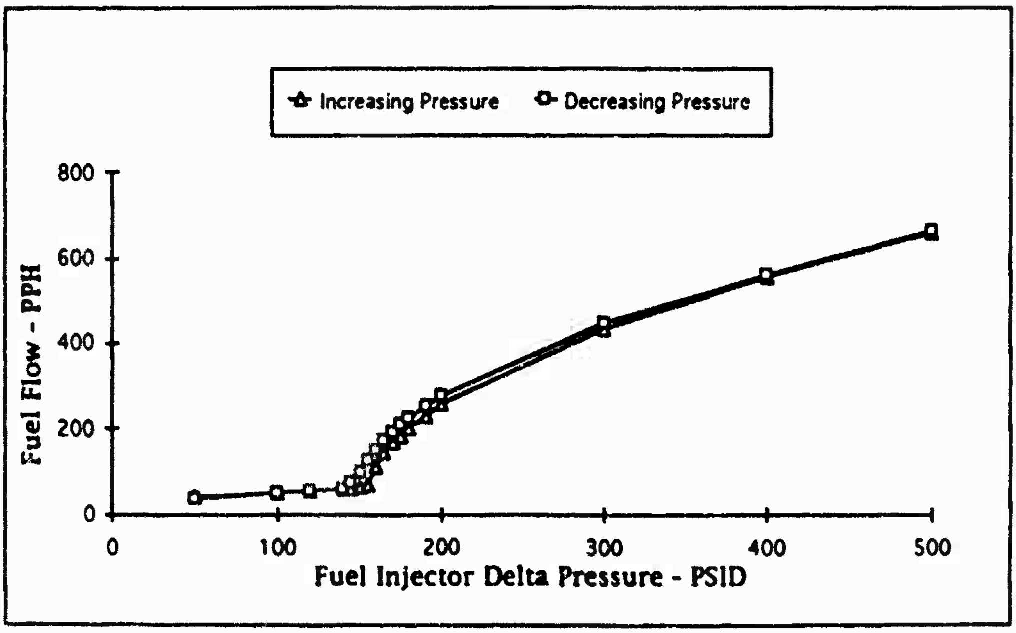


Figure 4.4-19 Hysteresis Effects of Pressure Regulated Flow Divider Valve

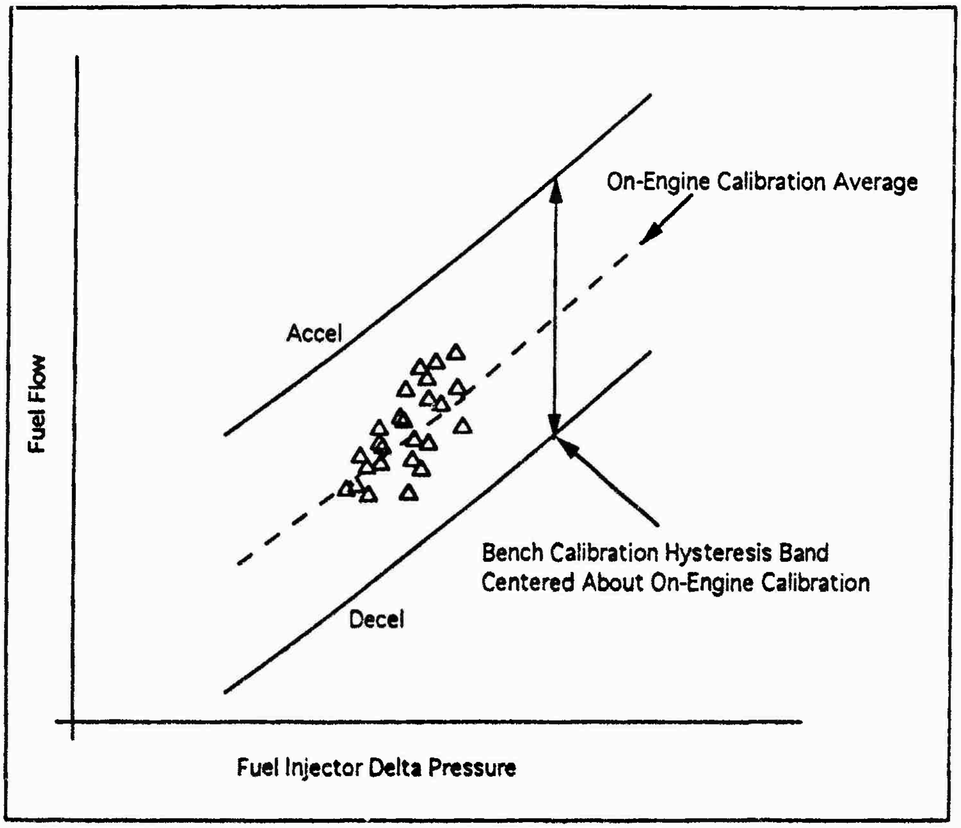


Figure 4.4-20 Fuel Injector Hysteresis (Bench versus On-Engine Calibration)

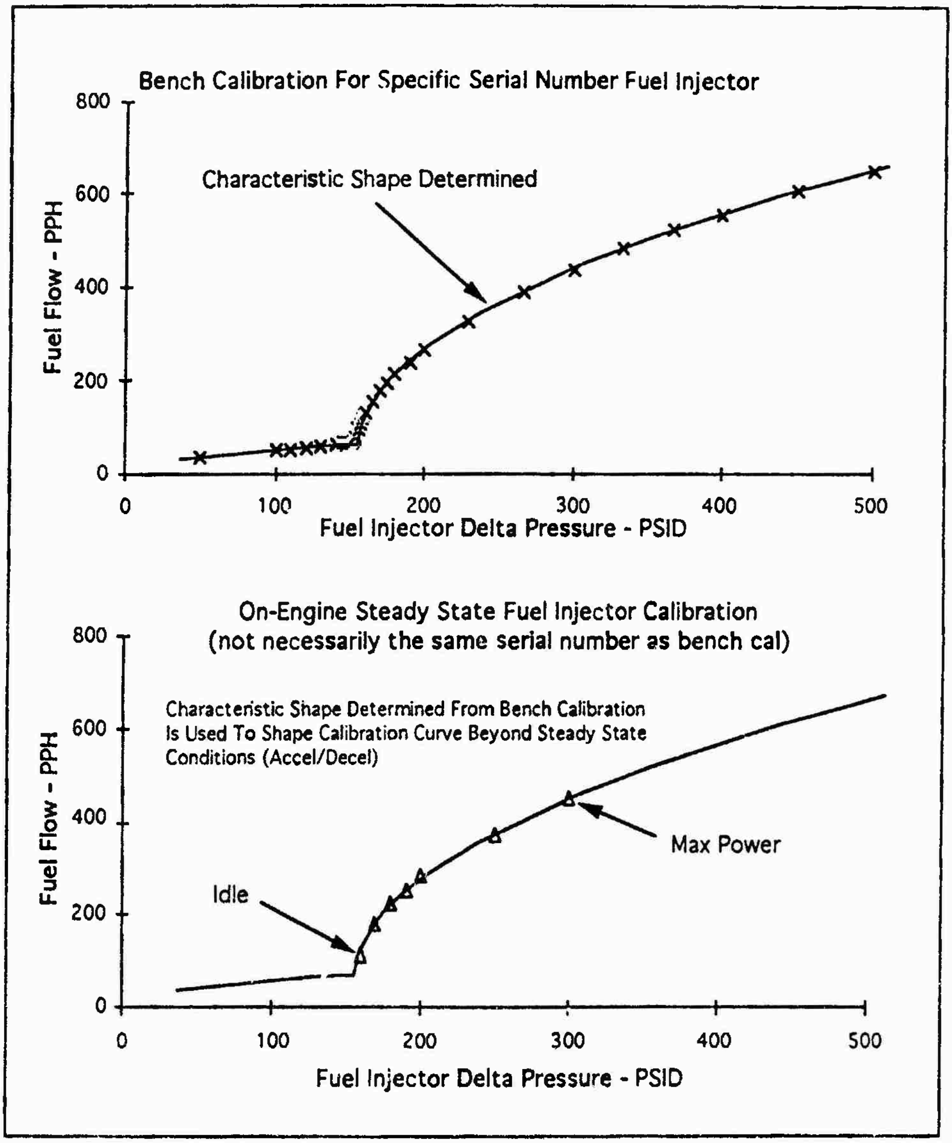


Figure 4.4-21 Fuel Injector Calibration Design Example

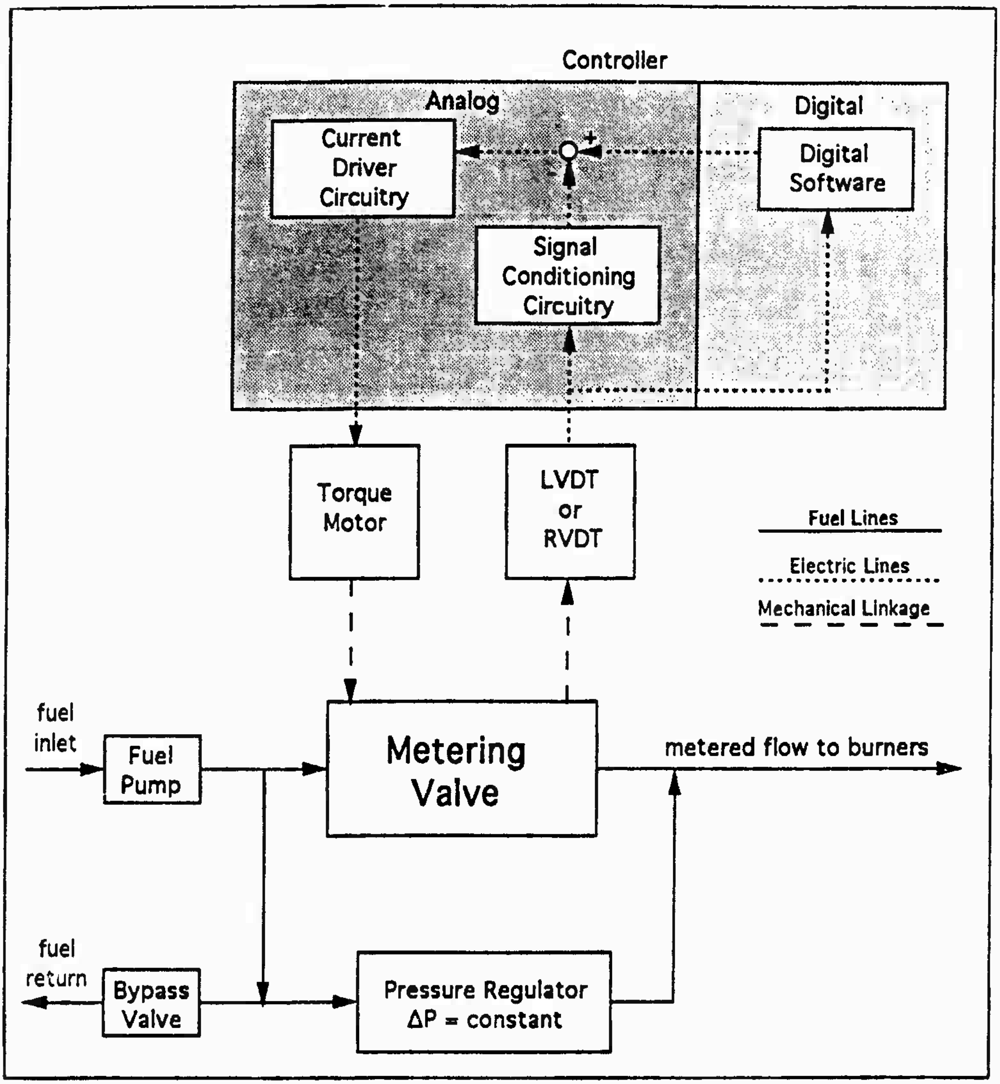


Figure 4.4-22 Fuel Control Unit Functional Diagram

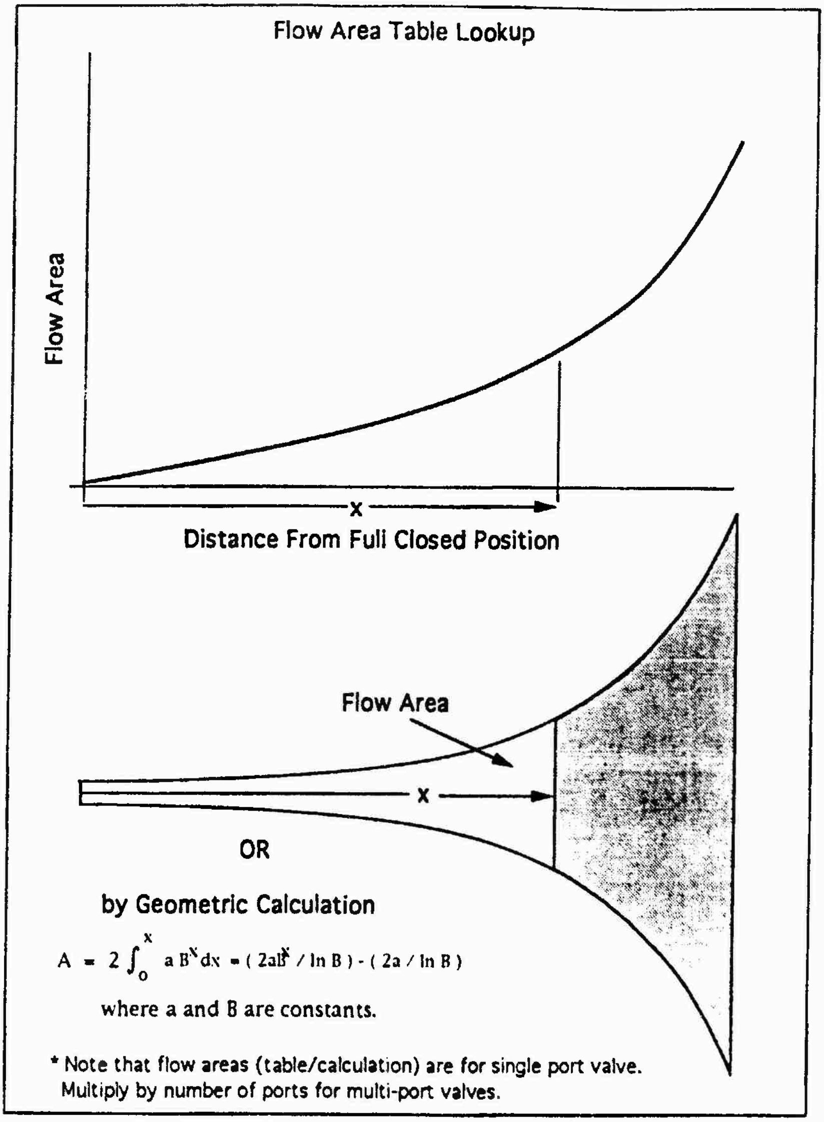


Figure 4.4-23 Logarithmic Valve Stroke to Flow Area Conversion

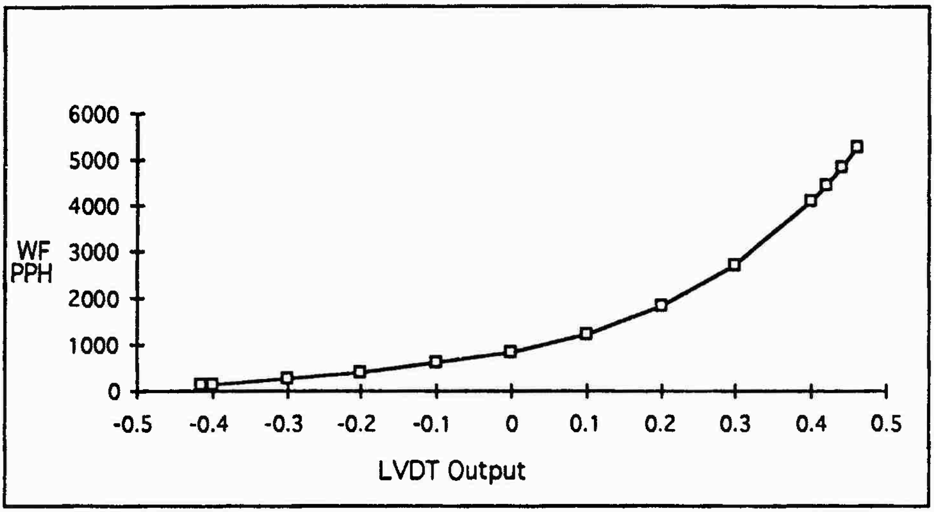


Figure 4.4-24 FCU Bench Calibration Data

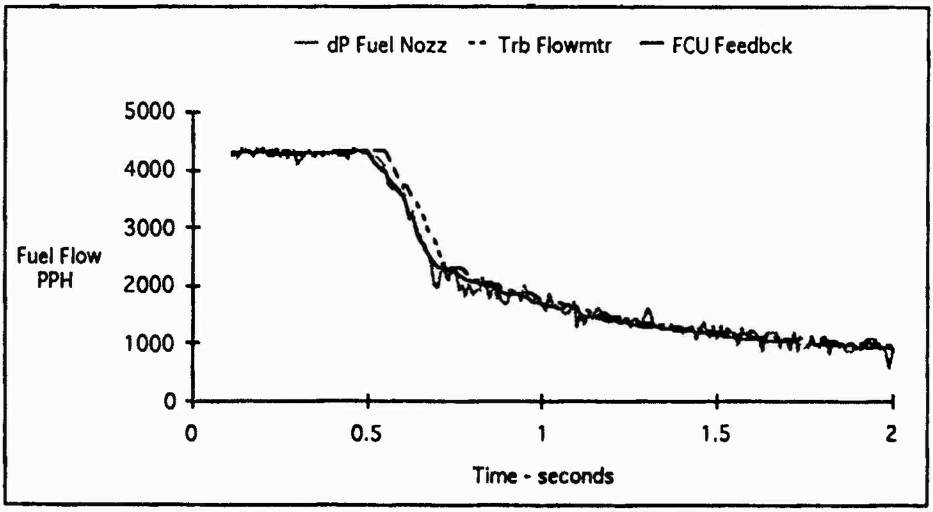


Figure 4.4-25 Fuel Control Unit Feedback Design Example

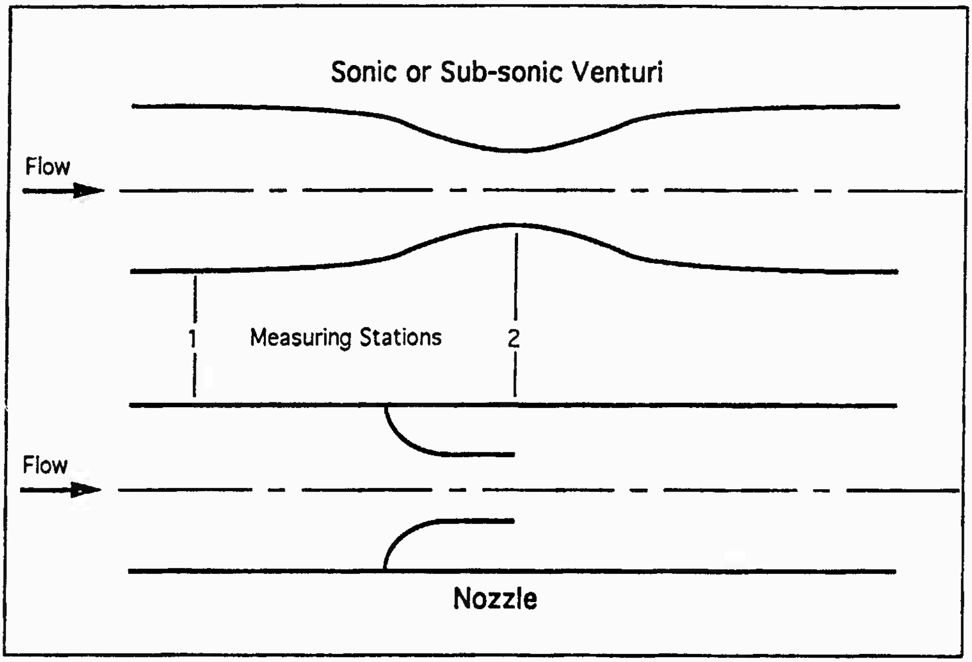


Figure 4.4-26 Sonic/Subsonic Venturi and Nozzle with Measuring Stations

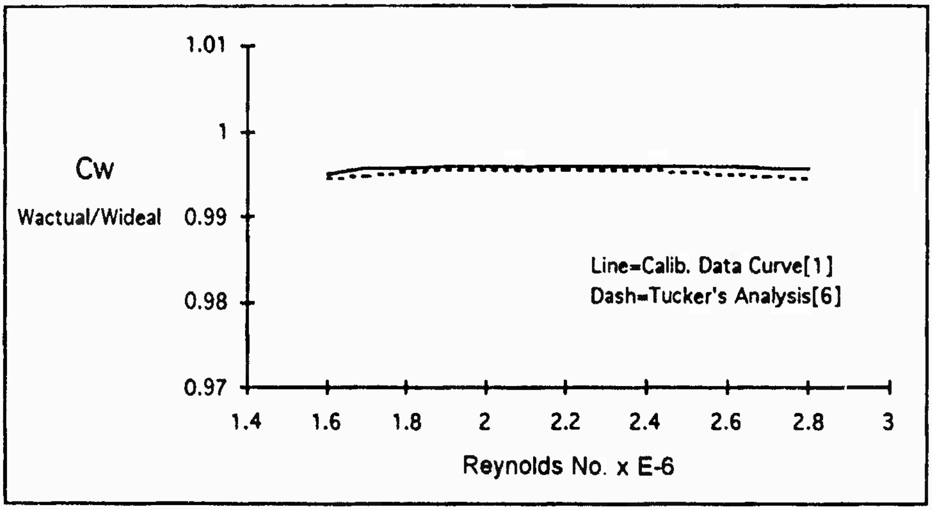


Figure 4.4-27 Subsonic Venturi Experimental vs. Theoretical Flow Coefficients
(Reference 4.4.9)

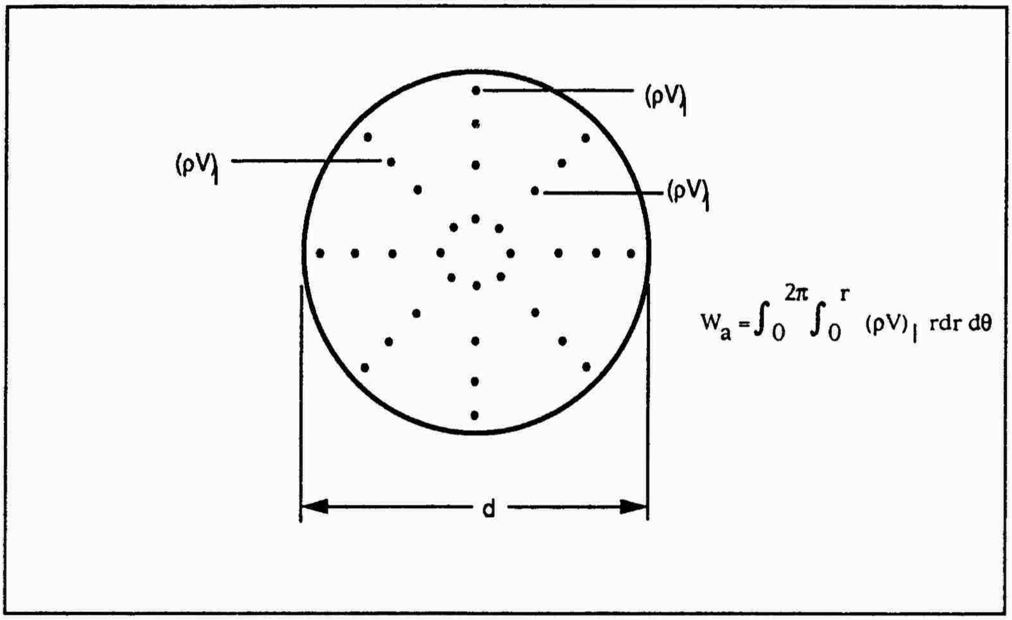


Figure 4.4-28 Calibration by Traverse
(Referencd 4.4-3)

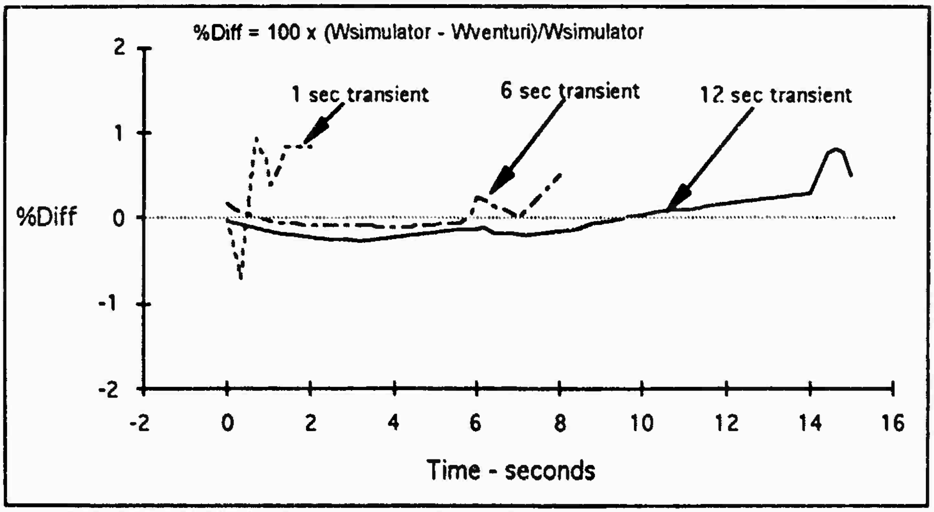


Figure 4.4-29 Subsonic Venturi Deviation from Airflow Simulator
(Reference 4.4-9

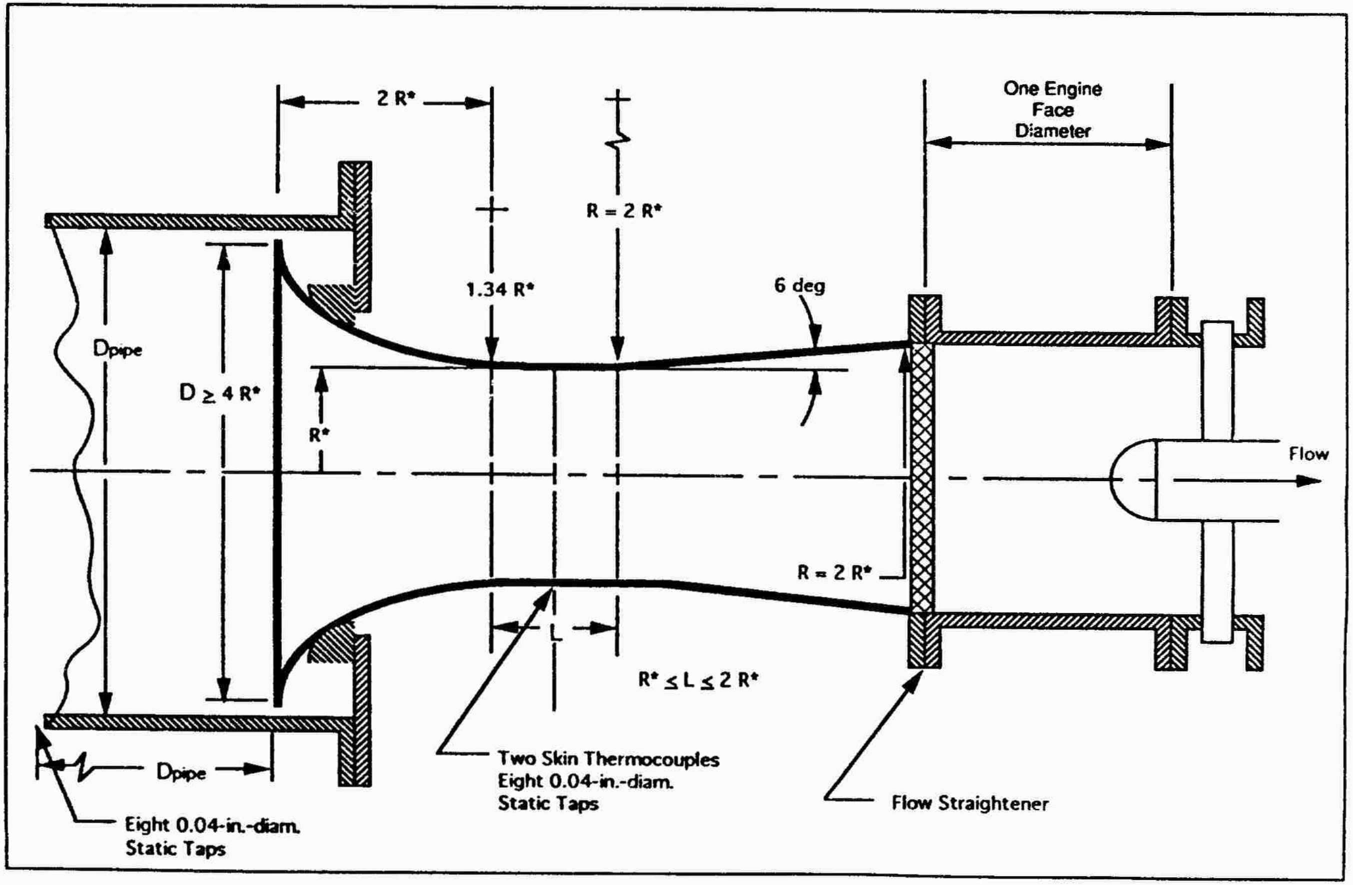


Figure 4.4-30 Subsonic Venturi Design Example
(Reference 4.4.10)

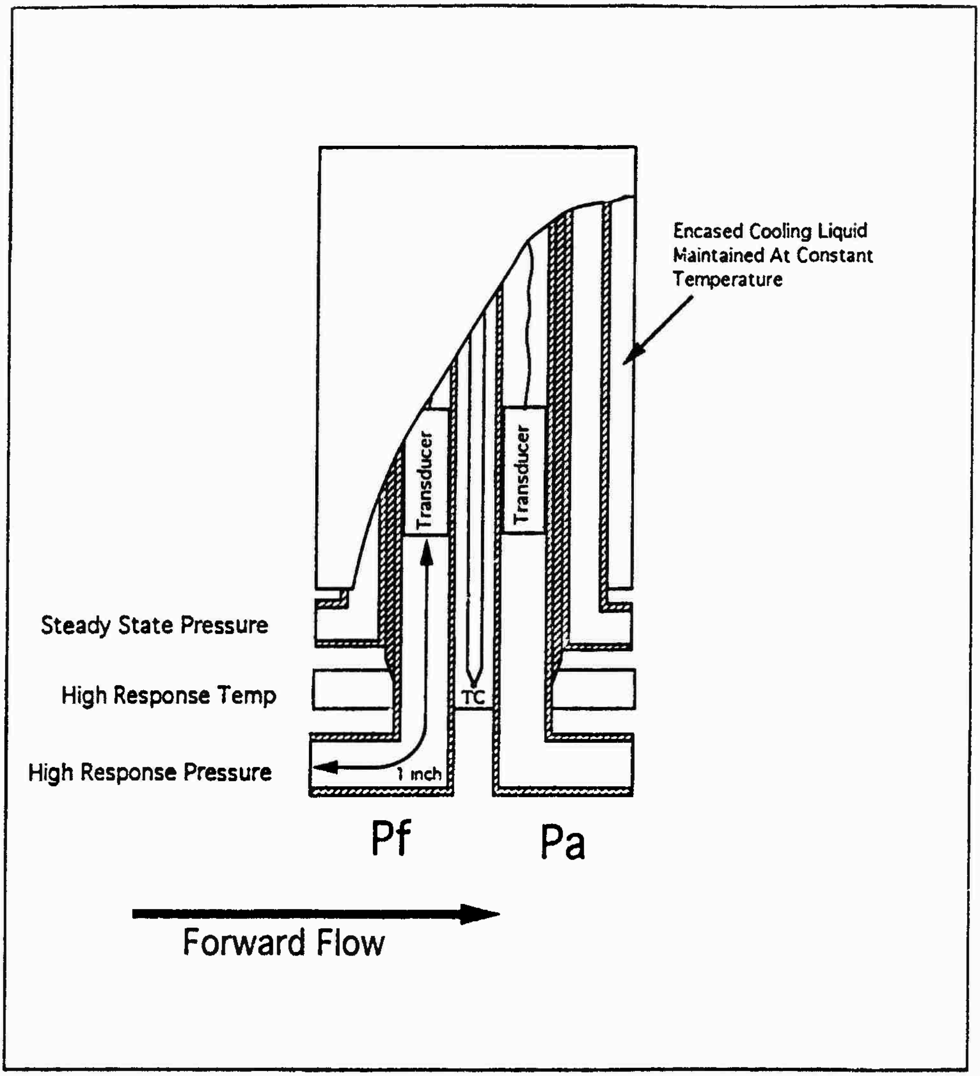


Figure 4.4-31 Fore-Aft Probe Schematic

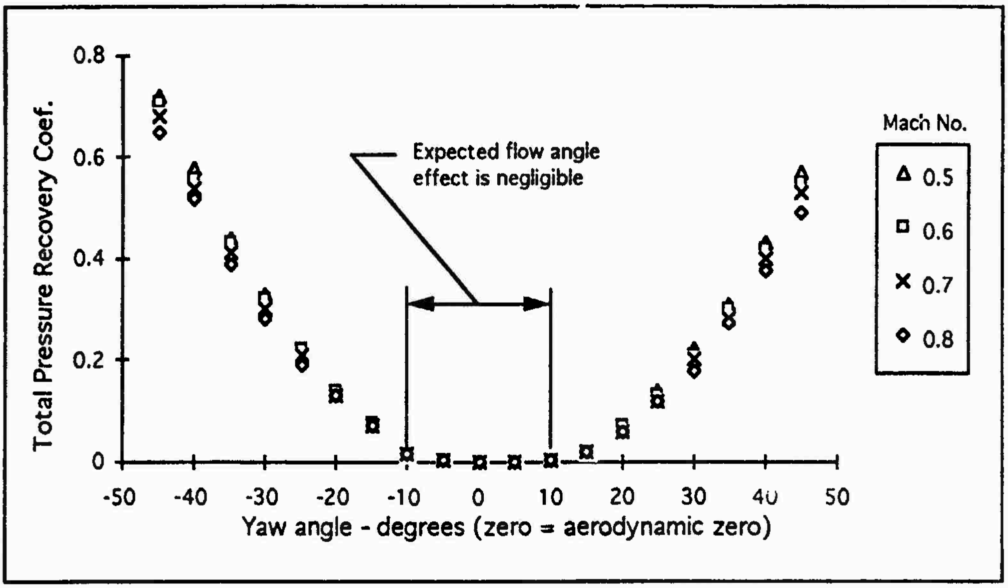


Figure 4.4-32 Fore-Aft Probe Yaw Angle Effect

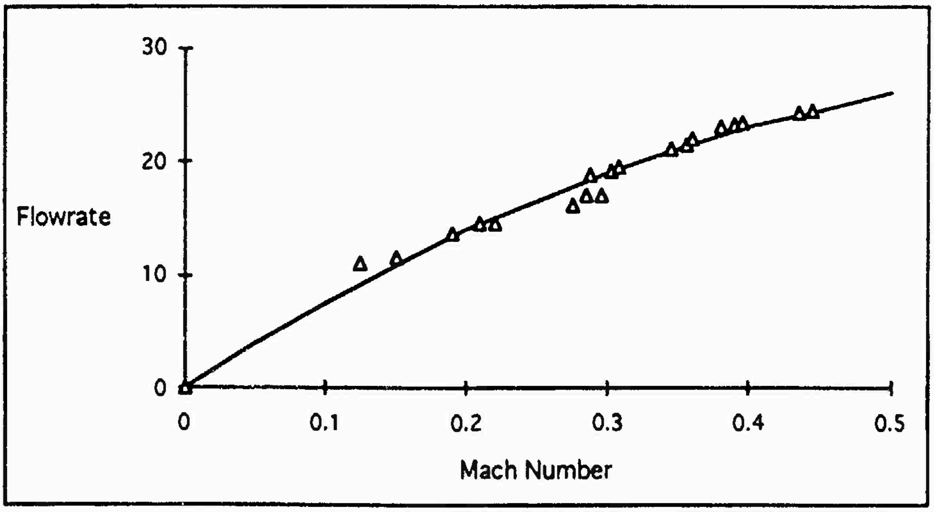


Figure 4.4-33 Mach Number to Average Flow Correlation

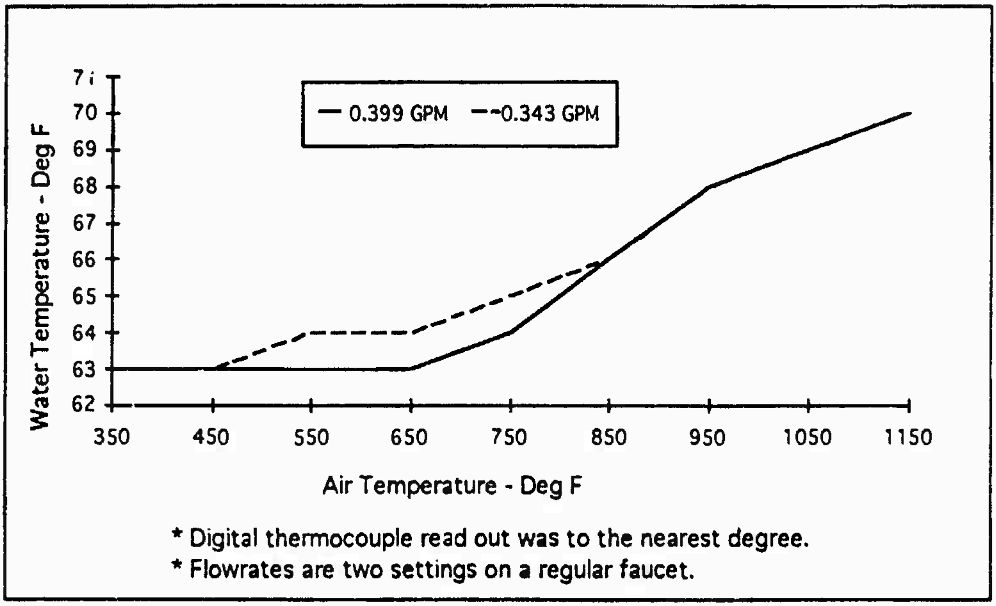
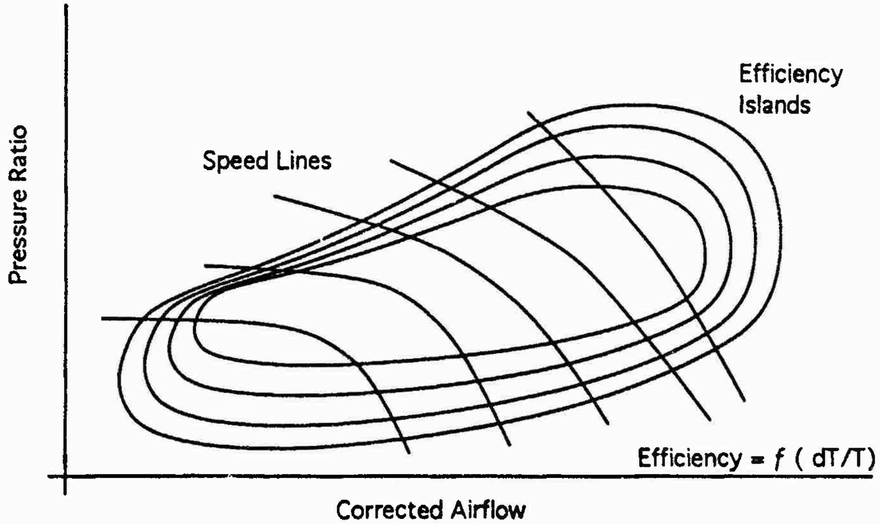


Figure 4.4-34 Fore-Aft Probe Cooling Effectiveness Investigation



Airflow can be determined with:

- Measured speed, inlet pressure, and exit pressure.
- Measured speed, inlet temperature, and exit temperature.

Figure 4.4-35 Determination of Transient Airflow Through Aero-Map Relationship

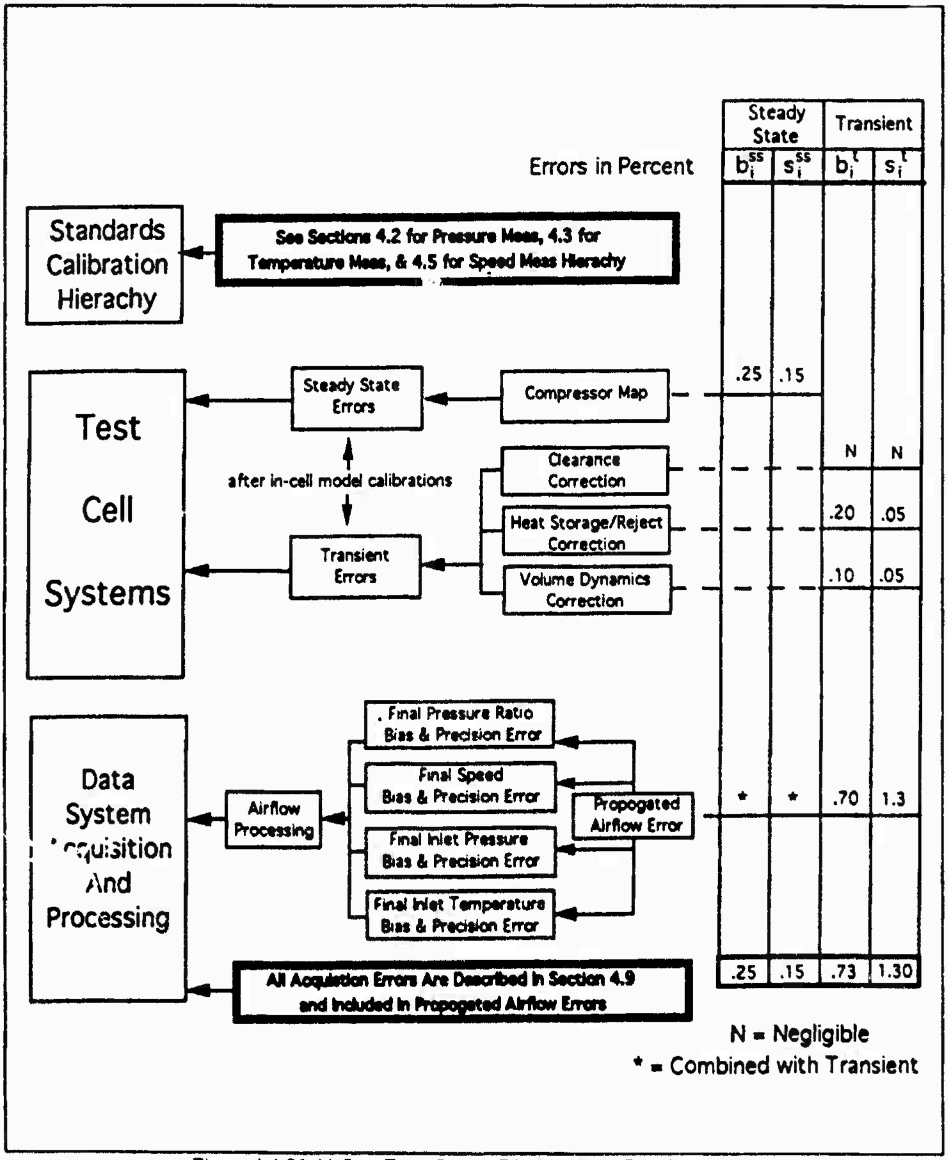


Figure 4.4-36 Airflow Error Source Diagram for a Fuel Pulse Test

4.5 GEOMETRY[1]

4.5.1 Introduction and Definitions

This chapter discusses the measurement of physical changes related to the engine structure during transient operation. Three main subject areas may be distinguished:

a) Rotational speed
The shaft speed is a primary parameter used in the fuel control and from it is derived the corrected speed N/√T, often used as a control parameter and required to draw the operating point or transient line on the compressor map. Both the rotational speed and the speed rate are important parameters during transients.

b) Variable geometry regulated and controlled by the engine control.
Most engines in use today have many items regulated and controlled by the engine control. These items are the Variable Inlet Guide Vanes (VIGV), Compressor Inlet Variable Vanes (CIVV), Variable Stator Vanes (VSV), Variable Area Nozzle and bleed valves for anti-surge and aircraft conditionning. The positions of all these items determine the engine's geometry which influences the equilibrium point (Steady State operating point) and the transient operation of the engine. Further, some future engines, e.g. (supersonic and hypersonic engines) will have an extended variable geometry as variable bypass ratio is obtained by regulated flow valves in the flowpaths.

Surge and rotating stall can be induced by an incorrect position of these items. Therefore, the instantaneous positions of vanes, bleed valves and nozzle, i.e. the instantaneous geometry, must be measured and recorded during transients. The available instrumentation for linear and angular positions will be discussed in the following paragraphs.

The calibration procedures for Variable Area Nozzles are unique and are discussed in detail in Section 4.5.3.6.

The measurement of the angle of the pilot's power lever (PLA) utilizes transducers similar to those used to measure changes in engine geometry instigated by the engine control. The considerations that affect the choice of transducer for PLA measurement under transient operating conditions are discussed in Section 4.5.8.

c) The geometry determined by the structural deformations.
The clearances between blades and stator, in the air and oil seals, and between discs and static structures are not only important for the engine's equilibrium point but can also induce surge and stall. The measurement of these clearances are rather difficult and needs measurement equipment and test cells only available in a few large test establishments.

4.5.2 Shaft Rotational Speeds

The measurement of the engine rotational speeds is a fundamental necessity in all turbine engines. Engine performance, control and safety are all inherently related to engine rotational speeds and their limits of operation. The measured speed can also be used as a primary control parameter to provide stable operation of the engine. In addition, in an engine development program the engine rotational speed can provide:

1. An intermediate step in obtaining the measurement of some parameter of primary interest, such as thrust or torque.
2. Functional checks of engine performance in events such as flame out, relight, instability, etc.
3. The determination of the transient and steady state engine performance characteristics.

There are a number of techniques available for engine speed measurement. These techniques vary from mechanical governors to variable reluctance magnetic sensors. The accuracy required of the measured speed dictates, to a large extent, the technique employed. However, the required accuracy of the speed measurement depends generally on the application. To obtain a more precise engine speed control and to enable analysis of the engine performance, an accuracy of 0.05% may be considered necessary, whereas an

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[1] Tables and Figures for Section 4.5 begin on page 4-183

accuracy < 1% may be considered sufficient when the measured speed is used to provide aircraft cockpit indication to ensure a safe operation related to speed limits. A precise engine speed control is particularly desired to avoid "beat" resonances due to minor differences in rotor speed on multiengined propeller aircraft.

The sections that follow provide brief overviews of the different engine rotational speed measurement techniques, calibration requirements, their advantages and disadvantages, together with a design example of variable reluctance magnetic speed measurement techniques discussed in some detail. There are many devices available for measuring the rotational speed but, in this section, only the principles of the speed measurement are discussed.

4.5.2.1 *Centrifugal Tachometer*

This technique for measuring and regulating the rotational speed uses the ball-head speed sensor (flyweight governor). The principle of operation of the flyweight governor is illustrated in Figure 4.5-1. As the speed increases, the force tending to move the flyweight outwards increases as the square of the engine speed. The centrifugal force (F) acting upon mass (m) is

$$F = m\omega^2 r \qquad 4.5\text{-}1$$

where m is the mass of the flyweights, ω is the rotational speed, and r is the radius of the centre of mass from the axis of rotation.

As the centrifugal force increases, it compresses the spring, and by measuring the distance ΔL (i.e. the reduction in spring length) the engine speed can be determined. This speed measurement system can be used for mechanical control applications and to actuate an indicating system. Any force that is required to actuate an indicating system, or operate as a servo, acts as a load and will decrease the effective travel (i.e. ΔL) of the rotating mass with speed. The system is also sensitive to friction, which causes hysteresis in the output. By using compensating masses on both sides of the bell-crank pivot the sensitivity to acceleration is reduced and the system can be operated in any position.

Advantages and Disadvantages

Mechanical speed governors provide effective engine speed governing and limiting function as the engine fuel flow can be directly controlled. However, the indication of the speed requires an additional displacement measurement device or a precision mechanical linkage. The loading due to mechanical linkage will affect the accuracy of the speed reading and friction will add hysteresis to the reading.

4.5.2.2 *AC Tachogenerator*

A tachogenerator is a small alternator which usually consists of a permanent magnet rotor with a number of poles, within a three phase winding stator. The stator typically has three windings whose axis are geometrically displaced from one another by 120°, so as to generate a three phase signal.

A schematic of a typical tachogenerator is shown in Figure 4.5-2. The tachogenerator is attached to the gearbox which is mechanically coupled to the shaft whose rotational speed is to be measured. A step down gear ratio is usually used depending on the shaft speed to be measured, to result in an industry standard of 4200 rpm tachospeed which relates to 100% engine speed design point. However, for special applications, the available tachogenerators can run up to 10,000 rpm.

The frequency of the three phase signal available from the generator is proportional to $N \times P$, where N is the engine rotational speed and P is the number of poles of the magnet. The engine speed is determined by measuring the frequency of the generator output by various means. The three phase signal obtained from the tachogenerator can be directly used in an electronic engine control to provide engine speed control in a monitoring system to provide engine protection or to provide cockpit indication.

The speed measurement is not available at very low engine speeds, as the amplitude of the generated EMF is less than a threshold level which is dependent on the type of indicating device being used. The amplitude of the signal is given by

$$EMF(peak) = KBN$$

where K = constant for the given tachogenerator configuration

B = flux density

N = engine speed.

The minimum measured speed is generally about 1% of full speed. The error of the speed measurement is typically < ±0.1% of full speed. The temperature range is usually limited to about -40 to +150°C.

Advantages and Disadvantages

AC tachogenerators involve the transmission of an electrical voltage when the information is contained in the signal frequency. The measurement range is typically between 50 rpm and 5000 rpm (although some modern units may go as high as 10,000 rpm), therefore a step down gearing is usually required. The upper speed of the tachogenerator is limited as a result of the power losses due to the hysteresis loop of the material of the stator and eddy current losses in the magnetic circuits. A particularly attractive application occurs when the dedicated AC Generator is used to provide the power supply to the electronic engine control and the obtained frequency of the induced EMF is utilized to measure engine speed.

The tachogenerator requires a dedicated "drive pad" for the generator and is heavy and large in comparison to magnetic sensors.

4.5.2.3 *DC Tachogenerator*

DC tachogenerators use an AC tachogenerator with a rectifier assembly. The generator delivers a DC voltage proportional to the rotational engine speed. The DC generators are rarely used in modern gas turbines because of numerous disadvantages, the principle of which is lack of sufficent accuracy. For example:

1. The induced EMF tends to vary in time and as a function of temperature due to the permanent magnet field variation.
2. The induced EMF is affected by the load impedance of the receiving circuit or instrument.
3. The residual ripple voltage is superimposed upon the DC voltage. However, this may be reduced by increasing the number of commutator bars, but this complicates the design.

4.5.2.4 *Magnetic pulse probe*

4.5.2.4.1 *Description and Basic Theory*

The speed signal pick-up consists of a pole-piece, one or more coils, a permanent magnet and signal wires all embodied in the probe housing, Figure 4.5-3. The pulse probe is installed on the stator at the periphery of a toothed disc (phonic wheel) or the blades of a compressor disc with a small airgap. The variation of the magnetic field due to the displacement of the teeth or blade in front of the probe induces a periodic output signal from the winding. The output signal is close to a sinusoidal wave, but the shape of the tooth or blades has some influence on the waveform as shown in Figure 4.5-4. Figure 4.5-5 shows typical suggested dimensions of a phonic (gear) wheel design. With this geometry the raw signal available from the probe at 73% speed was as shown in Figure 4.5-6. For a given probe and tooth or blade form the output signal amplitude is a function of:

(a) the air gap. Although in theory the output signal should be proportional to the inverse of the square of the gap, in practice it is generally proportional to $1/r^n$, where $n<2$. Therefore, calibration is necessary.

(b) the speed of the tooth or blade relative to the probe. The amplitude increases with speed to a certain level, above this level amplitude decreases (Figure 4.5-7). The voltage amplitude must be sufficient to trigger the counting device, so the minimum speed to be measured is a factor in the probe selection.

If the counting must be done down to zero speed, an 'active' pick-up can be used in combination with signal conditioning circuitry. This unit needs an external power source.

The tooth height is important to the signal quality. Irregularities or metal discontinuities can result in erroneous double pulsing and falsify the counting. The integrity of the probe is checked by the measurement of the coil resistance.

The measurement of the rotational speed is based on the counting of the number of pulses in a given time interval. A signal 'gate' starts and stops the counting device and a frequency meter provides a digital readout. This is the normal and accurate indication of RPM in steady state operation.

Frequency meters are available as laboratory instruments. The output of the probe can be the input of the counter, if the amplitude of the pulses is sufficient. For the measurement of the pulses from the toothed wheel, the time gate of the counter must be between some 10 msec and 1 sec. The accuracy of the time base, and thus the gate, is very high and does not affect the accuracy of the counting.

The signal (RPM) can be read on a digital display and is, on modern counters, also available on an IEEE-488 interface bus which links the counter with the computer and data acquisition system. Some counters also have a digital to analogue converter which delivers an analogue output signal directly proportional to the digital input. This output can be a DC voltage between 0 and 1 volt with an accuracy of ± 2 mv.

The output of the probe can also be connected to a converter. This device converts the periodic signal of varying waveform and amplitude to a square-shaped wave of constant amplitude and width (Figure 4.5-8). The integration of these waves in a given time interval gives a DC output, proportional to the mean speed on this time interval.

4.5.2.4.2 *Frequency range and accuracy*

The magnetic probe is relatively light in weight (e.g. < 200 gm), the effects of vibration and temperature are negligible on the reading, it exhibits an accuracy of speed measurement < 0.05%, it is small in size, and the stress imposed upon the rotating shaft is negligible. The sensors are capable of operation under extremely severe conditions, such as being immersed in lubricating oil or exposed to temperatures between -40 and +450°C.

The maximum operational frequency of the sensor is limited to obtain an acceptable amplitude of the induced EMF signal. Considering the circuit model of the speed measurement system, there will be a wide variation in reactances between the low frequency operation and high frequency operation since the capacitances of the circuits become significant at high frequencies. Due to the above reasons the maximum frequency of the operation is usually limited to 15,000Hz. However, the probe may be used for high frquencies, as long as the signal does not fall below the threshold value of the frequency detection circuit. The load impedance is required to be within the specificed band. Large numbers of teeth on a gearwheel are usually used to obtain improved accuracy on the speed measurement.

The accuracy, if no false pulses are generated outside the tooth or blades, is essentially dependent on the number of teeth and the time gate in the steady state operation. In the transient measurement the DC signal is the mean value obtained by integration over a given time interval. Increasing the time gate improves the accuracy of the mean value but also augments the difference between the two extreme values of RPM corresponding to the start and the end of the integration time.

The number of blades on the fan or compressor is given by the engine design. In the case of a phonic wheel the number of teeth can be chosen for convenience (within reason). The output frequency can be increased by increasing the number of teeth but this will generally result in a lower output signal (depending on the electrical properties of the pulse probe) and a limitation of the maximum RPM. Often a phonic wheel with 180 teeth can be mounted on the engine tachometer pad.

On an engine with digital electronic fuel control, the update rate is about 50/sec which corresponds with a time interval of 20 msec.

4.5.2.4.3 *Design examples*

Examples of the uncertainty analysis will be presented for two typical cases (see Section 5):

(1) Surge Margin Measurement Using a Fuel Spike (see Section 5.2)

(a) Measurement of the rotor speed just prior to the surge event, steady state:

This steady state measurement can be done with a pulse generator on a phonic wheel (mounted on the tacho pad) and a frequency meter.

n = number of pulses per revolution

N_H = rpm of HP rotor

Np = rpm of the phonic wheel (typically $N_H/3$)

Δt = time interval of the frequency counter in sec, (for example, 20 msec).

The number of pulses in the given time interval is $Np.n.\Delta t/60$. The error or uncertainty is given by

$$\pm\frac{1}{\frac{Np\cdot n\cdot\Delta t}{60}}x100 \quad \text{or} \quad \pm\frac{60}{Np\cdot n\cdot\Delta t}x100 \quad \% \qquad 4.5\text{-}2$$

Example:

Phonic wheel with 180 teeth, $n = 180$

N_H = 11700 rpm

Np = 3900 rpm

Δt = 20 msec

The uncertainty is:

$$\frac{\pm 60}{3900\cdot 180\cdot 0.02}x100 = \pm 0.43\%$$

This represents the precision error (s). The only bias error in the steady-state measurement would be in the timer - which would be very small, and can be considered negligible in this case. (The output will be a digital signal updated every 20 msec.) Therefore, the absolute uncertainty for the measurement of the steady-state speed of 11700rpm is of the order of ±50 rpm.

(b) The speed measurement during the transient after the fuel spike:

The frequency counter indicates the mean value of the speed in the time interval.

ΔN = the speed increase in rpm

the mean value of the speed in the time interval is $N_i + \Delta N/2$, and the absolute error is $\Delta N/2$ if there is a continuous acceleration or deceleration and not an oscillation of the speed.

The relative error (bias error) is

$$\frac{\Delta t \cdot \Delta N}{2 \cdot N} x100 \quad \% \qquad 4.5\text{-}3$$

In the example (Figure 5.2-6):

Speed excursion = 50 rpm (0.5% of N_H)

Time derivative: = 1110 rpm/sec (approx. 10% N_H /sec)

The relative error (bias error) is then:

$$\frac{1110 \cdot 0.02}{2 \cdot 11700} \text{ x } 100 = 0.10\%$$

or an absolute error of 12 rpm.

Conclusions - Surge Margin Measurement Test:

In the limited speed variation of 0.5% it seems impossible to measure the instantaneous speed; the absolute error in the steady state is of the same order as the speed excursion (±50 rpm). The error in the transient measurement will be increased by the steady-state error.

It is impossible to improve this accuracy in the transient measurement by reducing or increasing the time interval Δt (increasing or decreasing the update rate).

(2) Acceleration Time Test (see Section 5.3, Figure 5.3-1)

(a) The steady state measurement error

The relative uncertainty is given by Equation 4.5-2.

Assume N_H (100%) = 16,500 rpm.

Then, the uncertainty (bias) is:

$$\text{for } N=100\%: \quad \pm \frac{60}{5500 \cdot 180 \cdot 0.02} x100 = \pm 0.30\%$$

$$\text{for } N=50\%: \quad \pm \frac{60}{2750 \cdot 180 \cdot 0.02} x100 = \pm 0.60\%$$

(b) The transient error.

The absolute value of the error is ΔN/2.

For the event we can calculate two values of ΔN%/sec:

From Figure 5.3-1,

For high values of N (85%): ΔN%/sec is about 42%N/sec, and

For low values of N (60%): ΔN%/sec is about 20%N/sec.

The absolute value of the error at N = 85% is, therefore:

$$\frac{0.42 x 0.85 x 16500 x 0.02}{2} = 60 \text{ rpm}$$

The relative error is:

$$\frac{60}{0.85 x 16500} \text{ x } 100 = 0.4\%$$

One could make corrections during the increase of the speed from the function N = f(time) with the known bias of ΔN/2.

4.5.2.5 *Turbine Blade Frequency Using the Pyrometer*

Some engines are equipped with a pyrometer to measure the temperature of the blade metal. The beam of the pyrometer is small and the output signal proportional to the measured temperature is periodic due to the variation of the temperature on the blade outer surface on a given radius (Figure 4.5-9). The peak temperature is on the leading edge. The signal can be used in a conditioning circuit to produce square shaped pulses. The pyrometer can be used for frequency measurement of the speed in case of an emergency, such as the normal pulse probes failing.

4.5.2.6 *FM Grid and Blade Tip Magnet*

In a development engine a grid can be installed on the compressor casing, and a small magnet inserted on the tip of the blade (Figure 4.5-10). Although the basic purpose of this measurement system is the vibration analysis of a blade, it may be used as a rotor speed measurement.

The high number of teeth (windings) in the grid, results in a high frequency signal. A typical example is 250 windings (grid) and a speed of 200 revolutions per second (12000 RPM). The resulting frequency is 50 kHz with an output signal in the millivolt range. This signal has a high resolution and can give accurate speed signals in steady state operations and during transients if an adequate integration time is chosen.

4.5.3 Variable Geometry, Measurement of Linear and Angular Positions

4.5.3.1 ***Potentiometer***

4.5.3.1.1 *Description and basic theory*

The variable-resistance transducer is a coil of wire on which slides a moving contact, through either linear or angular movement (Figure 4.5-11). It is also called a resistance potentiometer or rheostat.

4.5.3.1.2 *Transient measurement*

The problems that arise are due to the mechanical contact. The frequency response can be good, as high as 50 Hz. The linearity is good and can attain 0.1%. The temperature of the wire changes the resistance and some thermoelectric effects can occur. The principal problem in the application of potentiometers for transient testing is wear.

4.5.3.2 ***Displacement Linear Variable Differential Transformer (LVDT)***

4.5.3.2.1 *Description and basic theory*

The linear variable differential transformer is an electromechanical transducer that produces an electrical signal with an amplitude proportional to the linear displacement of a movable core fixed on the item (Figure 4.5-12).

The general arrangement consists of three coils, one primary and two secondary coils, which are equally spaced on a cylindrical coil form with a rod-shaped magnetic core positioned axially inside the coil assembly and providing a path for magnetic flux linkage between the coils.

When the primary, or center coil, is energized with an alternating current, voltages are induced in the two secondary coils. These two outer or secondary coils are connected in series opposition. The two induced voltages in the secondary circuit are therefore opposite in phase. The net output of the transformer arrangement is the difference between the two secondary coils.

When the core is in its centre position, the output of the transformer is zero. This position is referred to as the null position. If the core is moved away from the null position, the induced voltage increases in the coil toward which the core is moved, while the voltage induced in the opposite coil decreases. The output is a differential voltage which varies linearly with the core position. A movement of the core in the opposite direction, i.e. on the other side of the null position, produces a similar output, but with the phase shifted 180 degrees (Figure 4.5-13). In the vicinity of the null position a slight nonlinearity is encountered. This is due to parasitic capacitances between the primary and secondary coils.

For the user's convenience, the voltages of both coils can be rectified (Figure 4.5-14) and opposed. The obtained mean voltage is proportional to the core's displacement.

4.5.3.2.2 *Transient measurement*

The LVDT is well adapted for transient measurements. There is no mechanical contact, the frequency response is primarily limited by the inertia characteristics of the device. Although the LVDT could, in principle, be used for vibration measurements, it is not suitable for high frequencies or multi-dimensional vibrations.

The output frequency is a function of the frequency of the applied voltage. The rule is that the frequency of the applied voltage should be 10 times the frequency of the displacement of the core.

4.5.3.2.3 *Guide to selection*

Design considerations of windings, coil form and selection of materials can provide an accuracy and reliability with a friction-less operation and insensitivity to external electromagnetic and electrostatic influences.

The LVDT can be designed to special physical configurations like miniature, subminiature, long stroke to body length and high temperature applications. However, at high temperatures, the current through the primary coil is altered due to the changed coil resistance, and therefore affects the excitation of the primary coil.

A temperature compensation can be introduced by using the output sum of the two secondary coils, i.e., the deviation from a defined value as required input for a temperature correction. This method is also applicable for changes in the power supply and can be integrated as a closed loop correction. Another possibility to reduce the temperature effect is to increase the excitation frequency to 2.5 - 5 kHz.

The absence of contact is a great advantage as there is no wear of the measuring device. The sensitivity can be very high and displacements as small as 1 micron can be measured. Table 4.5-1 shows some technical specifications of an LVDT.

4.5.3.2.4 *Signal conditionning*

The primary coil is connected to an A.C. voltage with required frequency. It can also be operated using a DC power supply with an oscillator. The electronic oscillators, demodulator, temperature control, and amplifier can be built in easily and the device presents 4 plugs, 2 for input voltage and 2 for output or measurement signal (Figure 4.5-15).

4.5.3.2.5 *Comparison of potentiometer and LVDT*
Table 4.5-1 indicates the differences of the two linear displacement devices (Reference 4.5.1).

4.5.3.3 ***Resolver***
4.5.3.3.1 *Description and basic theory*
The resolver is an assembly of two immobile windings mounted at 90° and a rotating winding (rotor) as shown on Figure 4.5-16. u_1 and u_2 are the AC voltages with a phase difference of $\pi/2$ applied on the two immobile windings.

The voltage induced in the rotor winding is a sinusoidal wave dephased by ϕ/ω, where ϕ is the angle of the rotor and $\omega/2\pi$ the frequency of the input voltages. This angle ϕ can be measured with adequate electronic devices. In an alternative approach, the rotor winding is supplied with an AC voltage and the signals induced in the immobile secondary windings are used to calculate the angle ϕ.
4.5.3.3.2 *Transient measurement*
The applied input voltage is mostly of the order of 10 kHz and the accuracy is higher than 10^3 rad. The accuracy is limited by the electronic phase measurement.

A resolver is a rugged device, well suited for the measurement of angles of mechanical devices whose frequency components of rotation are well below 1/10 of the input frequency, i.e. below about 1 kHz.

4.5.3.4 ***Rotary variable transducer***
4.5.3.4.1 *Description and basic theory*
The principle of the rotary variable transducer is that of an AC-transformer. A given excitation voltage applied to the transformer input produces an output AC voltage without phase shift and with an amplitude, within certain limits, proportional to the angle of the rotor (Figure 4.5-17). In reality the measurement device is a rotary variable differential transformer fitted with two coils, a clockwise and a counterclockwise winding. The magnetic flux in the zero position is divided in two equal parts, half of the flux directed through the clockwise winding and the other half through the counterclockwise winding. In this position the sum of both voltages is zero (Figure 4.5-18).

When the rotor has a certain angle relative to the zero position the sum of the output voltages from both windings is an AC voltage, which is integrated to an RMS value. The output voltage during a 360° full rotation will be a two-cycle saw tooth profile (2-cycle RVT). The RMS value is linear function of the angle for rotations between -40° and +40° from the zero position (Figure 4.5-19).

The use of long-stroke or one-cycle RVT can be applied to a measurand where the sensor range may exceed the ±40°. The one-cycle RVT can cover the range ±80°, but the overall accuracy will be deteriorated.
4.5.3.4.2 *Transient measurement*
The maximum response in frequency is again determined by the frequency of the input voltage. This can be between 400 and 5000 Hz as indicated in Table 4.5-2.
4.5.3.4.3 *Guide to selection. Advantages and Disadvantages*
Table 4.5-2 lists typical operational characteristics and gives the guideline for a particular measurement problem.

RVTs are compact and can be attached to the measurand without backlash, giving a good response. There is no mechanical contact except the rotor bearings. RVTs have a very high reliability and long term stability. They have a linear response with high accuracy. They are resistant to harsh environmental conditions as well as shock and vibration. Additional shielding may be required in strong stray magnetic fields.

A disadvantage is the range ±40°, which might be too low in some cases.
4.5.3.4.4 *Calibration*
The calibration has to be accomplished with the classical mechanical or optical instrumentation for measurement of angles and comparing with the output signal.

Linearity is generally only within ±40° rotation relative to the electrical zero. To obtain a common, nominal output slope or scale factor, the trimming of a calibrating resistor across the output leads will be necessary. A variety of factors can influence the linear range:
- air gap size (rotor eccentricity and roundness),
- flux path permeability,
- actual ratio of coils in the input/output windings,
- temperature,
- impedance of the intended signal processing circuitry.

A typical temperature effect will be the increase in coil winding resistance with increasing temperature, causing current reduction and lowered magnetic flux, giving less output signal. The effect on linearity is neglible. Only the scale factor or output slope will suffer from a temperature deviation. Typical accuracy aspects are illustrated in Figure 4.5-20.

4.5.3.5 *Examples*

The resolver as well as the rotary variable transducer are used to measure the angles of VIGV, VSV, VBV, and possibly the nozzle and throttle position. (These last two items are detailed in Sections 4.5.3.6 and 4.5.3.7.)

In some engines, the angular position of the compressor inlet variable vanes is measured and given to the electronic supervisor by the signal of a resolver. Other resolvers are built in the hydromechanical fuel control on rods or cams whose angular positions are proportional to physical variables, e.g. burner pressure, rotational speed.

In other engines the position of the variable stator and bleed valves are measured by an LVDT. We give here an example of a tracking chart for a variable stator vane (Figure 4.5-21). This engine has an LVDT installed for cockpit reading of position.

The angle variation from closed vanes to full open vanes is about 50° (from -7° to +43°). The rate of angle displacement is in the order of 20°/s.

4.5.3.6 *Nozzle Throat and Exit Area*

4.5.3.6.1 *Introduction and definitions*

A variable exhaust nozzle area is necessary to fulfill several operational requirements from the engine and control system overall performance aspects.

The variable nozzle can be a multi-flap type convergent nozzle to save weight, or a more sophisticated convergent-divergent exhaust nozzle to obtain better performance, especially at high flight Mach No, even with floating links to obtain the correct exit area, i.e. to expand to the ambient pressure. The exhaust nozzle layout and components are shown on Figure 4.5-22.

The nozzle petals are operated by actuator pistons, powered by hydraulic cylinders or flexdrives connected to an airmotor, driven by engine bleed air.

The nozzle position or throat size is measured with a nozzle area transducer, which in a broad sense, is a position indicator.

The nozzle area sensor is normally a basic accessory item, i.e. a part of the control system. The raw transducer output signal will go into the control system circuitry where it must be buffered or split for measurement of nozzle indicator purposes (Figure 4.5-23).

4.5.3.6.2 *Transient measurement*

The operation of the nozzle from a normal area to a fully open nozzle within 0.5 sec or during a slam excursion to the full afterburner throat size within 1 to 1.5 sec indicates how fast the nozzle area may change for transient recording.

As the transducer is mechanically linked to the moving shroud, all nozzle movements will be sensed immediately by a changed transducer output, even small step changes or nozzle switching.

4.5.3.6.3 *Calibration procedures*

A fixed defined relationship between transducer output voltage and geometrical nozzle area is used by the control system, established as average values for the production line scatter band (Figure 4.5-24).

A more accurate relationship for the individual transducer can be established by a calibration procedure where special disks with defined areas are used as reference for the transducer output voltage.

A calibration disk is positioned into the nozzle and the petals are closed against the disk with a defined actuator force or torque.

The full range calibration is normally done by opening the nozzle in steps from small areas to greater areas and then down again to compensate for the mechanical resistance and hysteresis in the system. As the multiflap nozzle arrangement does not yield an accurate circular round shape, as indicated in Figure 4.5-25a, the geometrical reference area of the calibration disc is slightly greater than the circular area, using the disk diameter alone.

The actual size, i.e. applied correction to the disc, has to be measured on the drawing board and identified on the individual disks.

Typical correction factors are shown in Figure 4.5-25b. The real correction factor is somewhat variable due to the mechanical friction and position of the flaps, relative to each other, tolerated by the system design.

A special calibration exercise, illustrated in Figure 4.5-26, done three times with increasing and decreasing areas, shows the typical scatter in a nozzle calibration. The smaller areas, normally for dry operation, gives an expected accuracy of ± 0.3%. The larger areas, for partial and max. afterburner operation, do not give an accuracy better than ± 0.5%.

The calibration is done with a cold engine. The conditions during real engine operation with hot and expanded materials and gas pressure on the throat and petals may give a slightly increased actual area for the same transducer output. One way to compensate for the effect of hot materials is to carry out a calibration check immediately after a shut down from afterburner condition.

4.5.3.6.4 *Example*

A cable or link rod connects the shroud to the transducer and translates the axial movement into an electrical signal. It is recommended that the transducer be mounted in zones where temperatures and vibration levels are not too high.

A control area sensor will have its signal shape and characteristics corresponding to its accessory specification, i.e. normally a resolver pick-off with sine-wave output. Dedicated sensors for test bed instrumentation can be fitted to actuating rods or to the shroud. Position indicators can be connected to the individual petals or even to the angular position of the flaps to be used for special purposes.

However, the signal quality and the durability of the pick-off suffer when the pick-off is mounted next to the petals. The nozzle position is often indicated in the cockpit. This is done with a synchrotype gauge (Figure 4.5-27). The use of the cockpit nozzle position indicator in a transient test is illustrated in Section 5.3.

4.5.3.7 *Throttle/pilots Power Lever*

4.5.3.7.1 *Introduction and definitions*

The aircraft-installed multifunction throttle-box is a complex unit with integrated micro-switches and position indicator to allow simple starting, general operation and shut-down of the engine. The throttle grip itself may have relight-buttons, airbrakes, radio-transmission, other switches and push buttons incorporated.

The throttle lever normally has intermediate mechanical stops and detents to facilitate the operation in the scaled thrust ranges, like:

- shut off position,
- start and idle position,
- Max. Dry Condition,
- Afterburner/reheat operation,
- Combat override/Emergency Rating,
- Thrust reverser operation.

The connection between the throttle and engine control system can vary, depending on the engine standard:

- Mechanical linkage to the hydromechanical fuel control unit,
- Electrical, hardwired to the electronic control unit,
- Bus controller for transfer of digital data between pilot's lever and engine control system.

However, as the control system signals may not be cleared or permitted for instrumentation purposes, the throttle box in the aircraft or the test bed lever may require separate sensors to indicate the lever position.

The test bed instrumentation for recording purposes is normally one of:

- precision rotary potentiometer,
- rotary variable transformer,
- resolver.

4.5.3.7.2 *Considerations for transient measurements*

The pilot's lever demand is the prime input to the control system, and the engine is reacting to obtain the requested condition. Any engine major transient is therefore dictated by a foregoing throttle movement.

The throttle movement can be a moderate excursion or a snap change between maximum and idle throttle position, within a fraction of a second. The test bed-related pilot's lever sensor must be able to take such rapid changes without any delay or phase advance.

4.5.3.8 *Switches for open/close - lock/unlock*

Switches or microswitches can be used to indicate an event or a dedicated position of a moveable item. The functional aspect is to provide a yes/no-signal and give this information to the control system or to an event/alarm indicator.

A corresponding arrangement of switches can be fitted to:

- thrust reverser, to assure proper stowed or deployed position,
- bleed actuator, to indicate fully open or closed position,
- pilot's lever, to energize or deenergize coils and circuitry in the fuel system.

Tapping of switches and microswitches in the engine accessory equipment and additional switches for test bed instrumentation can be used to identify the exact time of a certain event or happening during a transient operation.

4.5.4 *Structural Clearances and Deformations*

During the operation of any gas turbine the varying mechanical loads, centrifugal forces and thermal gradients which arise can result in relative deflections between neighbouring components. These movements often become most apparent during transient operation and can, for example, lead to increases in compressor (or turbine) tip clearance resulting in a fall of efficiency or decrease in effective surge margin. On the other hand, when an interference (i.e. rub) occurs the erosion which takes place remains and this will often result in a permanently degraded engine performance and reduced surge margin.

Other deformations such as those movements which tend to cause a disengagement of labyrinth seals could, for example, lead to changes in cooling flows or hot gas leakage, thus contributing further to performance penalties and exacerbating component temperature gradients.

Many other types of movement take place within an engine, e.g. rotor blade untwist, but only a limited number of measurement techniques will be discussed below.

Although calculated estimates of structural displacements will have been made during the design phase of the engine or component it will be necessary to confirm these by direct measurement. In most cases it will be advisable to superimpose allowances for surge deflection and vibration on top of these to account for movements during the worst transients. In many cases the distortions will be non-axisymmetric, taking the form of casing out-of-roundness, eccentric rotation and tilt between neighbouring parts. These unsymmetrical distortions could result from inertia loads during aircraft manoeuvring, transfer loads from engine thrust pick up points, unsymmetrical temperature gradients, etc. If such distortions are suspected two or more probes must be installed at each axial station.

Taking compressor blade tip clearance as an example, it is usually adequate to determine the clearance of the longest blade, or a mean value, for each blade row. It is seldom necessary to measure the clearance to each blade. The total uncertainty required for these measurements will be dependant on the objectives of the tests but values within the range ±0.05mm are normally sufficient. Data of this level can usually be achieved providing care is taken with sensor installation and system calibration.

As well as measurements of deformation it will be necessary to take recordings of local structure temperature, rotational speeds and other essential engine operating conditions, all related to a common time base.

As engine testing proceeds, and the data bank of measurements increases, the theoretical model which is used to calculate displacements can be made more reliable and thus the necessity for gap measurements becomes less important.

There are several different methods for measuring gaps and displacements (Reference 4.5-2); five widely differing methods are listed below. Obviously these methods have different characteristics and therefore different applications.

The methods discussed are:

(i) Touch probes
(ii) Proximity probes
(iii) Capacitance probes
(iv) Optical triangulation probes
(v) X-rays

Probes (i) to (iv) are directly attached to the engine or component case and therefore care must be taken to ensure that they are mounted such that a true measure of the gap or displacement is detected. This must also apply to any calibration equipment in which a realistic engine environment must be simulated.

4.5.4.1 *Touch or interference probes*

Touch probes can take many different forms, the simplest being that in which the gap is indicated by the length remaining after the moving component has removed the excessive material. Such probes indicate the minimum gap which can only be measured following a strip of the engine or removal of the probes.

Other forms of touch probes are those which indicate the initial occurrence of contact through, for example, the completion of an electrical circuit (Reference 4.5.3).

4.5.4.2 *Proximity probes*

Proximity probes are normally used to indicate rotor blade tip clearance although with modification they may be used for other purposes (Reference 4.5.4). In this probe an electrode is sequentially advanced, using a precision stepper-motor-powered actuator, towards the moving blade tip and "contact" with the blade is indicated by an electrical discharge. It is normal practice when using these probes to operate the stepper motor at frequencies below that indicated by the once-per-rev pick up. In this case the gap indicated will be that of the longest blade. This type of probe has found widespread use for tip clearance measurement mainly because of its reliability and the simplicity of achieving a datum clearance calibration during engine or component build. Further advantages are that it is possible to achieve relatively high accuracy in practical applications, better than ±0.05mm, and that it can operate over the full range of temperatures experienced in modern gas turbines. Because of these features it is often used in parallel with other clearance measuring devices, e.g. capacitance probes, to act as a calibrator.

Stepper motor probes however, have the serious disadvantage that they are relatively bulky and therefore may not be suitable where space is limited or where a suitably robust mounting structure close to the measurement point is not available.

4.5.4.3 *Capacitance probes*

Capacitance probes can take many forms; their main use being the measurement of blade tip clearance or rotor axial movement. The general principle of operation is the formation of an electrical capacitor between the moving component and a sensor plate mounted in the neigbbouring structure. When used for blade tip clearance measurement the sensor will be mounted in the casing and the matching capacitor plate will be formed by the blade tip. The variation in circuit capacitance as each blade passes under the sensor, and any additional gap changes during a transient, can be calibrated to give a measure of the tip to sensor clearance of each blade. The actual value of electrical capacitance can depend upon many factors; the gap, blade end geometry, structure surrounding sensor, fluid properties within the air gap (ionisation/combustion), spurious build up of electrical charge, etc., and obviously the configuration of the sensor itself and its associated equipment.

Calibration is therefore essential for each installation by traversing the probe, surrounded by a structure representing the casing, radially towards a rotating model of the blade tip, or preferably the actual engine rotor itself. The zero datum is a particularly important parameter.

Two basic systems are currently is use; the Direct Current (DC) system or the Frequency Modulated (FM) system. The DC system has the advantage in that the sensor is compact and can with careful installation and calibration measure clearances to a total system uncertainty approaching ± 0.05mm. It has the serious disadvantage that it is significantly affected by gas ionisation (combustion) and the build up of electrical charge in the engine components. There are, however, developments of the DC probe which make it suitable for some compressor applications. One procedure is to periodically change the polarity of the DC signal (say every 10 seconds). This avoids or minimizes the disadvantages of ionisation and electrical charging. (see also Reference 4.5-5).

As the FM system is the most commonly used type it will be discussed in detail. A block diagram shown in Figure 4.5-28 illustrates the essential components. As capacitance varies as the inverse of the distance of the electrode separation the output of the system will be of the form shown in Figure 4.5-29. As a consequence the error in measurement will increase as the clearance gap gets larger. A typical variation is shown in Figure 4.5-30. These latter two figures are merely illustrations; the actual values for each probe installation/data acquisition system must be obtained by careful calibration. It is essential that the manufacturer's recommendations be observed. Some typical rotor blade tip clearance measurements taken on the HP compressor of a large civil turbofan, during a 50 minute flight cycle are shown in Figure 4.5-31. Because the FM system is insensitive to the ionised gas stream from the combustor, measurements within a turbine are possible. However, as some electronic components must be mounted close to the sensor, in current designs, cooling is often necessary, Figure 4.5-32. The resulting bulk of the instrument can therefore sometimes present installation problems on small engines. However, providing care is taken with installation and calibration an uncertainty within ± 0.05mm, for the total measurement system is possible. A more detailed discussion of the capabilities of this type of instrumentation is given in References 4.5.2 and 4.5.6.

4.5.4.4 *Optical triangulation probe*

An optical triangulation probe, shown schematically in Figure 4.5-33, uses a light beam focused onto the blade tip. As the clearance changes the light spot moves across the blade tip and the reflected beam is refocused on an array of light detectors. The movement of the light spot across the detector can be calibrated to indicate a blade-to-sensor gap measurement to an accuracy of the order of ± 0.05mm.

The advantage of this system is that the output is independent of blade tip geometry, it is unaffected by gas properties, and calibration is relatively simple. The disadvantages are that the probe is very bulky and as the prism must be mounted close to the gas stream this makes it prone to contamination. It is also possible to obtain measurements with this probe while the engine is stationary.

Further information relating to the capabilities of this type of probe is given in Reference 4.5-7.

4.5.4.5 *X-ray techniques*

X-ray techniques for component measurements are an entirely unique concept in that a hard copy or real time video image of the engine or component interior, during transient or steady state operation, is obtained from which metal movements and/or gap measurements can be deduced. In many cases, this information cannot be obtained by any other measuring technique. These images can be obtained without any modification to the engine and therefore provide information in a realistic test bed environment. In addition, conventional instrumentation can only provide information at predetermined points whereas X-ray images are often more effective in that they cover the whole region in view.

The major elements of the system (References 4.5-8 and 4.5-9) are shown in Figure 4.5-34 and consist of a traversable high energy X-ray source and radiographic (film camera) or fluoroscopic X-ray video (TV) imaging system. The power requirement of the X-ray source is typically 6 to 11 MeV, depending upon engine size (source to film distance) and material density through which the penetration is required. The images are formed when radiation passing through the engine is attenuated by differing thicknesses of metal components, thus creating a shadow picture. This image has the approximate appearance of a longitudinal cross section of the engine part in view (Figure 4.5-35). Unfortunately the varying depths of metal through which the beam must penetrate can often detract from the clarity of the area of interest. Other aspects influencing the interpretation and accuracy of the recordings will be discussed later.

There are two main modes of operation; continuous or pulsed beam. In the continuous mode only steady state or slow transient investigation are possible as radiographic film exposures between 3 and 6 seconds are normally required. However, within these restrictions it is possible to record differential movements by comparing a sequence of exposures Figures 4.5-36 and 4.5-37 (idle and max running X-rays). Results from a series of X-rays of transient operation, illustrating the change in turbine tip seal clearance, are shown in Figure 4.5-38 for a transient from idle to max power and return to idle.

The second mode of operation is used when it is desirable to arrest the motion of a single blade or to index through individual blades to examine blade to blade variations. Operation of the system in the pulsed mode (pulse width approximately 4 microseconds and pulse frequency up to 575 hertz) with the pulse rate controlled by an engine mounted inductive pick-up can provide a range of stroboscopic or slowly changing sequence of radiographic images. This method can be useful for the investigation of vibrations, blade and seal clearance variations, component distortions, etc., in nominally steady state operation or slow transient conditions.

In the case of fast transients, surge, investigations, vibration surveys, "blade off" tests, etc., a high speed imaging system is required. This can be achieved by running the X-ray source at its maximum pulse rate (or in burst mode) for a short period. The low intensity images captured are intensified electronically through systems incorporating fast decay phosphors coupled with high speed video recorder systems.

Hard copies of images produced, either directly as a radiograph or from an intensified/enhanced fluoroscopic video recording, can be used for direct measurement. Analysis and interpretation of these images should be carried out by skilled and experienced operators as nearly all images have blurred edges and are often overlaid by structures irrelevant to the particular investigation. Measurements are usually taken via x-y coordinate readers, and on average contrast/quality images, accuracies of the order of ± 0.2mm can be achieved. It is possible to demonstrate a 95% level of confidence of repeatability by statistically assessing the results of (say) 5 separate experienced readers. In addition to manual readings, automatic readers, comparators and digital image processors are now becoming available with the potential for eliminating manual reading bias.

The quality of the images produced can depend upon many factors: specification of the X-ray source, film characteristics when using radiography, and the image processor/intensifier in the case of video fluoroscopy. The stability of the unit, the construction of the component and the type of event being examined will also have a major influence on the sharpness and contrast of the image recorded.

In particular the beam must traverse through the full depth of the engine and the feature of interest, which must of necessity be viewed tangentially, may form only a small fraction of beam attenuation. This can result in the image of interest being faint and obscured by items of greater contrast. Also the finite dimensions of the X-ray source combined with restraints on source to object and object to image distances can also lead to a reduction in image quality.

The X-ray source and its associated data acquisition and processing systems represent considerable bulk and investment; the complete system being transportable from one test site to another. Also the X-ray source and receiving components must be traversable through the whole length of the engine, raised, lowered and tilted.

Finally, it is essential that the operation of any X-ray system be installed and operated in accordance with the national health and safety requirements. The most obvious features are normally substantial concrete shielding of the test cell, prohibition of personnel access and well positioned warning notices.

4.5.6 References

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Table 4.5-1 Comparison of Potentiometers and Differential Transformers (LVDTs) as Linear Displacement Transducers

	Potentiometer	Differential Transformer (LVDT)
Type of Input	Linear displacement or angular displacement.	Linear displacement.
Input range or level	Minimum level as low as 0.1% of total resistance.	Total range from ±0.1 to ±75 mm.
Input-impedance charcteristics	Varies widely, depending on the total resistance characteristics and physical size.	Depends on size. Forces from 0.1 to .03 g usually required.
Input Sensitivity	Less than .05 mm, or 0.2° in an angular measurement.	0.5% of total input range.
Error and noise characteristics	Deviation from linearity of the order of 0.5% of total resistance. Noise is usually negligible, of the order of 10μV at the contacts. Noise increase with "chatter" of contact.	Deviation from linearity about 0.5%; generally accurate to ±1%.
Frequency response	Generally not above 50 Hz.	Frequency of applied voltage must be 10 times desired response.
Temperature effects	0.002 to 0.15% $°C^{-1}$due to a change in resistance. Also some thermoelectric effects depending on types of contact.	Small influence of temperature may be reduced by using a thermistor circuit.
Type of output	Voltage or current, depending on connecting circuit.	Voltage proportional to input displacement.
Output range or level	Wide.	0.16 to 1.6 mV/μm/Vinput depending on frequency. Lower frequency produces lower output.
Output-impedance characteristics	Variable	Mainly resistive; low to medium impedance, as low as 20 ohms, depending on size.
Remarks	Simple, inexpensive, easy to use, many types available commercially.	Simple, rugged, inexpensive, high output, requires simple accessory equipment. Care must be taken to eliminate stray magnetic fields.

Table 4.5-2 Rotary Variable Transducer - Typical Operational Characteristics

			Two-cycle RVT		One-cycle RVT	
Input	Voltage		0-30 Vrms		5-30 Vrms	
	Frequency		400-5000 Hz		400-5000Hz	
	Impedance		300-1000 Ω		300-1000 Ω	
	Power		0.05-0.15 watts		0.05-0.15 watts	
Output	Sensitivity		0.1-0.25 Vrms		0.05-0.12 Vrms/deg.	
	Accuracy	Range	±40°	0.2-0.3 deg.	±80°	±1.0 deg.
		Range	±30°	0.1-0.15 deg.	±60°	±0.8 deg.
		Range	±20°	0.05-0.1 deg.	±40°	±0.5 deg.
	Impedance		200-400 Ω		200-400 Ω	
	Phase-angle		±5.0 deg.		±5.0-8.0 deg.	
	Sensitivity Temp. Coeff.		0.005-0.015 %/°C		0.01-0.02 %/°C	

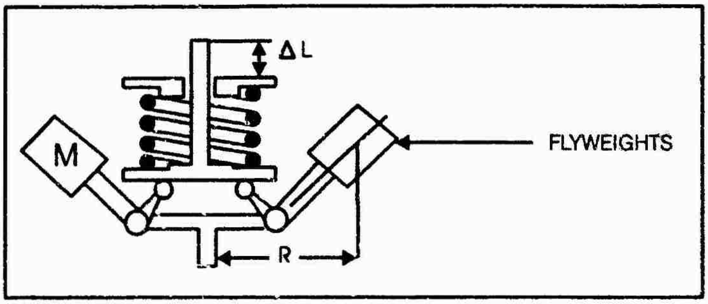

Figure 4.5-1 Speed Measurement Using Flyweight Speed Governor

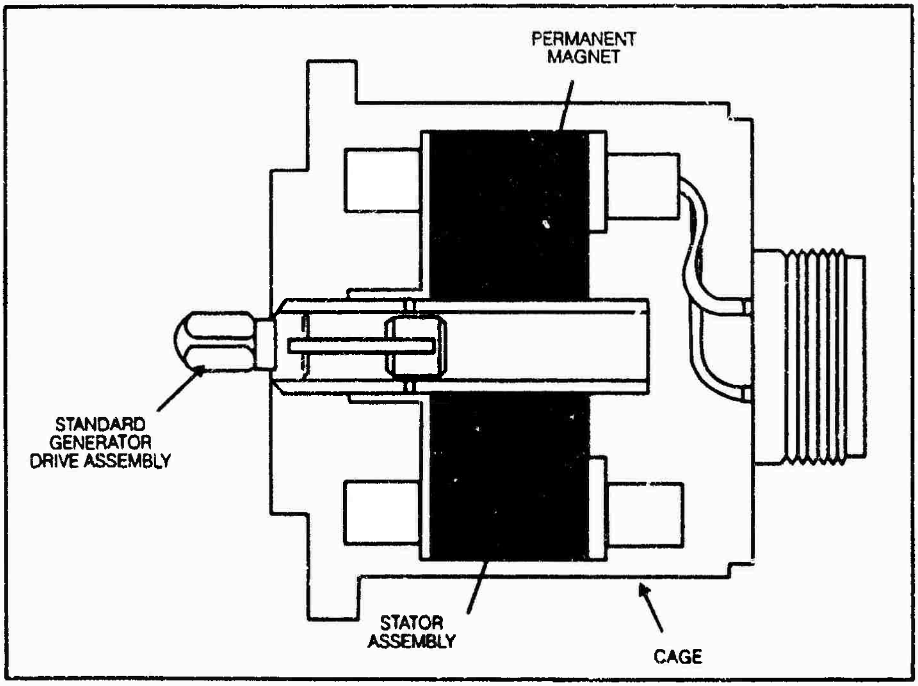

Figure 4.5-2 Schematic of Tachogenerator

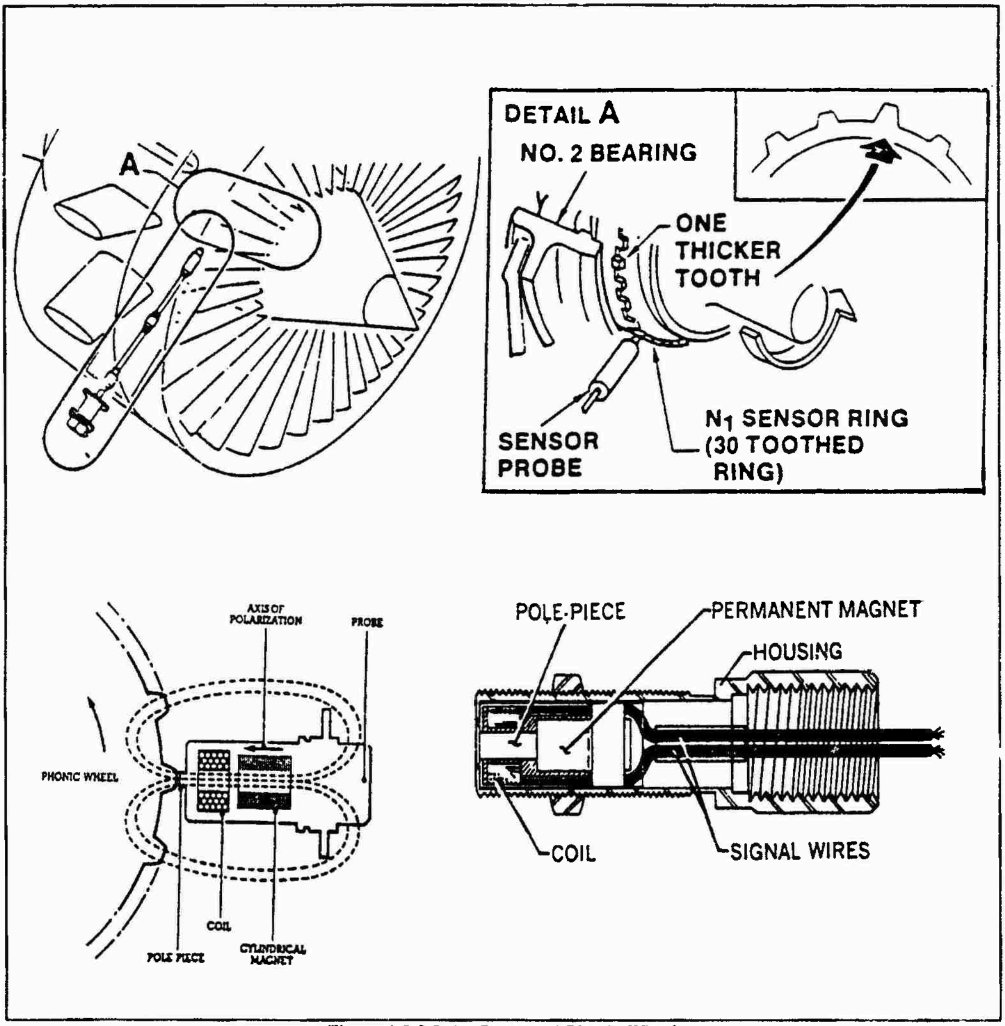

Figure 4.5-3 Pulse Probe and Phonic Wheel

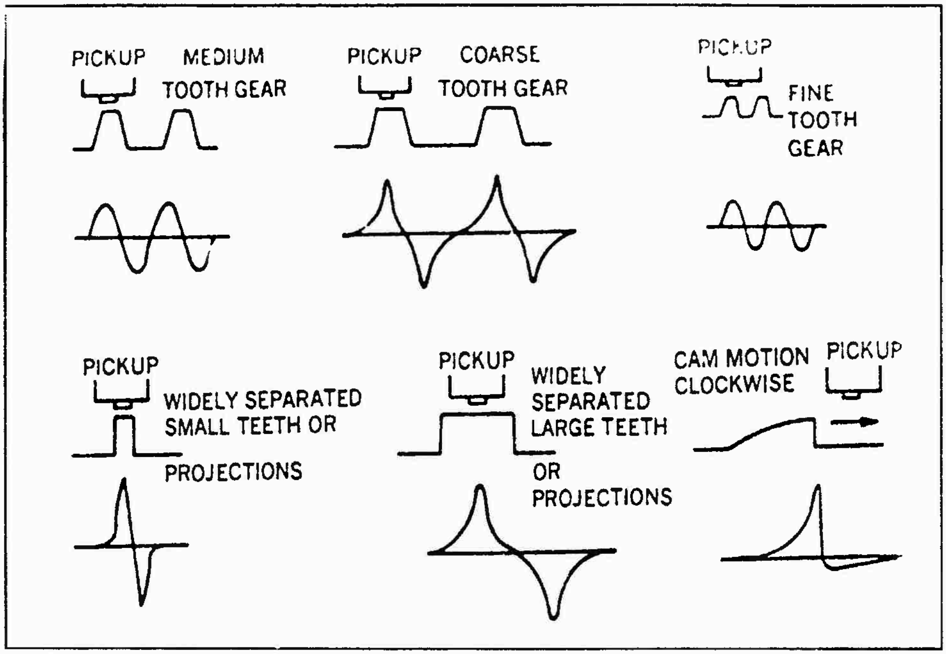

Figure 4.5-4 Waveforms of the Pulse

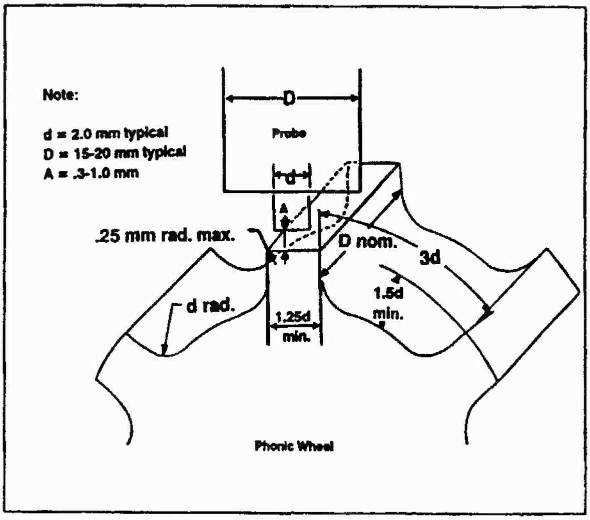

Figure 4.5-5 Suggested Gear Wheel Design Features for Optimum Speed Probe Outputs

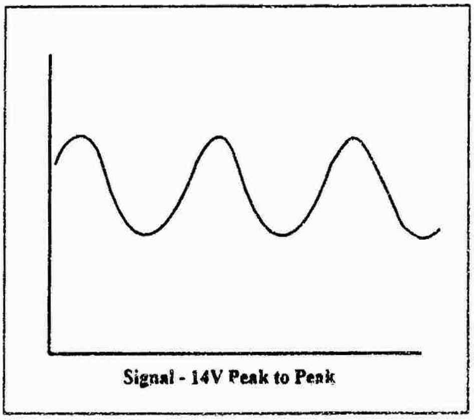

Figure 4.5-6 Typical Raw Signal Available at 73% Speed

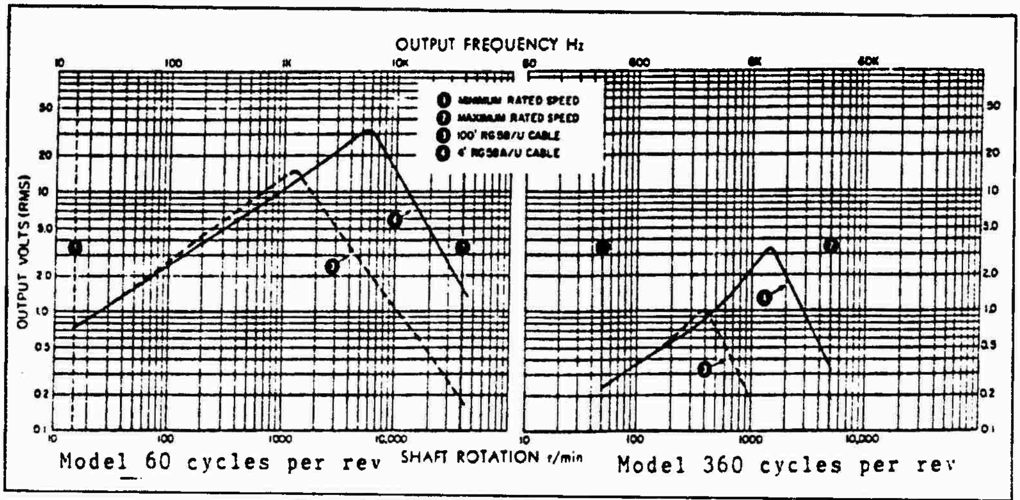

Figure 4.5-7 Output Amplitude of the Pulse Probe

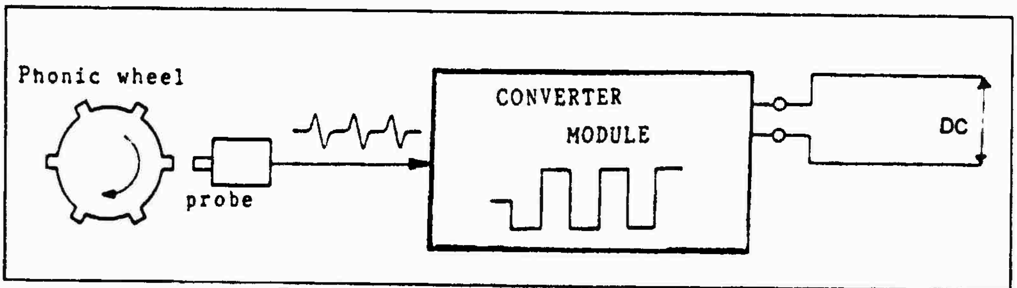

Figure 4.5-8 DC Signal from Frequency Measurement

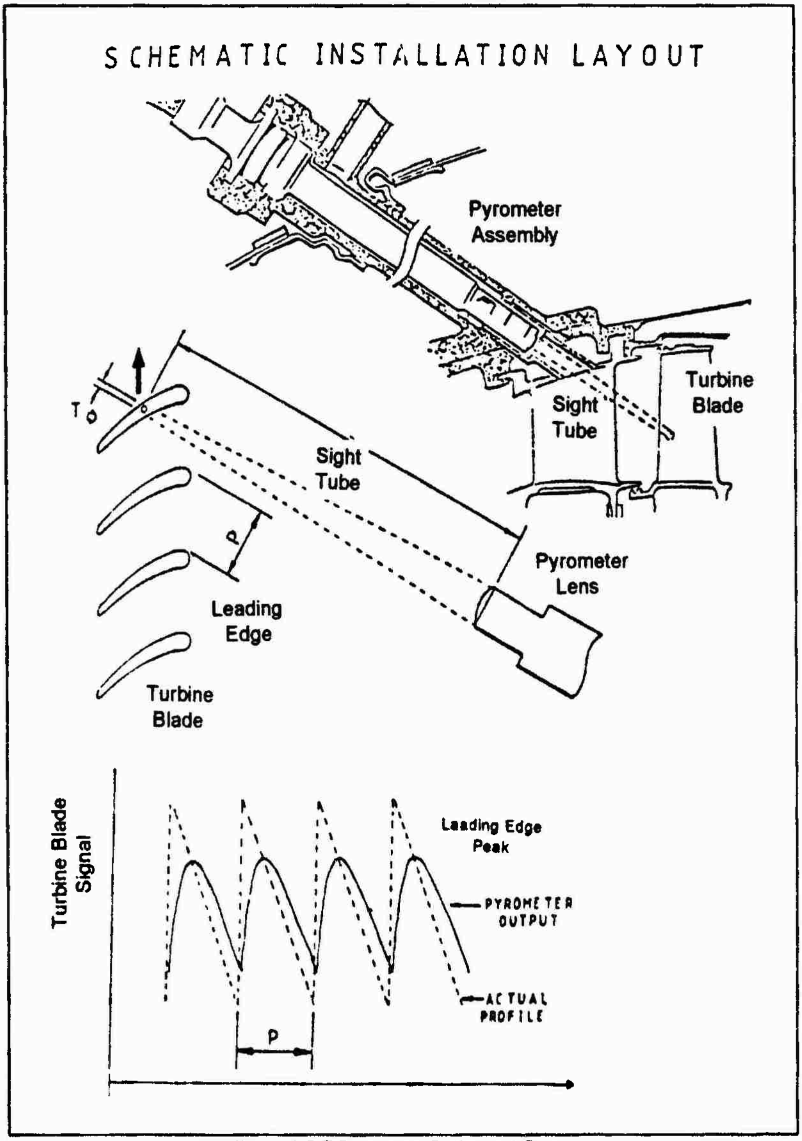

Figure 4.5-9 Pyrometer Probe and Output

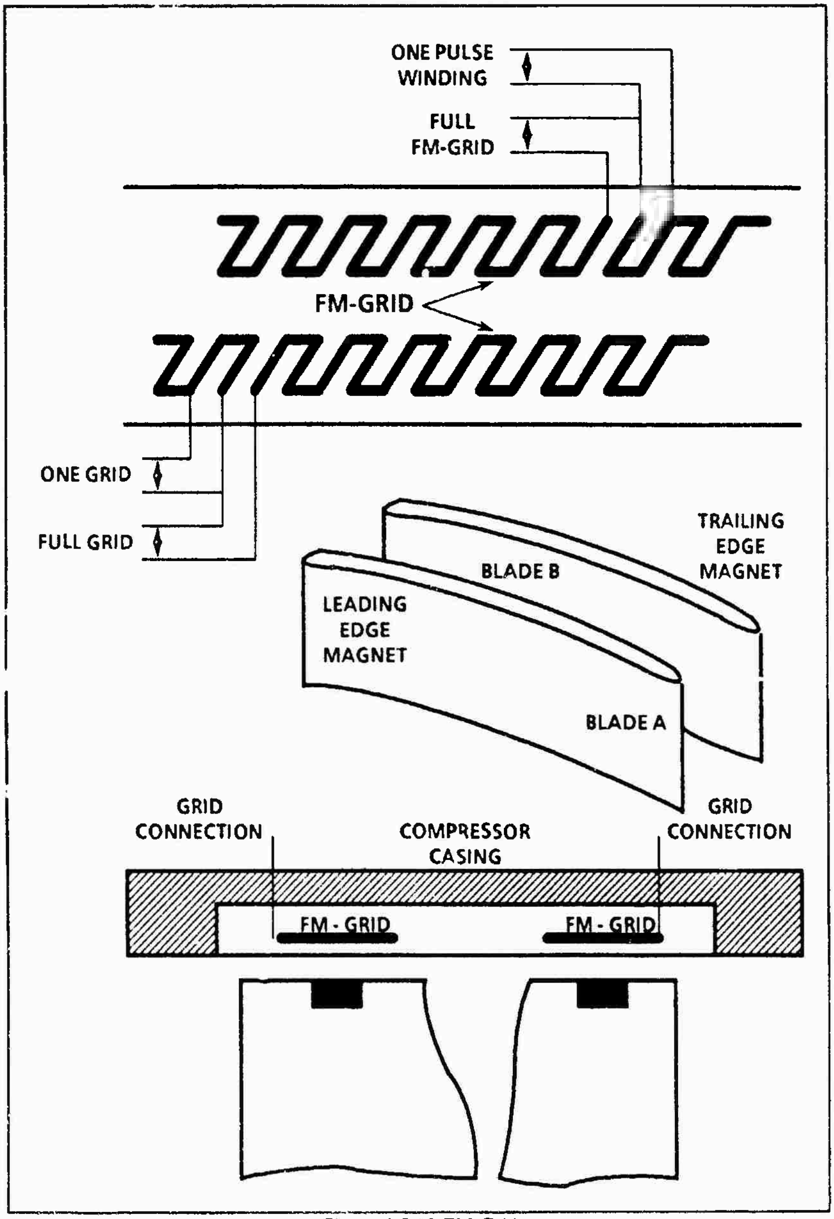

Figure 4.5-10 FM Grid

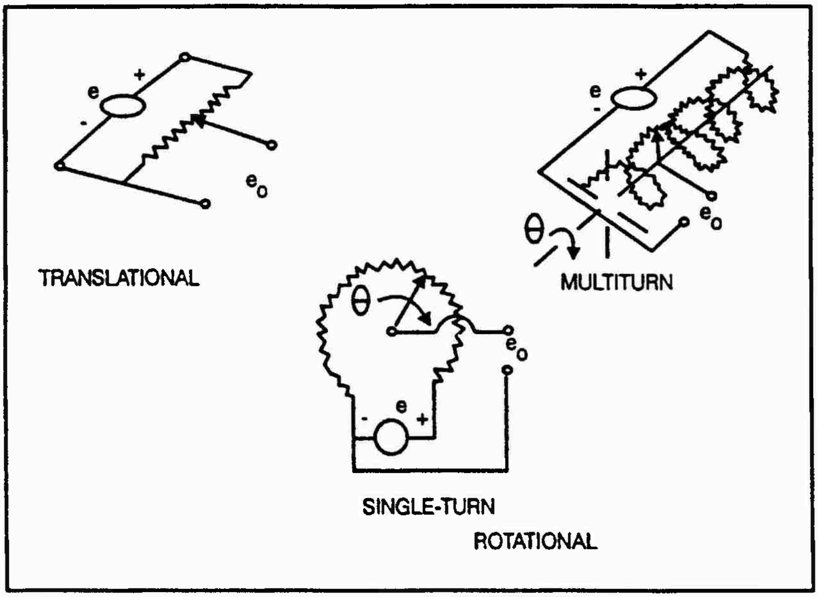

Figure 4.5-11 Resistance Potentiometer

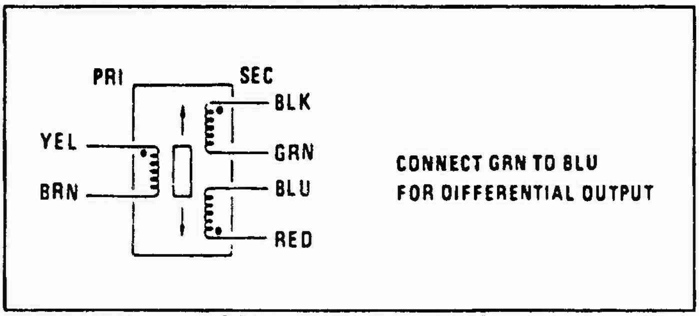

Figure 4.5-12 Linear Variable Differential Transformer

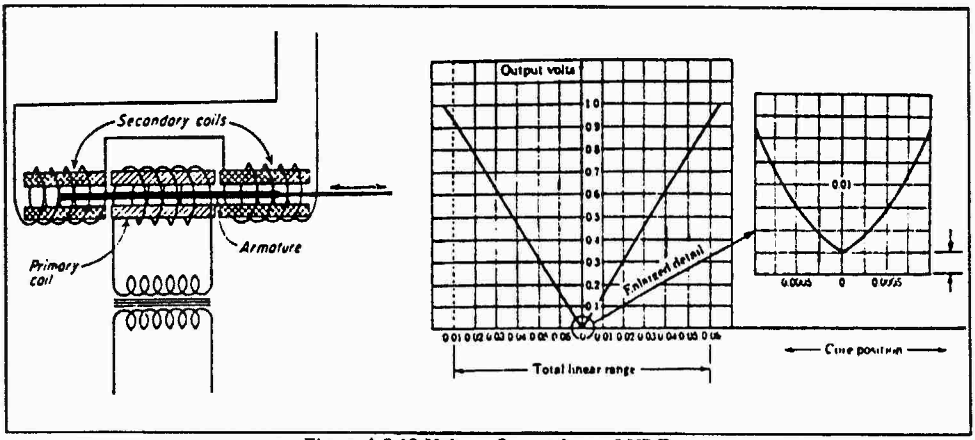

Figure 4.5-13 Voltage Output for an LVDT

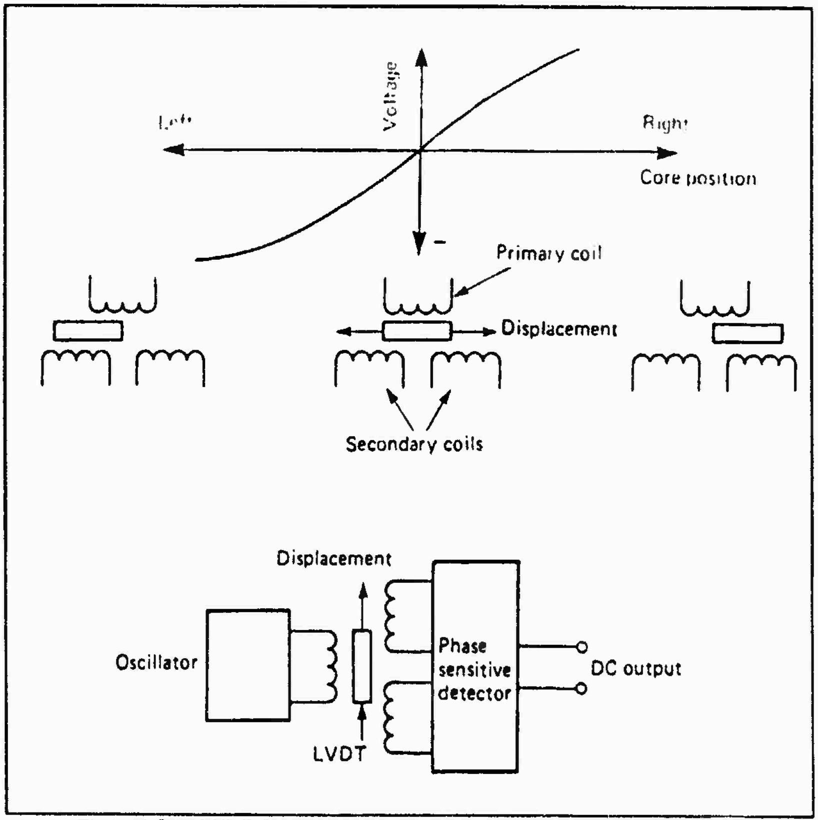

Figure 4.5-14 LVDT Output Voltage and Phase as a Function of Core Position

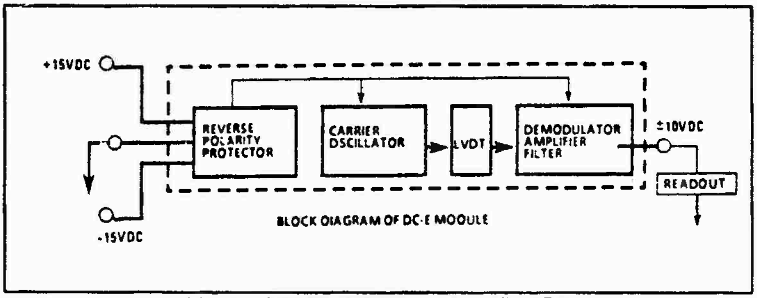

Figure 4.5-15 Block Diagram of a DC-LVDT

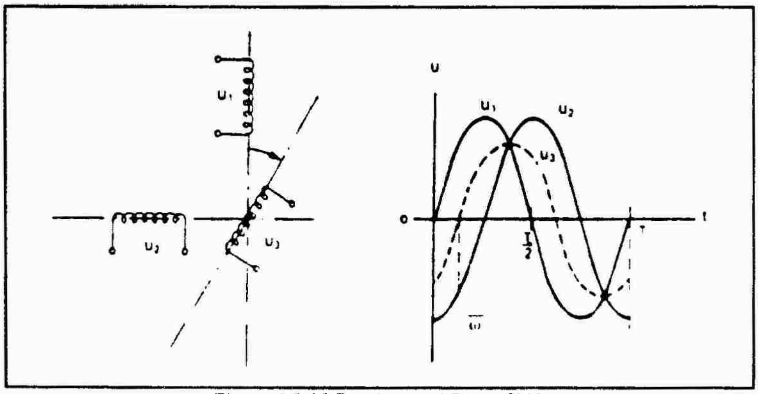

Figure 4.5-16 Resolver and Phase Shift

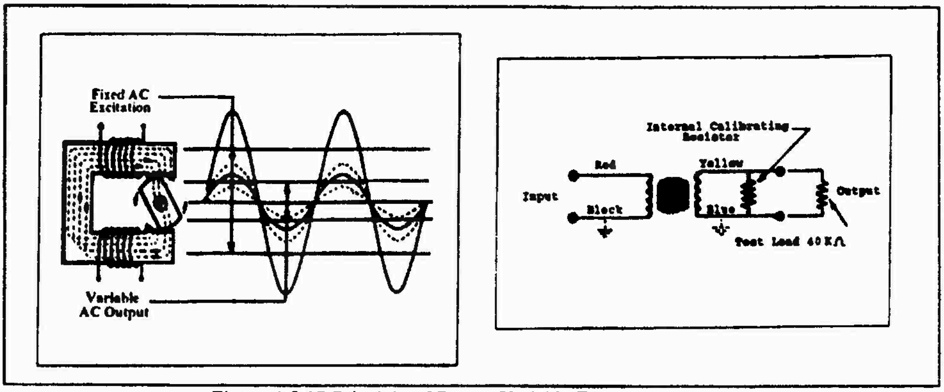

Figure 4.5-17 Principle of Rotary Variable Transducer (RVT)

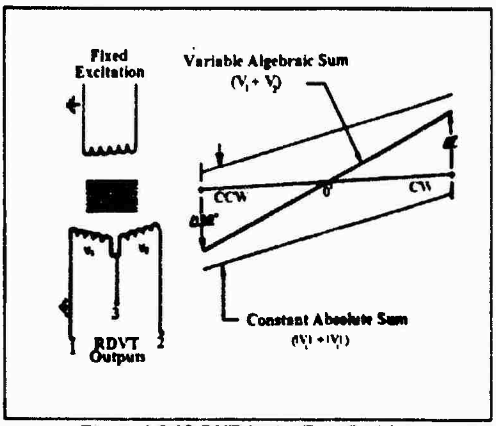

Figure 4.5-18 RVT in the Zero Position

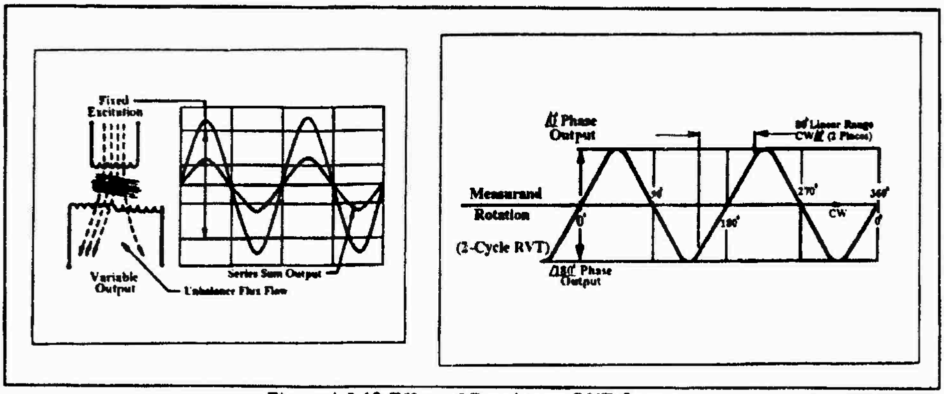

Figure 4.5-19 Effect of Rotation on RVT Output

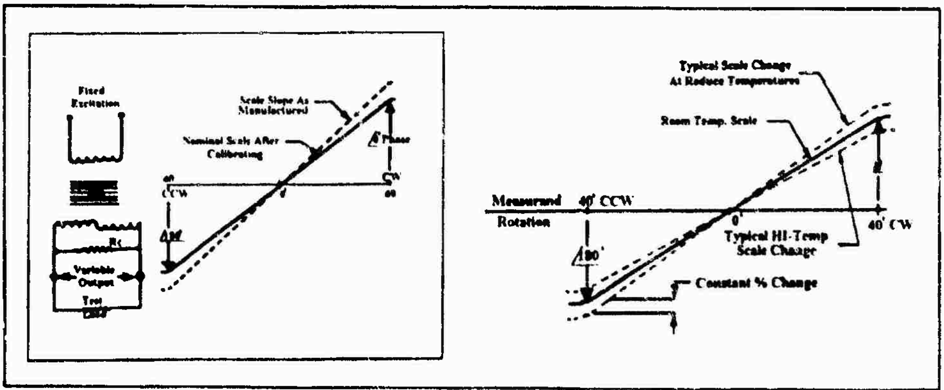

Figure 4.5-20 Accuracy Aspects of RVT

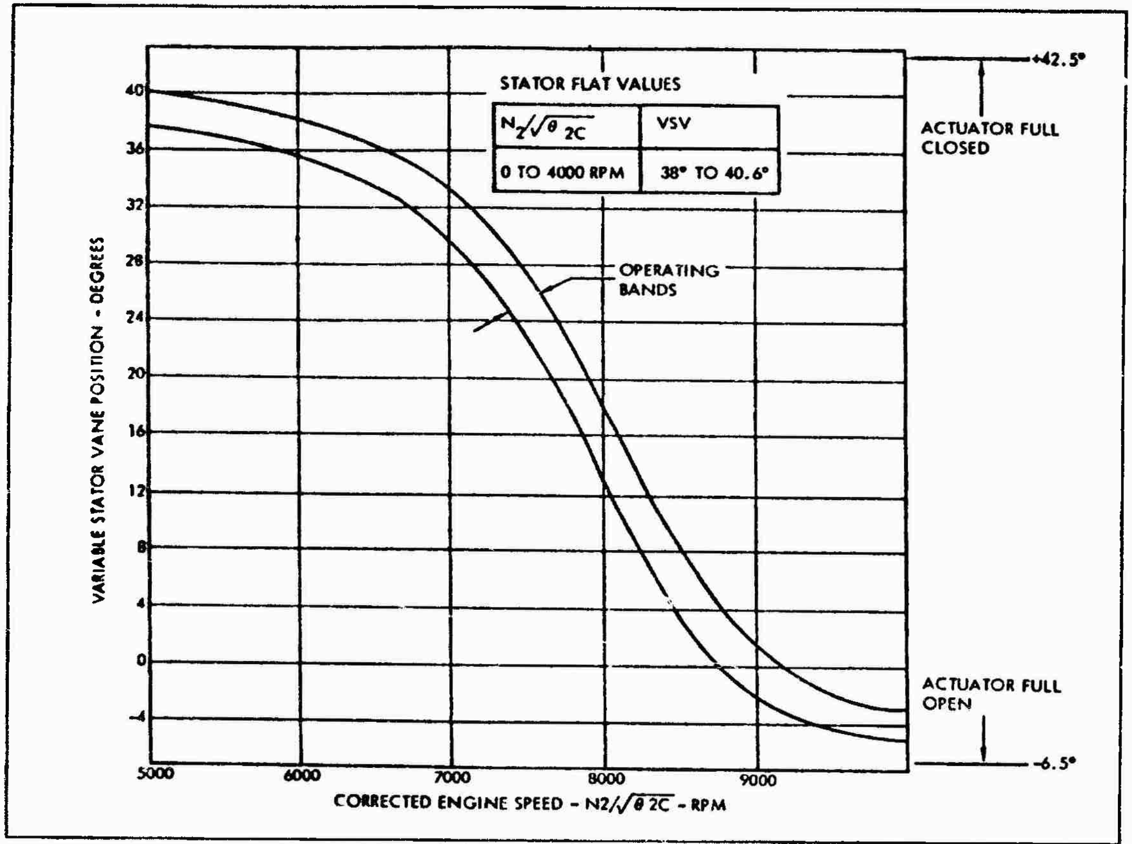

Figure 4.5-21 Typical Tracking Chart for a Variable Stator Vane

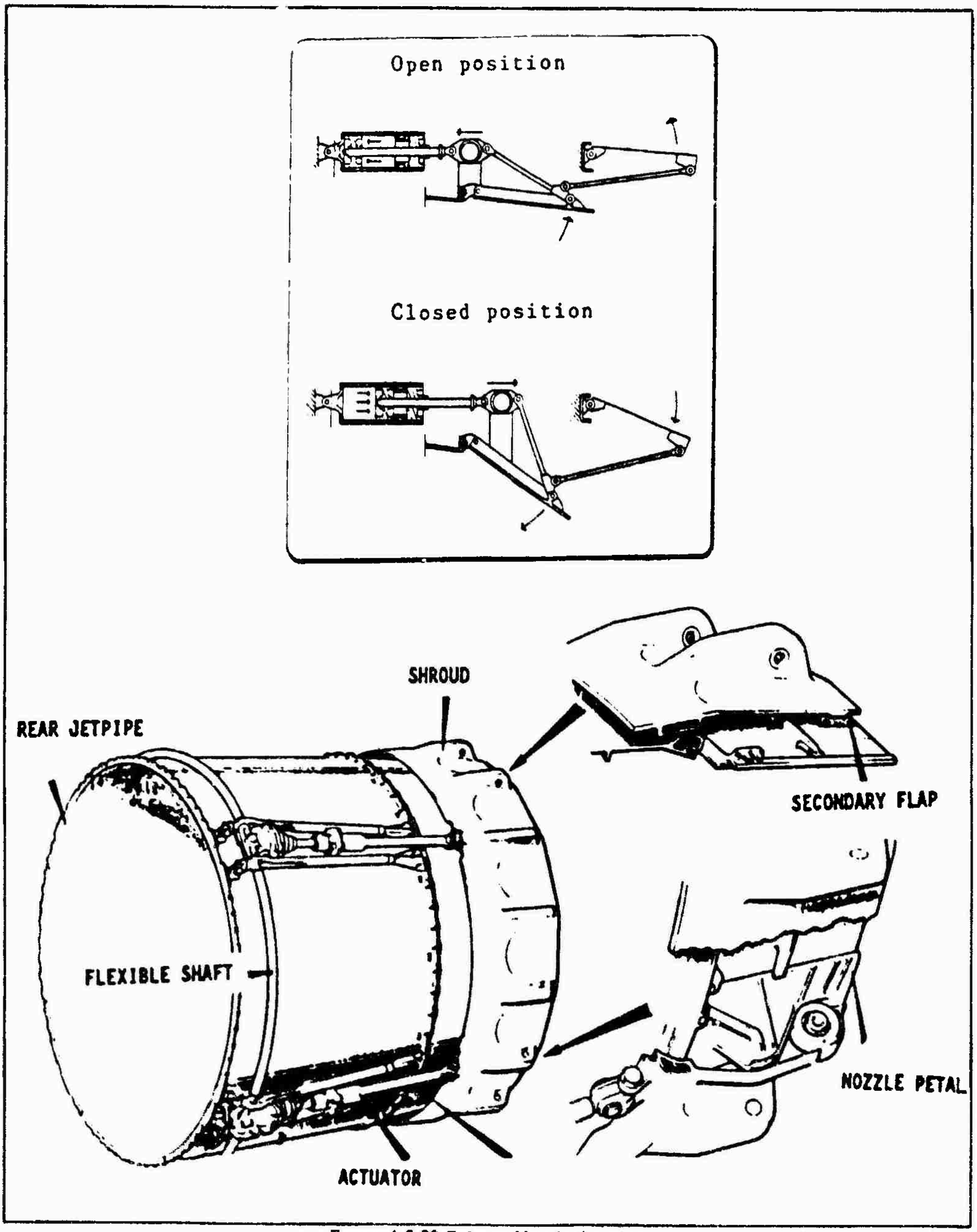

Figure 4.5-22 Exhaust Nozzle Actuator

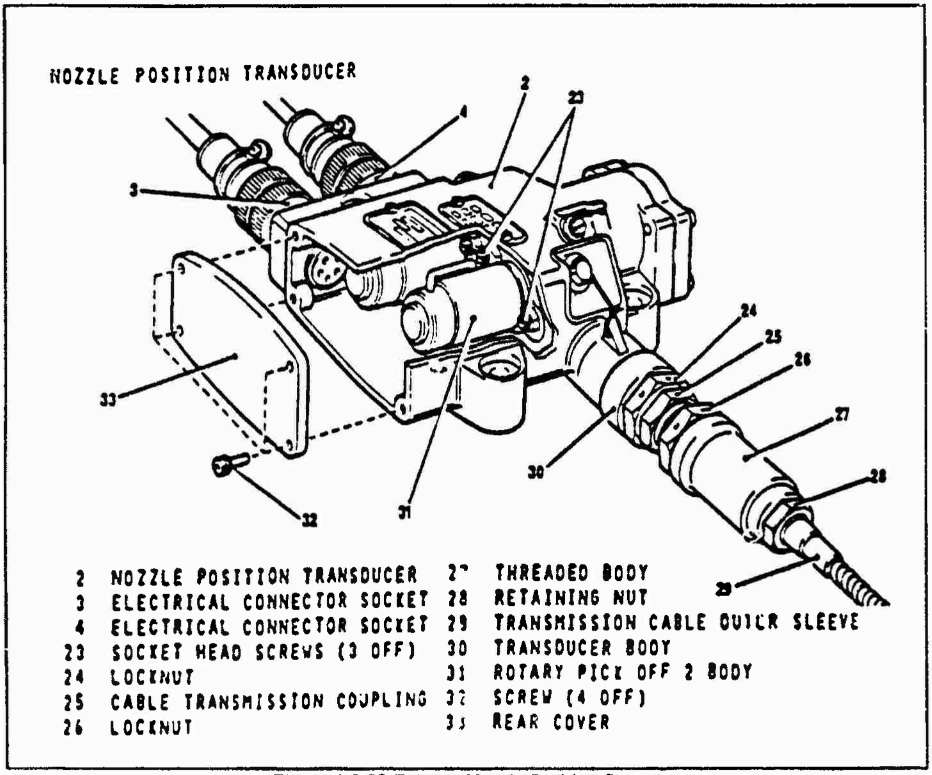

Figure 4.5-23 Exhaust Nozzle Position Sensor

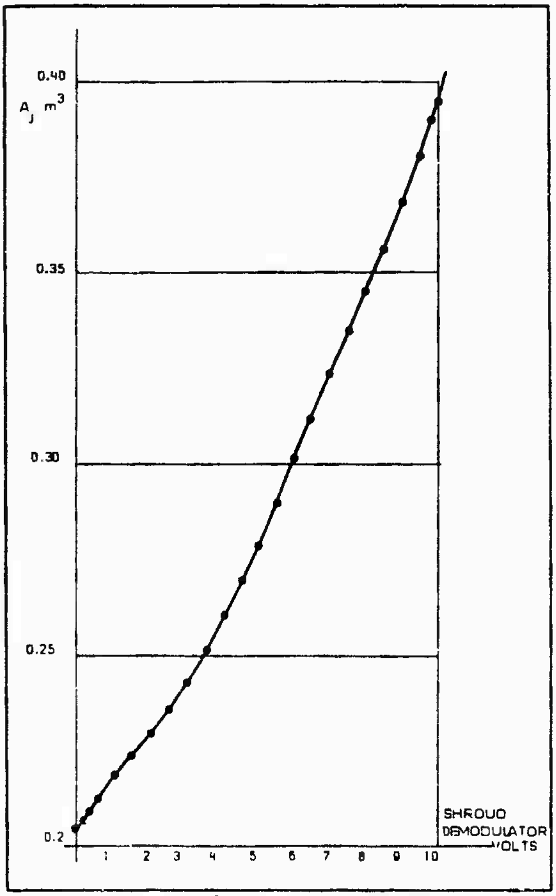

Figure 4.5-24 Nozzle Area Calibration

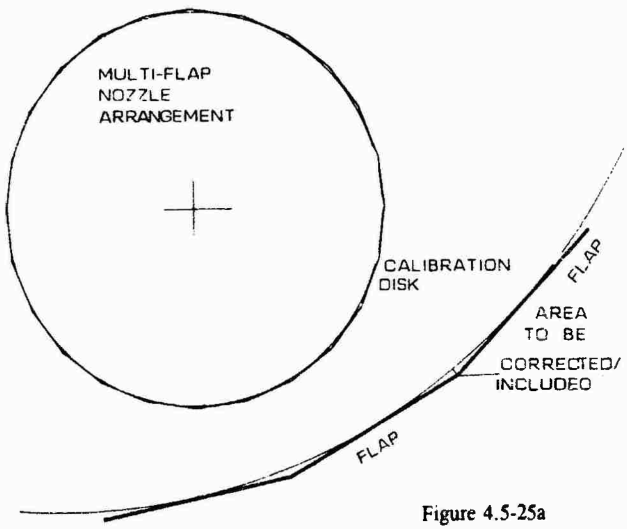

Figure 4.5-25a

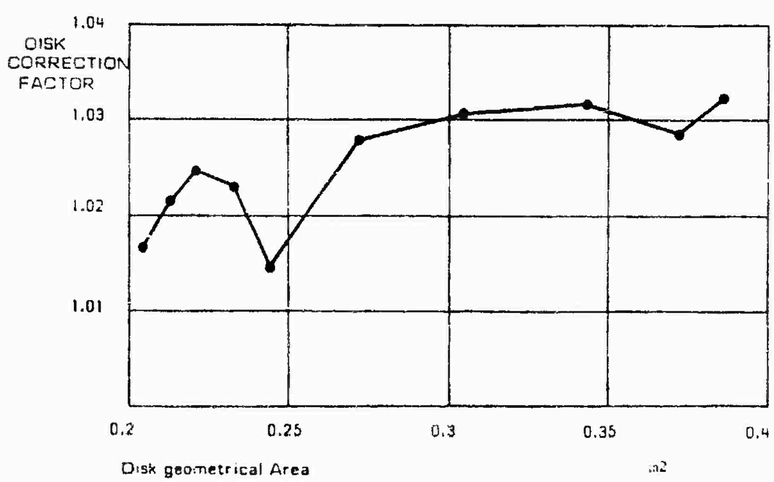

Figure 4.5-25b

Figure 4.5-25 Effect of Non-Circular Nozzle on Area Measurement

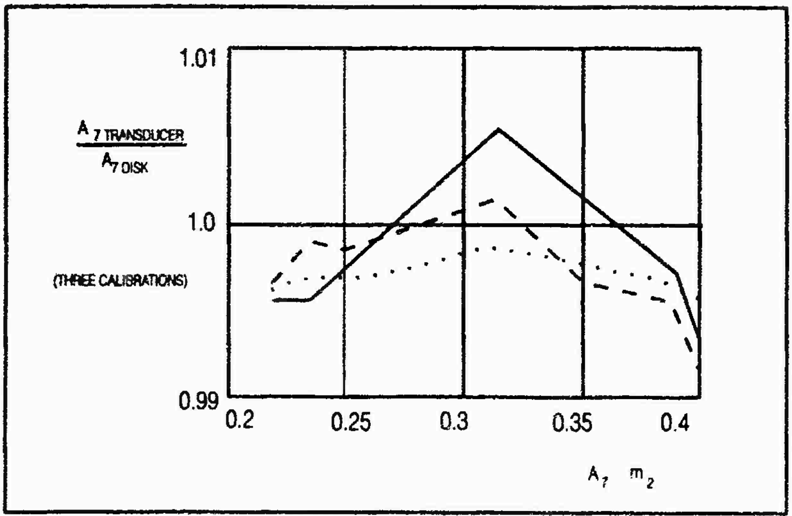

Figure 4.5-26 Nozzle Calibration with Disks

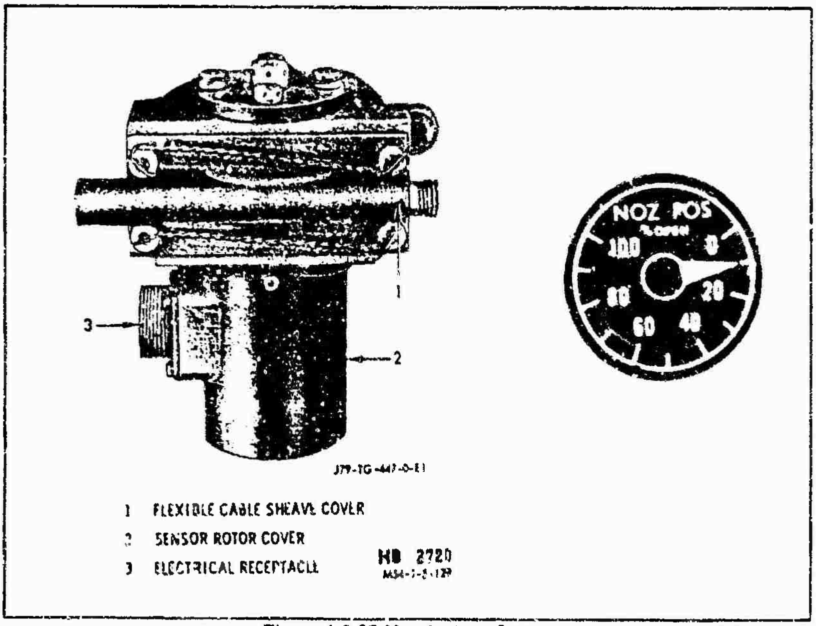

Figure 4.5-27 Nozzle Area Sensor

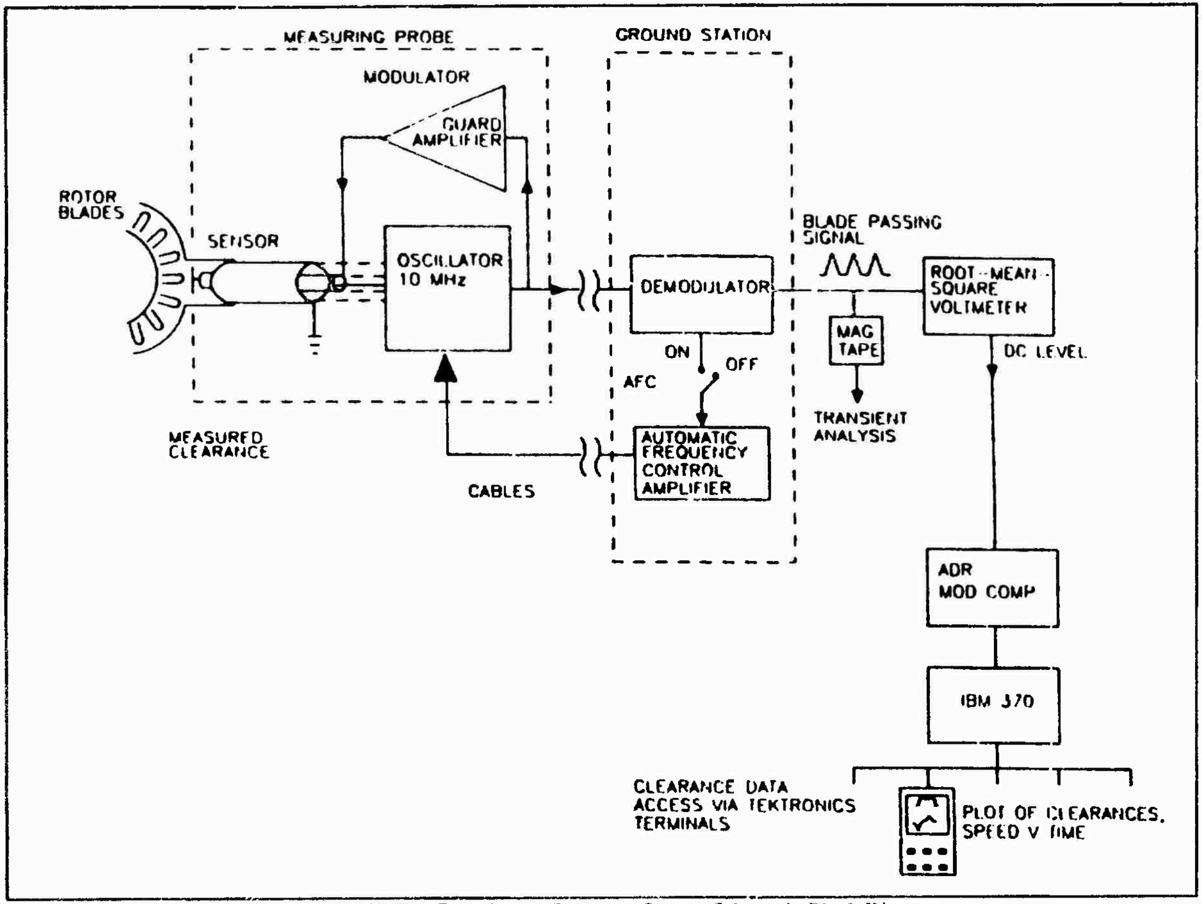

Figure 4.5-28 FM Capacitance Clearance System Schematic Block Diagram

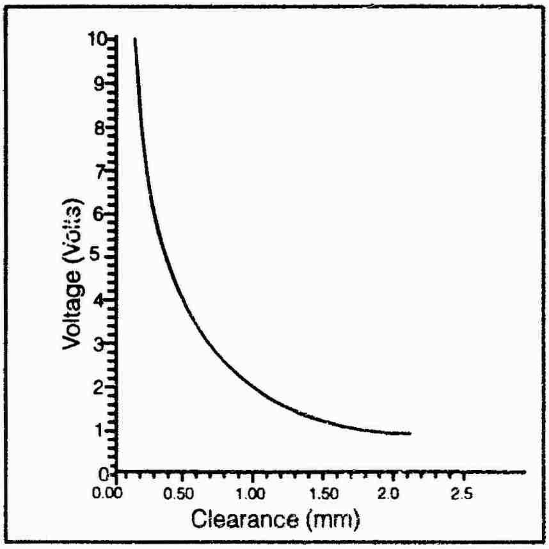

Figure 4.5-29 Typical FM Capacitance Probe Output Plotted Against Known Clearance

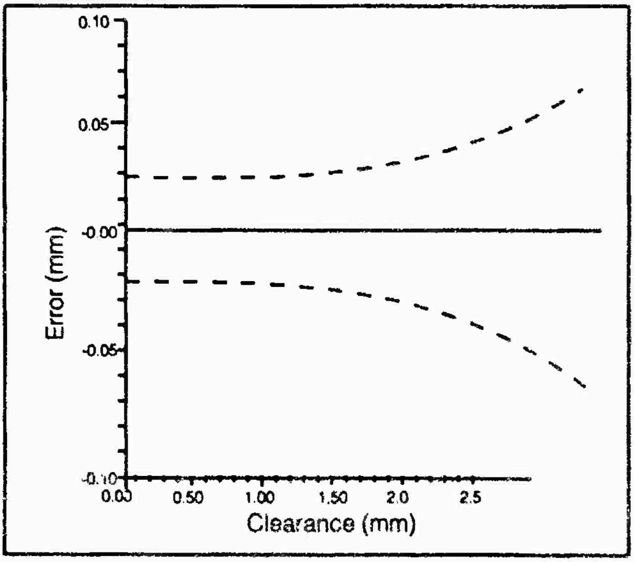

Figure 4.5-30 Typical Error in FM Capacitance Probe Measurement

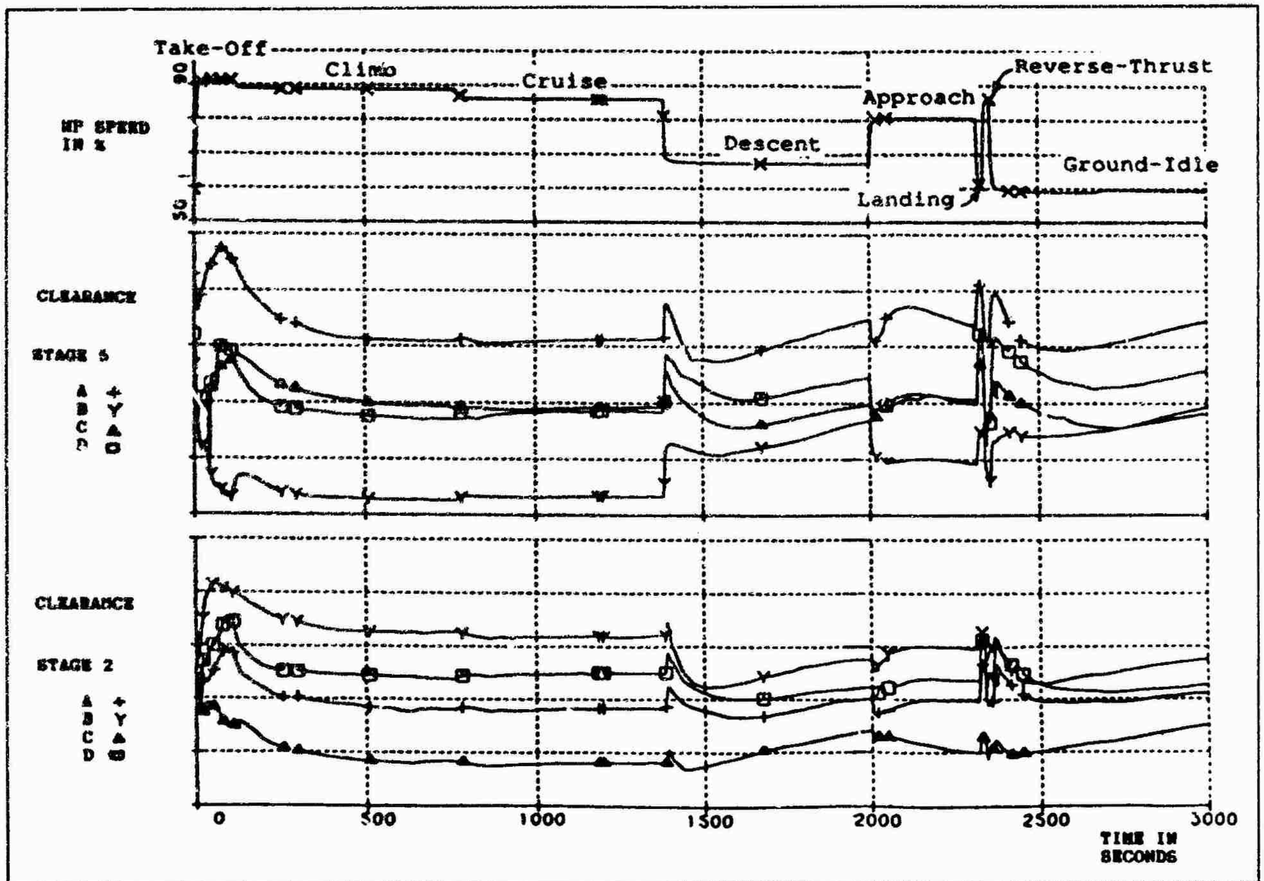

Figure 4.5-31 HPC Tip Clearance Measurements During Flight Cycle
(4 circumferentially positioned probes per stage)

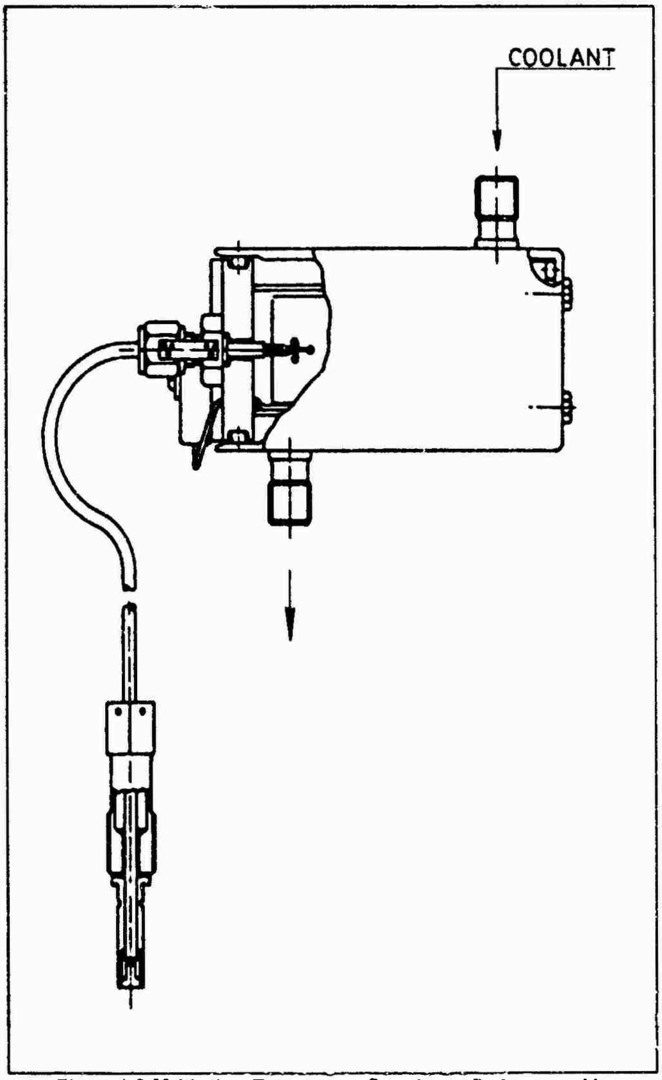

Figure 4.5-32 Medium Temperature Capacitance Probe Assembly

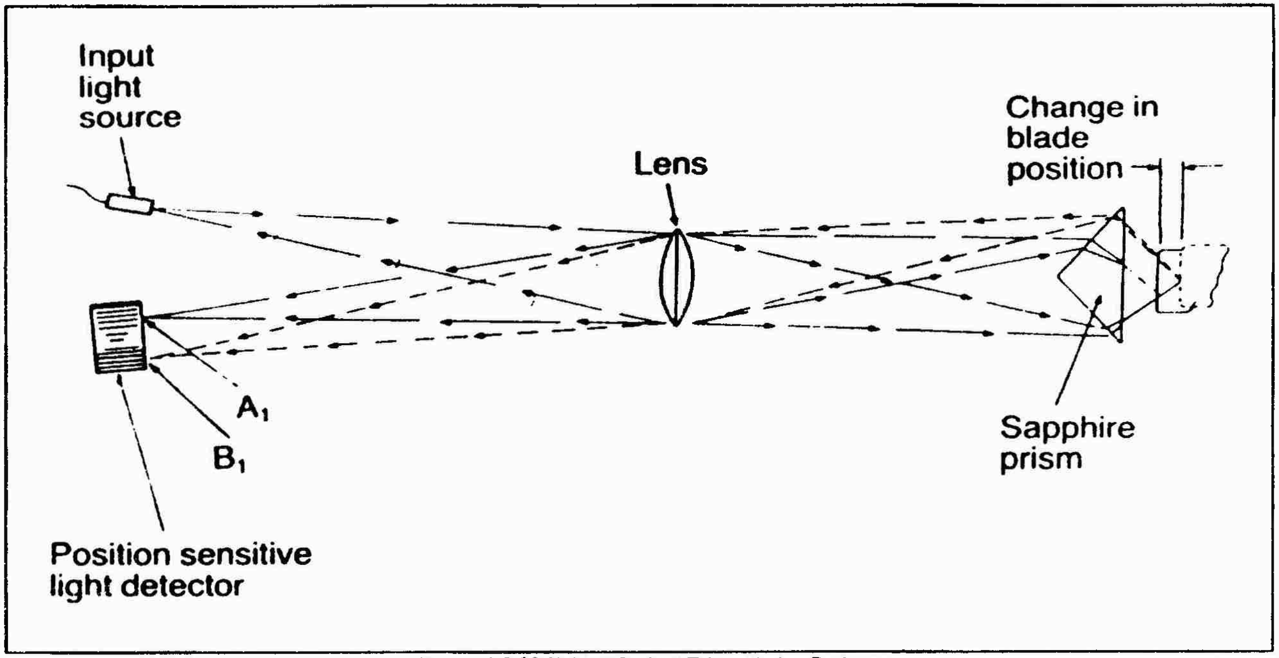

Figure 4.5-33 Folded Optical Triangulation Probe

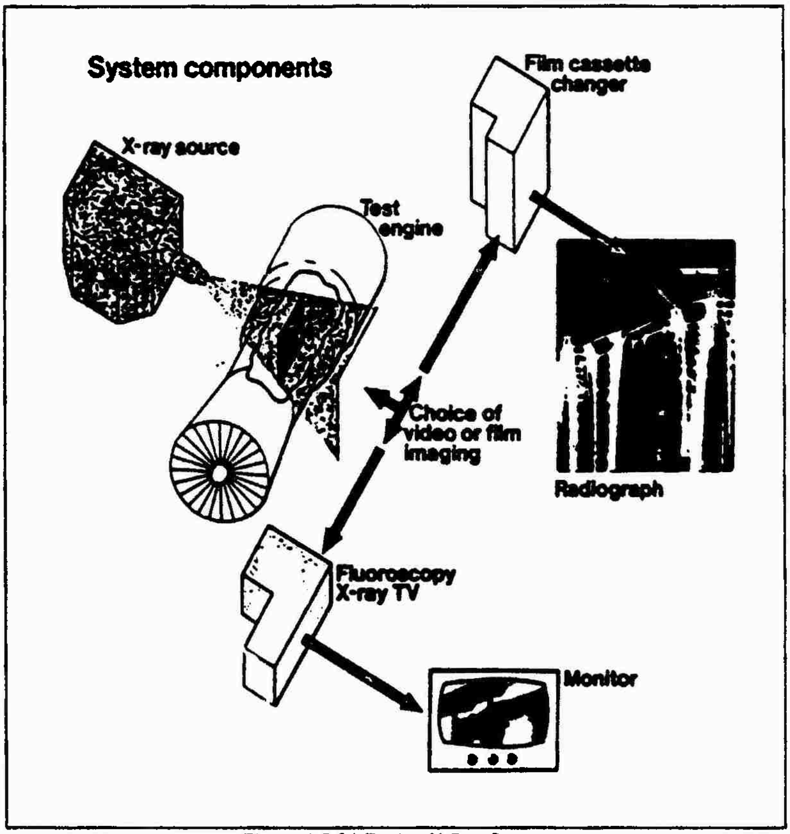

Figure 4.5-34 Engine X-Ray System

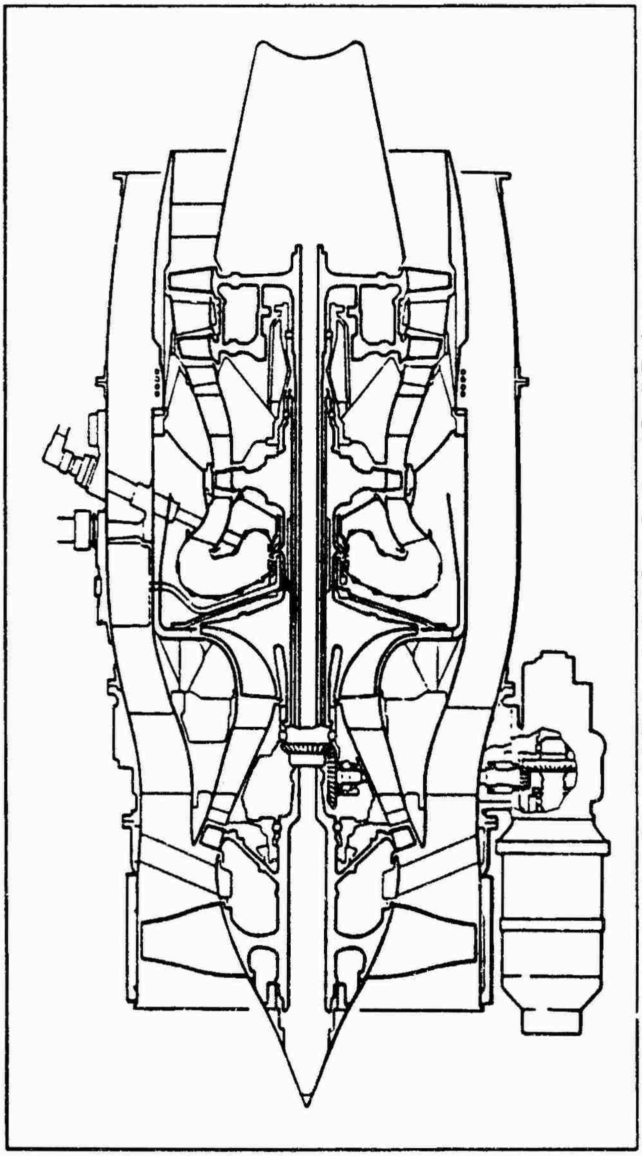

Figure 4.5-35a Longitudinal Cross Section of Small Engine

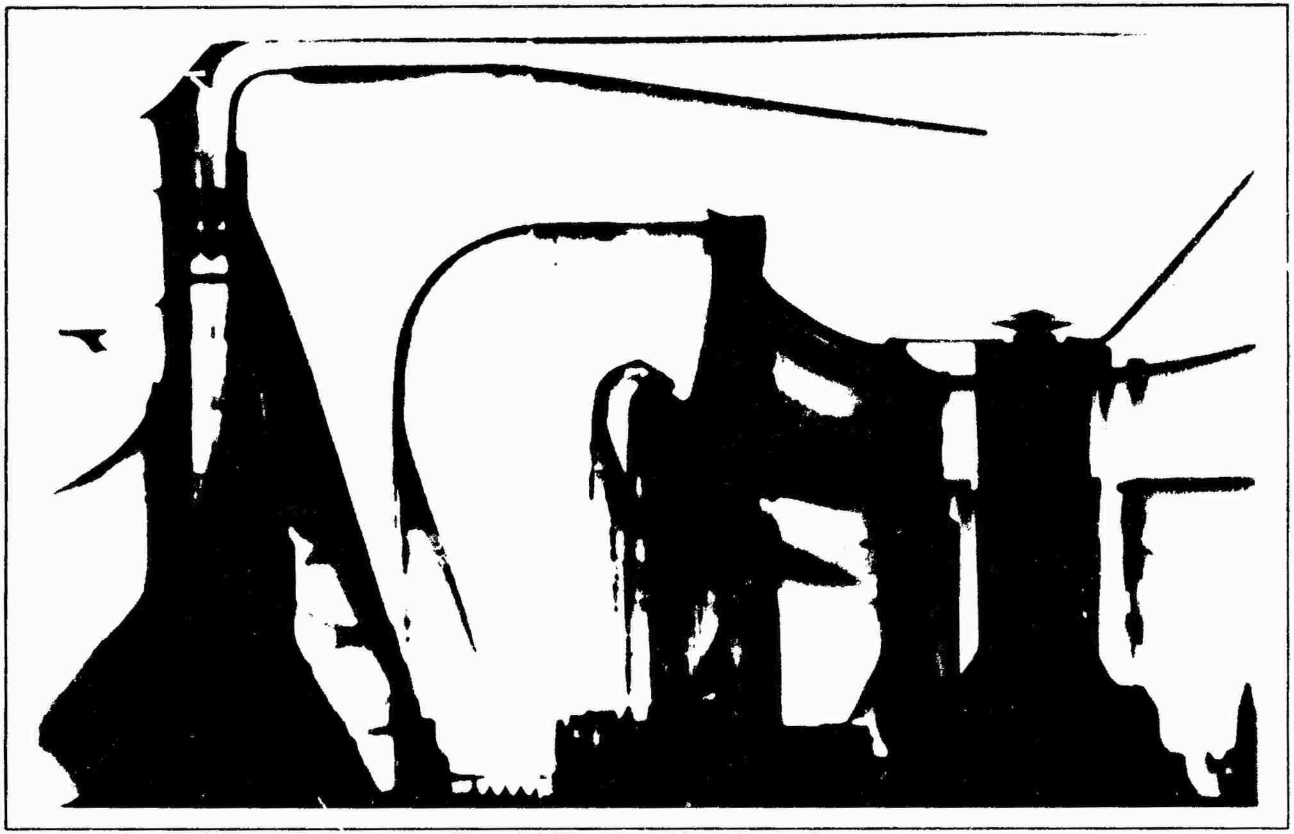

Figure 4.5-35b X-Ray of Small Engine Core
(see Figure 4.5-35a)

Figure 4.5-36 X-Ray of HP Turbine at Idle

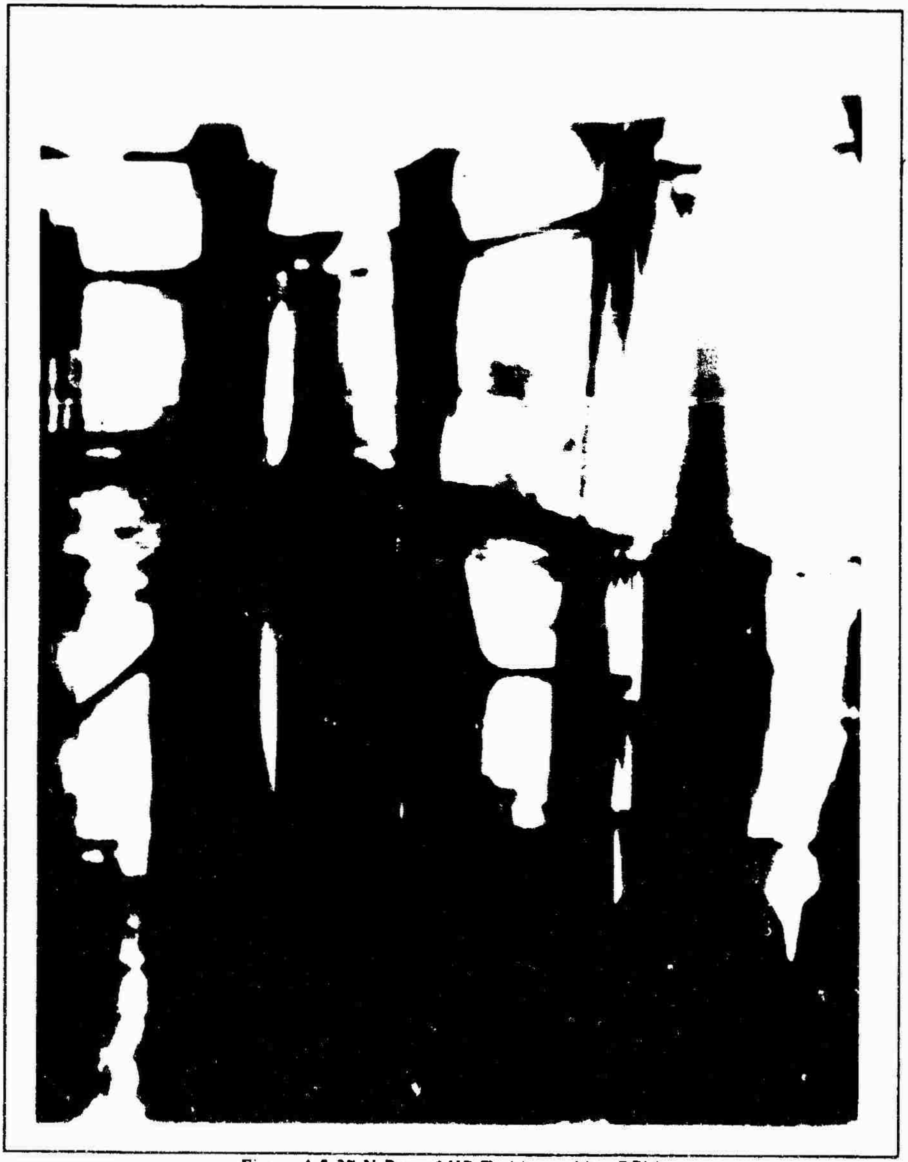

Figure 4.5-37 X-Ray of HP Turbine at Max RPM

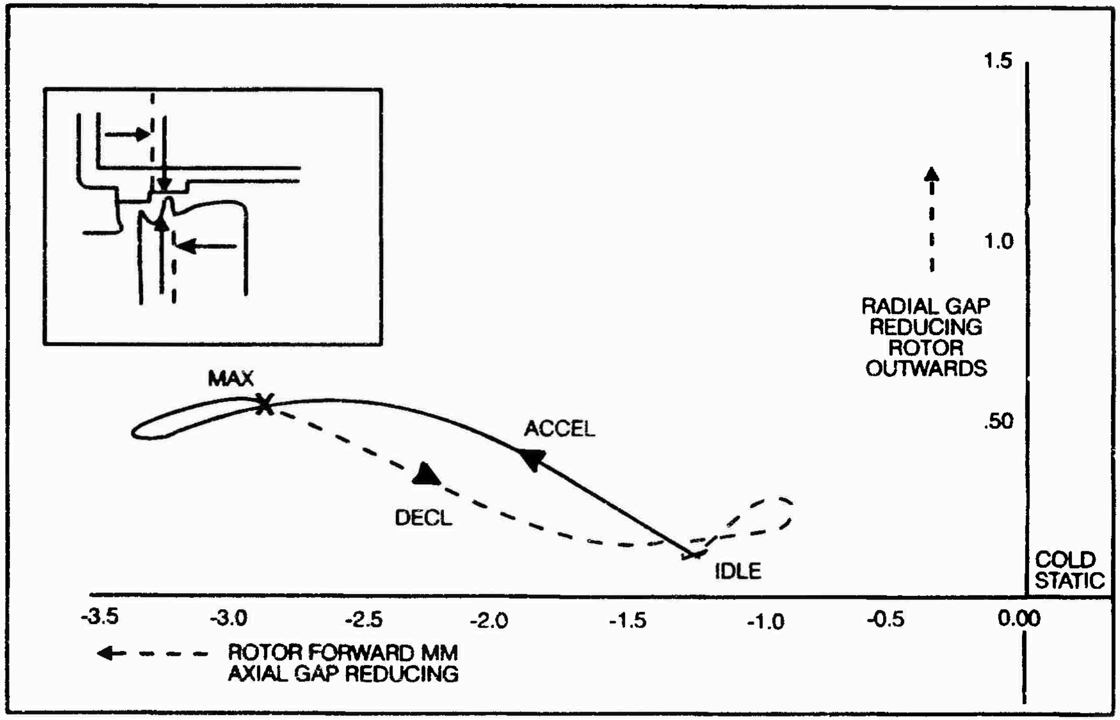

Figure 4.5-38 X-Ray Measurements of Turbine Tip Movement

4.6 THRUST AND TORQUE[1]

4.6.1 Thrust

4.6.1.1 *Introduction*

The determination of engine thrust for precise performance evaluation at stabilized conditions is a difficult task and often the subject of much debate. Beyond the fundamental thrust measurement and/or calculation methodologies are the problems of separating out installation and facility effects. Accounting for the actual test operating conditions at the engine inlet and exhaust (inlet total pressure and temperature and exit static pressure) requires additional measurements or calculations so that results may be properly reported or corrected to desired conditions.

Thrust cannot be evaluated as a precise measure of engine performance during the types of transient tests listed in Section 2. At non-stabilized conditions engine performance is path dependent making the results inappropriate for performance characterization. Also, test facilities other than open-air stands are unable to maintain constant inlet and discharge conditions during engine airflow transients. However, with the gross effects of non-stabilized operating conditions properly accounted for, transient measurements can be used to quantify variations in thrust with time. Such results are useful for understanding or documenting transient behavior of the engine.

Engine thrust versus time provides quantification of such things as augmentor lightoff, control stability, accel/decel time, or takeoff thrust droop. Engine thrust during transients is obtained by the same methods used in steady-state testing. The method used will depend on available facilities, instrumentation, and analytical capabilities (computer models). The test engineer must fully understand the limitations and uncertainties associated with the specific available method(s) relative to the end user's data requirements. Fortunately, the requirements associated with transient thrust measurements for the types of testing described in Section 2 often can be met by proper use of available resources.

Some examples of the uses for transient thrust are listed below:

- o thrust versus throttle position (thrust linearity)
- o takeoff thrust droop or bloom following throttle set
- o thrust jump associated with augmentor lightoff or cancellation
- o thrust stability at constant throttle position
- o thrust jump associated with control mode switches or simulated failures
- o thrust retention following bird, ice, or other foreign object ingestion
- o accel or decel times

For these types of tests, transient measurement techniques can be applied for the assessment of engine thrust variations with time.

4.6.1.2 *Basic Theory*

The fundamental definition of thrust and basic equations are presented in References 4.6.1, 4.6.2, and 4.6.3. Gross thrust is the momentum flux at the exit plane of the engine. Net thrust is defined as the gross thrust minus the momentum of the fluid entering the inlet (ram drag).

$$FG = W9 \times v9 + A9(PS9 - PS(cell)) \qquad 4.6\text{-}1$$

and

$$FN = FG - FR \qquad 4.6\text{-}2$$

or

$$FN = W9 \times v9 + A9(PS9 - PS(cell)) - W0 \times v0 \qquad 4.6\text{-}3$$

where FN = net thrust
FG = gross thrust
FR = ram drag
W = airflow rate
v = Velocity
PS = static pressure
A = area
and the numbers refer to the engine station. (see Figure 4.6-1, also Table 2-3 and Figure 2-3)

Net thrust is more closely related to the propulsive force provided by the engine and is often the parameter of interest. The ram drag term may or may

[1] Tables and Figures for Section 4.6 begin on page 4-227

not need to be determined during the transients depending on the method used and the specific test objectives.

A good overview of thrust measurement techniques for steady-state performance testing is presented in Reference 4.6.2. The three methods presented are 1) scale force from a load cell integrated with the thrust stand, 2) calculation based on a momentum balance using measured conditions in the exhaust nozzle with analytical models of the nozzle flow field and geometry, and 3) calculations using analytical performance models of the engine components with measured engine operating parameters as inputs. In most cases existing test facilities and analytical capabilities will dictate which methods are available to the tester. The following paragraphs briefly discuss the application of transient measurement techniques and considerations to each method.

4.6.1.2.1 *Scale Force Thrust Measurement*

Figure 4.6-1 shows the forces acting on the engine control volume as well as the momentum of the fluid entering and exiting. Scale force (FS) is the reaction necessary to equate the summation of forces on the free body with the change in momentum across the control volume. In the case of an engine in a test cell this is the net load on the mechanical structures which hold the engine in place.

By equating the summation of forces on the free body with the change in momentum across the control volume, another expression of thrust is obtained:

$$FG = FS + W1 \times v1 + A1(PS1 - PS(cell)) \qquad 4.6\text{-}4$$

Figure 4.6.2 gives an indication of the relative magnitudes of the three terms for high and low bypass ratio engine over a range of operating conditions. Scale force is obtained by measuring the force necessary to restrain the engine as reacted through a load cell. Test facilities with this capability are designed such that loads are carried through the engine mounts to a thrust frame which is restrained in the direction of thrust (typically axial) by a system containing a load cell. The force reacted through the load cell is converted to an electrical signal. Typical test cell configurations with thrust stands are shown in Figure 4.6-3. The equations above apply to all cell configurations. The less important terms, such as scrubbing forces and pressure-area for engine skin, supports, and slip joint, are not included. A more complete derivation of these equations is contained in Reference 4.6.2.

Transient engine operation in altitude test cells often causes variations from the desired value in inlet total pressure, cell static pressure, and inlet total temperatures. In certain cases, the inferred measurement of gross thrust can be corrected to the desired inlet total pressure and desired static pressure using the transient measurements. For a convergent exhaust nozzle operating above critical pressure ratio (or for a convergent-divergent exhaust nozzle operating above design pressure ratio) at all conditions along the transient path from the initial steady-state condition to the final steady-state condition, the following equation is applicable:

$$FG_{ref} = [FG + A9(PS(cell) - PS(cell)_{ref} \times (\frac{P1}{P1_{ref}})] \times (\frac{P1_{ref}}{P1}) \qquad 4.6\text{-}5$$

where FG_{ref} is at the desired conditions of $P1_{ref}$ and $PS(cell)_{ref}$, and
FG is at the measured test conditions of P1 and PS(cell).

When the inferred measurement of net thrust is required, additional corrections for the effect of pressure variations on engine airflow and freestream velocity can be applied.

Corrections to the inferred gross thrust caused by variations in inlet total temperature from the desired value cannot be determined from generalized thermodynamic relationships. In the special case of fixed geometry engines, the thrust behaviour corresponds to operation at the different corrected speeds. Almost no current engines meet the fixed-geometry requirement because of variable nozzles, variable vanes, and gas coupled (not gear-coupled) rotors.. For the general case of variable geometry engines, the variation in inlet total temperature corresponds to operation at slightly non-standard atmospheric conditions. In some rare instances sufficient derivatives of component parameters are available to allow corrections for variations in inlet temperature.

Another term not shown in the equations for thrust is the time rate of change in momentum within the engine (control volume). This term is discussed in References 4.6.2 and 4.6.3. The term is assumed to be negligible but becomes more significant for extremely rapid transient conditions. Engine thrust during conditions such as surge, is generally not of primary interest and unsteady terms are therefore not included in this discussion.

Note that the pressure-area term must be added to scale force for the general case. Transient measurements, or calculations, of inlet mass flow, velocity and static pressure are therefore necessary in order for these terms to be included. Only for the open-air test stand in Figure 4.6-3 with a large inlet area bellmouth supported by the engine/thrust stand is this term negligible. The ram drag term must also be calculated when net thrust is the parameter of interest. Free-stream velocity (v0) is calculated from P1, T1, and PS(cell).

The primary transient consideration of the thrust stand measurement is dynamic response. The thrust stand is a relatively large mass (engine, inlet bellmouth, and thrust frame) restrained primarily by the load train and load cell with its inherent spring rate and natural damping provided by the structures. The natural frequency of the system must be high enough, and the damping low enough, that transient thrust measurements are not significantly affected. Section 4.6.1.5 briefly discusses calibration procedures which can provide insight to the dynamic responses of the thrust measurement system. However, most test facility specifications are available and response characteristics can be evaluated analytically considering a spring-mass-damper system:

$$f_R = 1/2\,(K_S/m)^{1/2} \qquad 4.6\text{-}6$$

where f_R = natural or resonant frequency
K_S = effective spring rate
m = mass

System damping can be characterized by the damping ratio:

$$h = C/Cc \qquad 4.6\text{-}7$$

where C = damping coefficient of the thrust stand,
Cc = critical damping coefficient for which the system would achieve full response to a step input in a minimum time without any overshoot.

Figure 4.6-4 shows the response of a system with 3% damping to a spike input. Note the overshoot and ringing at the natural frequency. An experimental method for determining damping ratio is presented in Section 4.6.1.5. Thrust stands are designed to be relatively stiff so that the natural frequencies are above those of the primary input force variations (normal engine thrust variations). Large thrust stands typically have a natural frequency on the order of 10 hz and structural damping of about 3%. This capability is adequate for measurement of relatively slow thrust transients associated with engine throttle excursions. However, very rapid thrust changes due to hard augmentor lightoff or blowout or engine surge may be beyond the useful frequency response capability of the facility system. An example is shown in Figure 4.6-5 where underdamped oscillations (ringing) in the thrust measurement result from an engine surge. Note the presence of an oscillation in the thrust signal even before the surge.

Thrust stand data should be low-pass filtered to remove noise and higher frequency content which may result from system resonances. The data in Figure 4.6-5 are a good example of why this is necessary. The user's transient thrust requirements should be evaluated relative to the design specifications for the particular facility system. The predicted thrust stand response to engine thrust variations at the highest frequency of interest should be considered to assure that significant attenuation does not result from system damping and that resonances are avoided.

4.6.1.2.2 *Thrust Calculation by Momentum Balance*

The second method presented in Reference 4.6.2 is calculated thrust based on a momentum balance using measured pressures and temperatures in the exhaust nozzle. This approach requires complex and high quality measurements as well as analytical models of the nozzle flow field and geometry. A schematic taken from Reference 4.6.2 and the fundamental equations on which this approach is based are shown in Figure 4.6-6.

The equation for a rake at the nozzle exit in Figure 4.6-6 is a direct application of the definition of gross thrust. For rakes positioned at the nozzle throat or entrance, additional terms are added to account for scrubbing drag and pressure-area effects between the measurement plane and the nozzle exit. Just as with the scale force method, engine inlet conditions have to be measured to account for variations during the transient testing or to calculate ram drag to find net thrust.

The momentum balance method of thrust calculation requires instrumentation to survey total pressure, total temperature, and determine exhaust gas composition at a plane in the exhaust nozzle. If the instrumentation is in place and can provide transient data of sufficient quality, this method could be used for a first order assessment of thrust variation with time. Significant uncertainties in the correlations between measured and station-average pressures and temperatures may be introduced during non-stabilized operation. Analytical models of the nozzle flow field for those properties which are not measured directly and a nozzle geometry model are also required. The accuracy of these models during transient operating conditions may be questionable. Gas property and geometry model uncertainties are increased due to transient and off design flow effects, thermal growth, and mechanical deflections of the nozzle.

The difficulties associated with obtaining transient data of sufficient quality and the uncertainties in analytical flow field and geometry models during transient operation should be reviewed carefully. This approach may be impractical for transient measurements, with the possible exception of the case where a fixed conic exhaust nozzle is installed on the engine.

4.6.1.2.3 *Thrust Calculation by Performance Model*

Estimates of engine thrust are often obtained using aero-thermodynamic representations of the engine components combined with control logic to form an engine cycle model. The accuracy of the model will vary significantly with the maturity of the program and the amount of model updating done to match measured engine performance. A schematic of the engine cycle model components taken from Reference 4.6.2 is shown in Figure 4.6-7. Engine cycle models with the addition of rotor, variable geometry, and control system dynamics can be operated in a transient mode to evaluate transient thrust. The accuracy of the model should be verified by matching transient test conditions and comparing model responses to measured engine data. For example, match measured fuel flow versus time and observe the resultant speed transient relative to measured data. Or, match measured fuel flow and rotor speed versus time and observe the implied combustor efficiency relative to expected values. Experiments such as these can establish a confidence level in the model and also help the engineer to determine the best approach to using the model with the available test data.

A simpler approach is to use the engine cycle model or available steady-state test data to establish correlations between key measurable parameters and thrust. The appropriate parameters will depend on engine configuration, control scheme, and operating conditions but may include corrected rotor speed, engine pressure ratio, engine airflow, or augmentor fuelling level. This method is often used in the evaluation of time to thrust (accel or decel time) and requires the least amount of instrumentation and data analysis. This approach is well suited for the user with limited instrumentation/facilities or analytical capabilities.

4.6.1.3 *Advantages and Disadvantages*

The three methods for thrust calculation described above require varying amounts and types of instrumentation and analytical tools. The advantage of one method over another depends on the availability of instrumentation and analytical tools and the level of accuracy necessary to meet data objectives. A common requirement is to monitor inlet and ambient conditions so that the thrust values obtained can be corrected to a constant or reference operating condition.

Scale force (when available) is a relatively straight forward approach. Thrust stands generally have the capability to provide high quality transient data so long as resonant frequencies can be avoided. The pressure-area term must also be calculated for net thrust and inlet momentum included for gross thrust requiring additional transient measurements.

The momentum balance method relies on a significant number of measurements in the relatively hostile environment of the exhaust nozzle. The approach may be practical only in special circumstances where the appropriate instrumentation and analytical tools are available. The uncertainty associated with transient thrust calculated by this method will be difficult to assess, but is likely to be relatively large.

Methods which make use of a performance model or data correlations require only limited instrumentation. The number and types of measurements necessary will depend on the specific model and how it is used. The uncertainty in the calculated thrust will vary greatly with the fidelity of the model and the extent to which the specific model has been updated or matched to engine test data. Some variation of this approach can always be used to estimate engine thrust.

The following guidelines are suggested for specifying requirements so that advantages and disadvantages of available methods can be weighed against the test data objectives:

DESCRIPTION OF TEST CONDITIONS:

1. Identify the thrust measurement desired. Specify whether net or gross thrust is the required measurement and if absolute or deltas (changes in thrust) are the primary data of interest. Diagrams and equations can be helpful in communicating the specific need.

2. Describe the type of testing planned and the engine responses anticipated. Provide a copy of the test plan or matrix and test procedures to be used.
3. Define the anticipated range of thrust. The range should cover all conditions to be tested, operating speed range including shutdown and overspeed if appropriate, and off-design operation anticipated such as surge, stall, flameout, fuel steps, or other severe transients.
4. Define the frequency and amplitude of thrust transients which will result from the testing defined in Item 3 above. Generally each type of test or procedure will have its own representative transient thrust characteristics. Provide as much detail as possible; examples of previous test results may be helpful.

DATA REQUIREMENTS:

1. Specify how the data are to be displayed/-recorded. Indicate whether analog or digital data are required and what the intended display and/or recording systems will be. Specify whether absolute thrust level is of interest or is it sufficient to obtain deltas (changes in thrust level) only.
2. Specify the thrust range(s) of interest. The range may be less than what is described in Item 3 above when there are anticipated engine operating conditions or transients which are not of interest to the user. The data requirements may need to be broken down into more than one thrust range such as idle versus high speed or upper left corner versus lower right side operating conditions. It can be useful to specify data ranges for the type of testing included in Item 2 above.
3. Specify the frequency response requirements and associated fluctuating amplitudes. Provide realistic amplitude and frequency requirements consistent with the conditions described in Item 4 above and the intended use of the data. Specify the desired accuracy and also the maximum uncertainty which may be acceptable. Give the test or instrumentation designer sufficient information for trade-off studies and decision making. If requirements vary significantly for different types of testing, then specify requirements individually for each.
4. Describe briefly how the data are to be used. The test or instrumentation designer is better able to make decisions and suggestions when he understands how the data are to be used. Not only those things which the user sees as requirements should be communicated to the test or instrumentation designer, but also any items which the user does not consider important. This can prevent compromises in system performance resulting from requirements which are perceived but do not actually exist.

Key factors in selecting the best approach to transient thrust measurement, from those discussed in Section 4.6.1.2, are presented in Table 4.6-1. The comments contained in the table are indicative of how the various techniques might match up with specific user requirements and available test facilities and instrumentation.

4.6.1.4 *Signal Conditioning*

Signal conditioning requirements for recording the thrust stand load cell output are discussed in this section. The methods for calculating thrust from other measured parameters discussed in Section 4.6.1.2 rely on transient measurements of pressures, temperatures, fuel flows, airflow, rotor speeds, control parameters, and variable geometry positions. Signal conditioning requirements for these various measurements are discussed in Sections 4.2 through 4.5 and 4.7.

The scale force signal is an electrical output from a strain gauge bridge attached to a mechanical member in the load cell of the thrust stand. The strain gauge bridge is discussed in Section 4.2.1.2 as applied to pressure transducers. The theory is the same for the load cell. The bridge electrical output is proportional to the strain in the mechanical member resulting from the force reacted through it. Power supply and signal amplification requirements for transient measurements should be the same as for steady-state testing. The primary considerations for transient testing are filtering and data averaging.

The thrust measurement should be low-pass filtered. A cutoff frequency should be selected to remove noise and erroneous signals resulting from system resonant responses. When the transients of interest to the end user represent rates of change of thrust significantly below the response capability of the thrust stand, a lower cutoff frequency filter or a rolling average of the digitized data will provide cleaner data and remove the low frequency noise common in thrust signals. Most engine thrust measurement systems are designed and used primarily for steady-state testing and very low cutoff frequency filters are often used. Transient data acquired without proper attention to the filter used may be misinterpreted or lead to false conclusions.

Signal amplification will be required to match load cell output to the full scale input of the terminal device.

4.6.1.5 *Calibration Procedures*

Thrust measurement accuracy requirements for steady-state performance characterization are typically very challenging. On the other hand, some amount of uncertainty is generally acceptable for the objective of evaluating thrust variation with time during transient testing. The appropriate calibration procedures for transient tests therefore involve verifying correlation of the transient measurement with a steady-state reference and an assessment of the additional uncertainty due to transient effects.

Before spending too much time quantifying all potential errors, consider 1) the accuracy requirements stated by the user, 2) the relative magnitudes of the inlet momentum and pressure-area terms for the testing planned, and 3) the anticipated transient behavior of the parameters which go into the calculation of thrust using the method selected. Concentrate on the error sources with the greatest potential to impact overall uncertainty. It is likely that many of the errors are negligible compared to a few dominating factors.

4.6.1.5.1 *Uncertainty in The Scale Force Method*

When gross thrust is the data objective, the scale force and pressure-area terms must be summed with the inlet momentum term. Inlet momentum is calculated from airflow and velocity (W1 and v1) which are derived parameters discussed in Section 4.4. Appropriate methods for calculation of transient airflow and velocity must be determined and the resulting error sources identified for inclusion in the uncertainty analysis.

Inlet and exit static pressures (PS1 and PS(cell)) must be determined for calculation of the pressure-area term. Cell ambient pressure can be assumed equal to exit pressure for many test configurations but this assumption must be reviewed for each specific test setup. Inlet static pressure can be measured directly or calculated using measured total pressure, temperature, airflow, and inlet area. The discussions of transient measurements and potential error sources presented in Sections 4.2, 4.3, and 4.4 should be considered in the definition of required instrumentation and error values for the uncertainty analysis.

Error sources in the scale force measurement are shown in Figure 4.6-8 with descriptions in Table 4.6-2. Because of the importance to performance testing, steady-state scale force error sources are typically well understood. Transient error sources should be reviewed considering the characteristics of the various system elements. It is likely that these effects can be estimated based on component specifications, historical data, or engineering judgement.

4.6.1.5.2 *Dynamic Thrust Stand Calibration*

The dynamic response of a thrust stand can be determined analytically by calculating the natural frequency and amount of damping provided by the structure (see Section 4.6.1.2.1). When necessary, experimental techniques can also be used to evaluate these terms.

A step input can be applied by loading the thrust stand through a cable in tension and then severing the cable. Analysis of the measured response provides both the natural frequency and damping ratio. The natural frequency should be obvious by inspection of the recorded force versus time trace (see Figure 4.6-4). Damping ratio can be calculated by taking the natural logarithm of the ratio of two successive amplitudes:

$$\delta = 2\pi\sqrt{1 - h^2} \qquad 4.6\text{-}8$$

where δ = natural log of the ratio of two successive amplitudes.

Once the natural frequency and damping coefficient have been determined, the dynamic response of a second order system is:

$$\text{amplitude ratio} = \frac{1}{\sqrt{(1-\beta^2)^2 + (2h\beta)^2}} \qquad 4.6\text{-}9$$

$$\text{phase} = \tan^{-1}\left(-\frac{2h\beta}{1-\beta^2}\right) \qquad 4.6\text{-}10$$

where β = frequency / natural frequency 4.6-11

4.6.1.5.3 *Uncertainty in the Momentum Balance Method*

General categories of error in the momentum balance method are listed in Table 4.6-3, and errors associated with individual measurements are covered in the other parts of Section 4 of this report. The level of uncertainty is increased in most of the categories during transients by more than just measurement error. That is because this method relies on analytical models in order to calculate thrust.

Rake drag and flow profiles impact the correlation of measured conditions with the true values (unaffected by the instrumentation). These effects are potentially larger and corrections more difficult to establish for transient conditions. This is especially true when the transient test results in operating conditions which deviate significantly from steady-state operation. Swirl/viscous effects may also be larger or at least different during transients compared to stabilized operation.

Determination of gas properties becomes more difficult during transients due to off-design fuel-air ratios and uncertainties in the measurements which go into the calculations. Uncertainty in nozzle geometry and leakage could be significant if variable geometry is involved. Even with fixed geometry, there may be effects due to thermal growth and mechanical deflections under transient conditions.

Each of these effects must be considered and estimates made of the potential errors for the uncertainty analysis.

4.6.1.5.4 *Uncertainty in the Performance Model Method*

As with the momentum balance method, it is impossible to generalize the uncertainty associated with determining thrust using a performance model. Uncertainties in the individual measurements which are utilized can be assessed as described in other sections of this report. At stabilized operating conditions results of the performance model can be compared with other measurements or calculations of thrust if available. In the end, the engineer must determine the uncertainty in transient results based of the particular method used and models or data correlations employed in the method. This assessment will rely heavily on historical data and engineering judgement.

4.6.1.6 *Design Example*

The following example illustrates a typical approach to evaluating engine thrust variations with time. Note that the facility/test and analytical capabilities availabte are well suited to the end user's stated data objectives. When this is not the case, the existing capabilities should be reviewed with the user to determine whether or not useful data can be obtained.

The user wishes to evaluate the thrust transients which result during switches from primary to secondary engine control mode. Primary mode is the normal operating condition for the engine control giving full performance and transient capability. For certain sensed failure scenarios the control reverts to the secondary or backup mode. In secondary mode the engine is operated on simplified control schedules and both steady-state thrust at any given throttle position and thrust response to throttle transients may be affected as a result. The testing planned to evaluate the impact of switches from primary to secondary mode is outlined in Table 4.6-4.

The user's requirements are stated below in a format consistent with that suggested in Section 4.6.1.3.

DESCRIPTION OF TEST CONDITIONS:

1. It is required to measure net thrust variation with time during switches from primary to secondary control mode.
2. The testing to be accomplished consists of manual switches from primary to secondary control modes during steady-state and transient engine operation. A representative test matrix is included as Table 4.6-4. Power management and variable geometry schedules are changed between primary and secondary modes resulting in thrust transients. The largest effects are due to cancellation of augmentor operation and a reduction in maximum airflow. At some part-power conditions the steady-state thrust level may actually be increased. Transient response of the engine should not be greatly affected.

   Each test will be a comparison of primary mode operation to the corresponding condition with a switch to secondary mode. For steady-state conditions, the transient resulting from the switch is of interest. For the transient conditions, a back-to-back comparison of the engine response with a switch to secondary will be compared to the same throttle movement in primary mode.
3. The conditions to be tested are shown in Table 4.6-4 with engine thrust levels ranging from below idle to max augmentation.
4. Testing planned consists of steady-state and transient operation including rapid throttle movements and reversals. Thrust transients in primary mode will cover the full thrust range from idle to Mil power as shown in Table 4.6-4. Switches to secondary mode during steady-state operation result in rapid thrust changes (less than 1 second) to the secondary mode level. Switches during engine transients may alter the transient characteristic as well as the end point.

DATA REQUIREMENTS:

1. The transient thrust data are to be recorded on the digital data system for subsequent analysis. A strip chart recording of the analog thrust measurement is also required for test direction and monitoring. Absolute accuracy of this on-line display is not important so long as the general response is indicative of the actual engine behavior.
2. The full range of engine thrust from below idle to max augmentation is of interest.
3. Thrust variations associated with the maximum engine control responses during normal throttle transients and switches from primary to secondary mode are of interest. For large thrust transients associated with full throttle movements the time to accel or decel is on the order of seconds. Thrust variations resulting from switches to secondary mode occur in less than 1 second. Representative thrust transients due to switches from primary to secondary at steady-state conditions are indicated in Figure 4.6-10.
4. The data which are acquired on the digital system will be used to validate computer model simulations. The computer model in turn will be used with a flight simulator to evaluate the impact of control mode switches on aircraft operation. The on-line strip chart display will be used during the test to monitor engine responses. This information will provide the design engineer indications of the magnitude of the transients and any unusual or unexpected responses to be used in directing the test.

DESIGN APPROACH:

The requirements for this example are summarized in Table 4.6-5 and an approach to meeting the stated requirements is outlined in Table 4.6-6. The altitude test cell to be used has a thrust stand which should have adequate response for the thrust variations and frequencies required. The thrust stand data will be low-pass filtered below the resonant frequency and sampled at a sufficiently high rate to avoid erroneous content in the data. Variations in inlet total pressure are anticipated during engine airflow transients and will be recorded on the digital data system. Post test data analysis will need to include corrections for the inlet pressure variations.

The pressure-area term will be calculated using cell ambient pressure and close coupled static-pressure measurements in the inlet.

THRUST STAND DYNAMIC RESPONSE:

The thrust stand is known to have a natural frequency of about 9 hz based on available data and the damping coefficient is estimated to be 3%. Based on the thrust variations indicated in Figure 4.6-9, a 2 hz periodic oscillation will be assumed to estimate dynamic response. This is 4 to 5 times the fundamental frequency of the transients shown. From the relationships of Section 4.6.1.5.2:

$$\text{amp ratio} = \frac{1}{\sqrt{(1-\beta^2)^2+(2h\beta)^2}} = 1.052$$

where $\beta = 2/9$ and $h = .03$

This implies as much as 5.2% overshoot in scale force for a 2 Hz oscillation.

FILTER SELECTION:

A low-pass filter will be used to reject noise and signal amplification due to the thrust stand resonance. A second-order filter (such as a Bessel or Butterworth) with a cut-off frequency of 4 Hz is a good choice. This filter results in approximately 5% attenuation at one half of the cut-off frequency or 2 Hz. The filter characteristic is therefore well suited to offset the amplification caused by thrust stand resonances.

UNCERTAINTY ANALYSIS:

The error sources which impact the determination of net thrust for this approach consist of uncertainties in the scale force measurement and transient measurements for the pressure-area term. Refer to Section 4.2 for a detailed discussion of transient pressure measurement system design and error sources.

The error sources for scale force at the sea level/static test condition are listed in Figure 4.6-10 and are numbered for reference in this discussion. The steady-state error values indicated in the table are typical of what can be achieved in a modern test facility. Where applicable, the steady-state errors represent corrected values since the objective of this testing is to measure thrust variation and not absolute level. The rationale for the estimated transient effects are listed below:

2) and 3) Load cell dynamic calibrations - are assumed to be negligibly small compared to the other transient errors.

4) Thrust stand alignment - could be impacted during thrust transients. Twice the steady-state

correctable error of 0.1% is assumed for the transient effect.

6) Labyrinth seal effects - are assumed to be significantly larger during engine airflow transients resulting in inlet pressure variations. A factor of 5 was assumed.

11) Pressure effects on the load cell - can be corrected for a high degree of accuracy in steady-state measurements but are assumed to not be correctable for transient measurements.

14) Temperature effects on the load cell - resulting from this type of transients are assumed to be negligible.

21) Thrust stand dynamic response - is estimated to result in an error of up to 1.7% of the scale force measurement. This is based on assuming that the low-pass filter reduces thrust stand overshoot (estimated above at 5.2%) by half. From Figure 4.6-10 the rapid thrust transient is as large as about 65% of max thrust. Therefore, (5.2 × 0.5 × .65) = 1.69% of max thrust.

The error values from Figure 4.6-10 must be combined in accordance with the methodology of Section 3. The uncertainty analysis should be repeated at each test condition in Table 4.6-4 considering the relative magnitudes of the scale force and pressure-area terms as shown in Figure 4.6-2. At the sea level/static condition the scale force represents almost all of the net thrust, and errors in the pressure-area term will have little impact. At 0.9 Mach No. the scale force and pressure-area terms are approximately equal in magnitude, and at 1.8 Mach No. pressure-area is the dominant term.

4.6.2 Torque

4.6.2.1 *Introduction and definitions*

Torque measurement falls into two major classes, the first where the measurement is made directly on the shaft transmitting the torque and the second through secondary measurements that include insertion of a torque meter in series with the torque shaft and indirect measurement such as the reaction on the carcass of a load dynamometer. Torque measurement is most commonally associated with driving output shafts in turbo prop and turbo shaft engines, but there are also measurements made on any rotating shaft such as those driving gearboxes, tachometer couplings, etc.

In the majority of cases, the engine has a built in torque measuring system that is not is located in the drive train. An external torque measuring system must be installed in the actual output shaft so that actual torque output to the load can be measured and the performance of the engine torque system verified.

The most common methods of measuring torque are described in Reference 4.6.5. These include the torsion bar dynamometer, strain gauges and reaction load cells on dynamometer carcasses. There are in addition, hydromechanical units that are designed into the reduction gearbox which produce a hydraulic pressure proportional to the torque generated (Reference 4.6.6). The various methods of measuring torque are illustrated in Figure 4.6-11. Additional information on the various methods of measuring torque are given in References 4.6.7 through 4.6.10.

4.6.2.2 *Basic Theory*

The measurement of total load on the test section during a transient couples torque with shaft speed. Torque is a reaction to change against which the engine works and the rotational speed of the shaft determines how rapidly the energy is extracted (see Section 4.8 Horsepower). So the variation of the horse power extraction during a transient recording is temporally related to the torque and shaft speed.

The strain gauged torque shaft is illustrated in Figure 4.6-11(a). Twisting of the shaft produces an unbalance in the bridge made up of the four gauges. For this application, excitation power must be supplied to the bridge either through slip rings, transformer coupling or on the shaft battery power. The signal outputs can be fed out again through the slip ring, transformer coupling or telemetry.

The reaction load cell arrangement is illustrated in Figure 4.6-11(b). The carcass of the dynamometer is mounted on flexures that permit limited rotation around the axis of the drive shaft. The load cell reacts to pressure exerted through the arm.

The torsion bar torquemeter is illustrated in Figure 4.6-11(c). The two discs are welded to the torsion bar. As the bar twists, the teeth on the discs move relative to each other. This displacement is sensed either using magnetic pickups or optical sensors. From the phase shift observed between the teeth as the shaft rotates, angular displacement between the ends of the torsion bar is measured and interpreted through calibration in terms of torque.

The hydromechanical torquemeter is illustrated in Figure 4.6-11(d). Rotation of the ring gear is resisted by helical splines, which impart an axial movement to the ring gear and to the torquemeter piston. Movement of the piston forces the valve plunger against the spring, opening a metering orifice and allowing an increased flow of pressure oil into the torquemeter chamber. Piston movement continues until oil pressure in the torquemeter chamber is proportional to the torque being absorbed by the ring gear. Any change in engine power recycles the sequence until equilibrium is again reached. As the external pressure and the pressure within the reduction gearbox may vary, the difference between the torquemeter hydraulic pressure and the gearbox internal pressure gives a more precise measure of the output torque. The pressure difference is measured with a differential pressure transducer where one side is oil and the other an oil mist/gas combination.

The ability to relate the test results to the actual torque response in the test vehicle requires that any loading device have an inertia closely resembling that of the actual installation. In the case of a turbo prop, the dynamometer must be as closely matched to propeller characteristics as is practically possible. Differences will have to be taken into account in analysing the uncertainty in the data.

The time dependancy of typical torque measuring systems is illustrated in Figure 4.6-12. The contributions to bias and precision errors in the steady state and transient modes are shown in Figure 4.6-13.

4.6.2.3 *Advantages and Disadvantages*

For transient test conditions, direct measurement from the torque shaft is preferred. This reduces the errors due to compliance in coupling to the secondary sensing systems. In many cases, the built-in engine torque shaft cannot be modified or accessed easily so indirect methods must be employed. Special care must be taken to ensure that the uncertainty in the data is kept to a minimum.

The response of strain gauges (and sensors working on a similar principal) mounted directly on the shaft, is very fast. For other techniques such as optical displacement or phase changing across toothed wheels as used by the torsion bar dynamometer, the electronic processing will cause time delays which will require temporal compensation. The response of the electronica, depending on the design, may require a number of measurements over a time period dependent on the rotational speed of the shaft. It is important that, for transient measurements, the dependency of the time constant on the response to changes be independent of as many external, and designed in, influences as possible. Reaction load cells on a load dynamometer carcass are simple to use but are relatively remote from the measurand.

The hydromechanical systems have an intermediate step in the need to convert to pressure and relate that pressure to the torque. Precautions in the application of pressure transducers are detailed in Section 4.2.

The influence of external sources, such as a load dynamometer on the torque reading can be problematic. Effects range from friction of bearings, windage on rotating shafts and flywheels, forces in the connection of service lines (hydraulic line flexing) through to the dynamometer load control system transfer function which may be working with or against the test schedule.

4.6.2.4 *Signal Conditioning*

Signal conditioning configurations are illustrated in Figure 4.6-14.

For the strain gauge set-up, the choice of slip rings, coupling transformer or telemetry will determine what signal conditioning may be required. With slip rings, the arrangement is the same as for any strain gauge bridge, that is, excitation is supplied to the bridge, the outputs are fed to an amplifier and then out to the recording systems through a filter. With a coupling transformer, a regulator is required on the rotating shaft for the excitation and the output signal from the bridge may need demodulation before amplification and filtering. To improve signal quality when using transformer coupling, frequency modulation is recommended. Telemetry modules mounted on the shaft usually contain their own regulators and the off-shaft receivers demodulate and amplify so the output signal may only require filtering before passing on to the data recording systems. The choice of system used will depend on the quality of the data required for the particular test in progress. Slip rings are relatively inexpensive but do introduce additional noise to the low level signals that may degrade the signal to an unacceptable uncertainty level. FM telemetry does have superior signal quality but is expensive.

The reaction load cell is the simplest set-up. Since it is mounted off-shaft, the excitation is directly coupled to the unit and the output signal is simply amplified and filtered.

The torsion bar system usually comes with an electronics package that does all the processing. The only addition that may be required is a filter.

The hydromechanical system has to take into consideration the response of the differential pressure sensing system which will have in general only oil on one side of the diaphragm and oil mist/air on the other.

4.6.2.5 *Calibration Procedures*

Calibration in the running rotational mode presents the first difficulty. Static calibration is fairly straight forward if appropriate precautions are taken. Calibration of the rotating shaft presents difficulties as there are no rotating standards for torque. Power transfer through a rotating high speed shaft may not be represented by the shaft twist as determined under static conditions. Corrections can be applied using secondary measurements from a reaction load cell on the dynamometer to infer the correct calibration of the shaft. Transient measurements require additional precautions in relating the transfer function between the measurand and the readout devices.

A method for calibrating rotational torque is by use of a four square dynamometer as illustrated in Figure 4.6-15. These systems operate either in a fixed preload mode or with a hydraulic, usually variable, applied load. The assumption is made that the load applied does not vary over the operating speeds. It is however possible to obtain a "feel" for the torque system response during simple accelerations and decelerations.

The simplest torque system to use and calibrate is the reaction load cell. In this case known weights are applied to a known position on a calibration load arm. The calibration is performed with the dynamometer services applied, e.g., for a water brake, the water must be running into the dynamometer so that the stiffness induced in the supply pipes is included in the calibration.

Strain gauged shafts can be calibrated in static conditions by simply applying a twist to the shaft. Precautions are necessary to eliminate stiction and off-centre loads. Techniques such as counter-rotating driven support bearings on each end of the shaft plus a yoke attachment for balancing the applied forces are necessary for best accuracy.

For torsion bar systems (phase shift), the procedure is complicated by the fact that the shaft must rotate relative to the sensors. A static calibration similar to that for the strain gauged shafts can be performed by rotating the sensors relative to the shaft and applying twist to the shaft taking precautions as described above. The feature, rotation of the sensors relative to the shaft, is available on some commercially available torque meters.

4.6.2.6 *Design Examples*

Before addressing a specific design example, it should be noted that special precautions need to be taken for installation effects when using instrumented shafts. These installation effects include thermal gradients across and along the shaft modifying the shaft stiffness, induced vibrations/orbiting of the shaft, and compliance between the shaft and the sensors. Heating in the shaft occurs as the torque is cycled so monitoring of the shaft temperature may be necessary to provide correction of the data obtained if on shaft measurements are being used.

A specific example of a transient test which requires torque measurement is simulation of "wave off" of a helicopter in autorotation as illustrated in Figure 4.6-16. The rotor blades generally take a minimum of 1 sec for a full travel from 0 to 100% pitch. Engine rating in normal flight is typically between 60% at zero forward speed and 80% at maximum speed. A realistic test condition is obtained with a collective pitch increase to 70% within 0.75 sec., the critical operating condition being for a helicopter at low altitude. The collective pitch (CLP) is used by the engine to anticipate changes in load due to pitch modification to the rotor thereby improving engine response time. The output power shaft coupling to the helicopter rotor gearbox runs in a constant speed mode at 6000 rpm.

Ideally, the use of an actual helicopter drive train and rotors would be the closest to a real simulation. Unfortunately, this is not practical for engine manufacturers and so simulation of the loading characteristics are generally achieved through the use of load dynamometers (Figure 4.6-17).

The evaluation of the performance of the engine under test requires that the torque loading along with shaft responses be recorded relative to the movement of the collective pitch control. Figure 4.6-18 shows a typical response to a 1 second change to 80% of the CLP for the engine torque, power turbine speed (Np), and gas generator speed (Nh), when operating in an actual helicopter. The events, caused by the movement of the CLP lever, restabilize in a new steady-state condition within a 5 second period.

The engine torque overshoots the final steady-state level by nearly 20%. A resolution of the measurement of this parameter of 0.33% at 100% is acceptable (10 times better than the uncertainty band). The torque is applied at a rate of 100% in a time of 1.5 sec. To resolve the 0.33% at the turn-around point needs samples every 0.005 sec, i.e. a sample rate of 200 per second. A common sampling rate of 200 per second will satisfy the overall resolution requirements.

In order to meet the rapid response requirements, an in-line strain gauge torquemeter is used as illustrated in Figure 4.6-17. The strain gauge excitation and signal leads are routed through slip rings from the rotating shaft to the data recording system. A low pass filter is necessary to remove the unwanted noise inherent in the slip rings plus the vibration induced noise generated by the dynamometer loading system. A low pass filter with a cut-off frequency of 80 Hz will suit this application. The filter will accommodate the 200 per second sample rate of the data acquisition system and reject the unwanted high frequency noise but will introduce a lag in the output signal of 12.5 msec, i.e. 2.5 sample periods. At 100% torque, 2.5 sample periods gives a bias lag of -0.8±0.17 %. The 0.8% is bias that can be added directly to the output, while the ±0.17 % due to sampling error is part of the overall uncertainty. In this example the total contributions of sample period uncertainty have been lumped together as a 1.0% uncertainty due to lag.

As a convenient method of on-line calibration confirmation of the stability of the torquemeter, the torque applied to the dynamometer is verified through the use of a reaction load cell on the carcass. The test setup is illustrated in Figure 4.6-17. Calibration of the reaction load cell is performed using calibration weights loaded onto an extension arm. This is a static calibration which does not take into consideration friction and windage loading that will be present under running conditions. For the test being described these contributions to uncertainty are not considered significant as the reaction load cell is used as a pre and post test comparison at steady-state conditions to establish that the in-line torquemeter has not changed characteristics due to environmental or physical effects. The low pass filter in the system is necessary to reduce high level noise due to dynamometer vibrations.

The uncertainty for the system described in this example is summarized as follows:

Bias (B) = ± 0.26% and Precision (S) = ± 1.12%, from Figure 4.6-14.

Then, total uncertainty URSS = $\pm [(B^2) + (2S)^2]^{1/2}$ = ± 1.6% , for the measurement system up to the data recording system.

The last step is to determine the transient characteristics of the loading system. This may be done using an engine which is accelerated at different rates of change over the torque range of interest to produce a series of curves similar to those of Figure 4.6-18. The dynamometer control is then fine tuned. During the test being described the dynamometer operates in a constant speed mode with the torque loading applied according to a preprogrammed schedule.

4.6.2.7 *Advanced Sensors*

There are many variations on the measurement of the torque in shafts in development. Techniques range from improvements to those already described above to measurement of changes in electrical properties induced in the shaft material by stress as twisting occurs. The choice depends on the application and accessibility to the measurand. References 4.6.8 to 4.6.10 give more detailed information on sensors.

A non-contacting, non-intrusive torque meter and load condition monitor, utilizing the photoelastic principle to measure torque, bending and tension loads under rotating conditions, is presently in the development stage. This concept is electro-optically based, and employs the principle of classifying the interference patterns produced in an epoxy film applied to the loaded shaft. It has already been proven that a unique optical signature exists for each load condition. A major advantage is elimination of any mechanical slip ring or FM transmission system which can be noisy and complex. Since the system does not depend upon optical intensitities, a relatively clean environment is not required. Demonstrated static accuracies for single and multiple load conditions are in the order of ±0.2%, while expected operational system accuracy should be better than ±2%. The system takes advantage of recent advances in optical detection and signal processing techniques, and is based upon ideas originally published by Dr. F. Zandman in 1959 and 1962.

4.6.3 References

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Table 4.6-1 Advantages and Disadvantages of Thrust Measurement Methods

Method	Instrumentation Required	Analysis Required	Confidence Level	Appropriate Method Application (Typical)
Scale force (Thrust stand)	o Thrust stand with load cell o Inlet pressure and temperature o Ambient pressure o Air flow/velocity for FG	o Correction for inlet pressure variations o Calculation of inlet momentum for FG	Good for thrust transients well below the resonant frequency of the thrust stand	Frequency response limited by thrust stand characteristic
Calculation by momentum balance	o Exhaust nozzle pressure and temperature o Ambient pressure o Exhaust gas composition o Nozzle geometry o Fluid flow rates	o Exhaust nozzle flow field model o Exhaust nozzle geometry model o Calculation of inlet momentum for FN	Undetermined (best with fixed conic nozzle)	Limited
Calculation by performance model	o Inlet pressure and temperature o Ambient pressure o Fuel flows o Rotor speeds	o Transient engine cycle model	Varies with amount of model validation	Throttle transients including augmentor
Correlation with measured engine parameters	o Inlet temperature o Rotor speed o Engine pressure ratio o Fuel flows	o Steady-state data base	Varies with type of correlation	Throttle transients including augmentor

Table 4.6-2 Thrust Stand Error Sources

1	Error from standard lab calibration of load cells, including traceability to national standards.
2	Error from dynamic calibration of load cells.
3	Error from standard lab calibration of clock.
4	Error due to misalignment between the engine force vector and the force vector measured by the data load cell train.
5	Error due to shift in load cell calibration caused by attachment of adapters and flexures.
6	Error due to pressurization of the labyrinth seal.
7	Error caused by the measurement of the forces on an axis different from the engine centreline.
8	Error due to system hysteresis.
9	Error due to system non-repeatability, as determined by repeated calibration both pre and post test.
10	Error due to system non-linearity.
11	Error due to the effect of changes in cell pressure on the load cell.
12	Error due to the effect of changes in cell pressure on the test cell wall which is the thrust system ground.
13	Error due to the effect of changes in line pressure on the tare forces exerted on the thrust measurement system by service lines, etc., routed to the engine.
14	Error due to the effect of a change in temperature on the load cell.
15	Error due to the effect of changes in temperature on the tare forces exerted on the thrust measurement system by lines routed to the engine.
16	Error due to thermal growth of the thrust stand.
17	Error in force measurement as a result of inlet air ram effects on sea level test stands. (This error is also present for altitude test cells but will be taken into account in the elemental error propagation activities.)
18	Error in the force measurement as a result of secondary airflow external drag effects on engine surface and service lines.
19	Error due to the effect of vibration on the load cell.
20	Error due to the effect of vibration on the thrust stand.
21	Error due to dynamic response of thrust stand to transient force input.

Table 4.6-3 Error Sources in Momentum Balance Method for Transient Thrust Calculation

Rake Drag	Theoretical/Experimental corrections
Flow Profiles	Total pressure/temperature
	Static pressure
	Flow angularity
Flow Measurements	Working fluids
Swirl/Viscous Effects	
Gas Properties	High/Low FARs
Engine Geometry Definition	Thermal Transients Deflections
Nozzle Leakage	

Table 4.6-4 Test Matrices for Design Example of section 4.6.1.6

Inlet Conditions	Transient Tests	Thrust Variation/ Delta Time
o Sea-level static o 9.15 km / 0.9 Ma o 15.2 km / 0.45 Ma o 12.2 km / 1.8 Ma	o Switch from primary to secondary mode - Mil power - Max augmentation - Idle o Switch from primary to secondary mode - Accel, idle-mil - Accel, mil-max - Decel, mil-idle - Reburst, mil-idle-mil	- Mil - 80% mil/<1 second - Max - 80% mil/<1 second - Supersonic idle - subsonic idle/ < 2 seconds - Idle - mil/2-12 seconds - Mil - max/1-6 seconds - Mil - idle/1-5 seconds

Table 4.6-5 Data Requirements for Design Example of Section 4.6.1.6

Transient Thrust Measurement	Frequency Response	Data Recording or Display
o Thrust vs. time during engine transients and control mode switches	o Approximately 2 Hz for thrust variations up to + 25% of max augmentation	o Digital recording along with other engine and facility parameters
o Repeatability and thrust variation (deltas) more important than accuracy of absolute value	o Approximately 1/2 Hz for full thrust variations, i.e., idle-max (static)	o Strip chart display on-line

Table 4.6-6 Transient Thrust Measurements for Design Example of Section 4.6.1.6

Measured System/Approach	Instrumentation	Signal Conditioning
o Facility thrust stand measurement	o Load cell	o Low-pass filter at 5 Hz (load cell signal)
o Record inlet pressure for post test analysis (data correction)	o Transient inlet pressure	

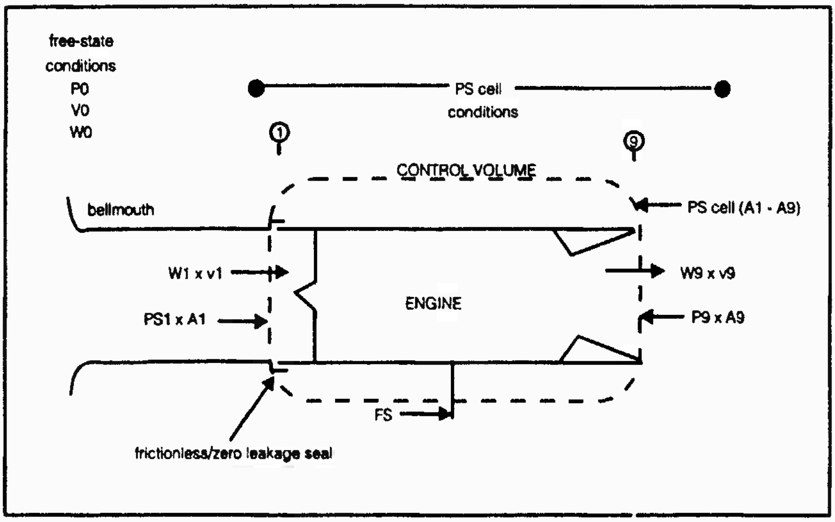


Figure 4.6-1 Engine Control Volume for Thust Definition

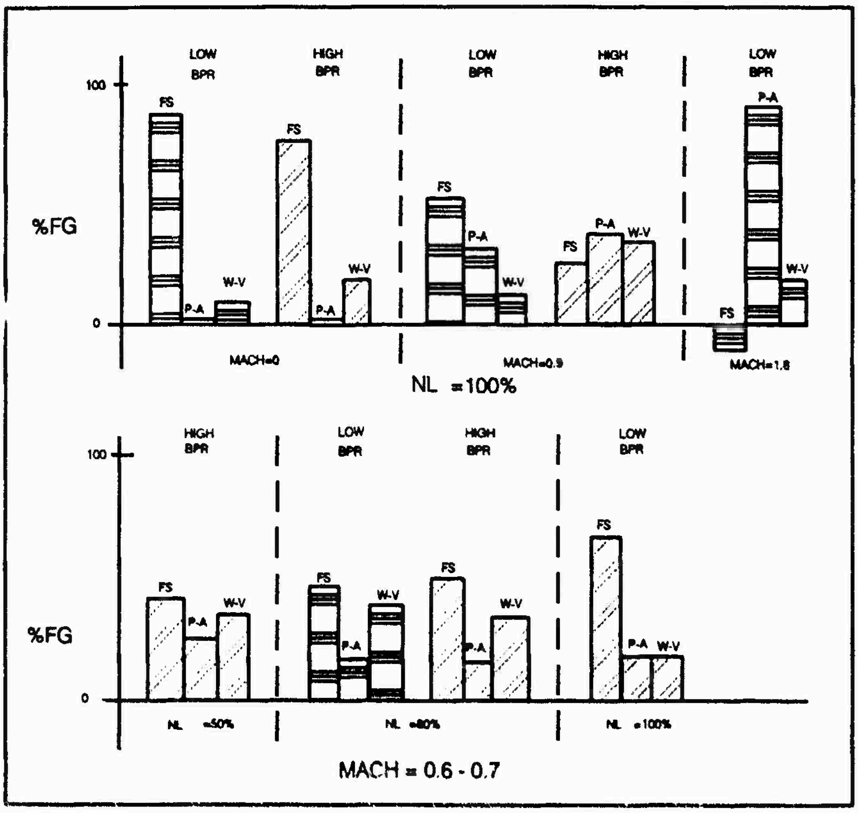
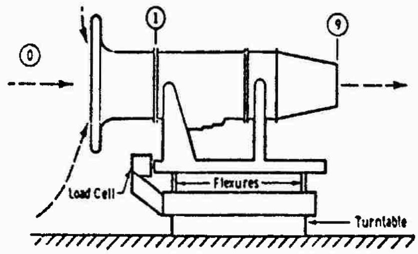
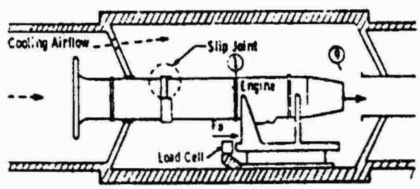


Figure 4.6-2 Relative Magnitudes of Gross and Net Thust and Ram Drag



OPEN-AIR TEST STAND

FG = FN = Fs   assuming v0 = 0 and uniform static pressure around the engine/bellmouth



ALTITUDE TEST CELL

FG = Fs + W1v1 + A1(Ps1 - Ps cell)

assuming negligable friction in a cylindrical duct between the slip joint and engine inlet (Station 1)

Figure 4.6-3 Typical Thrust Stand Configurations

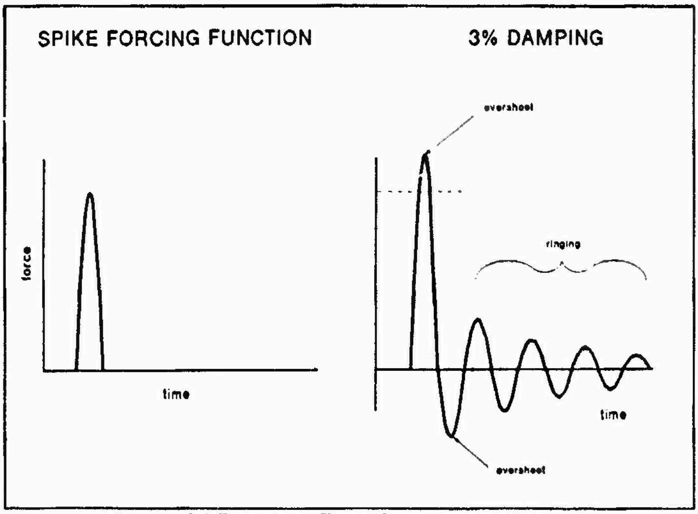


Figure 4.6-4 Example of Thrust Stand Dynamic Response

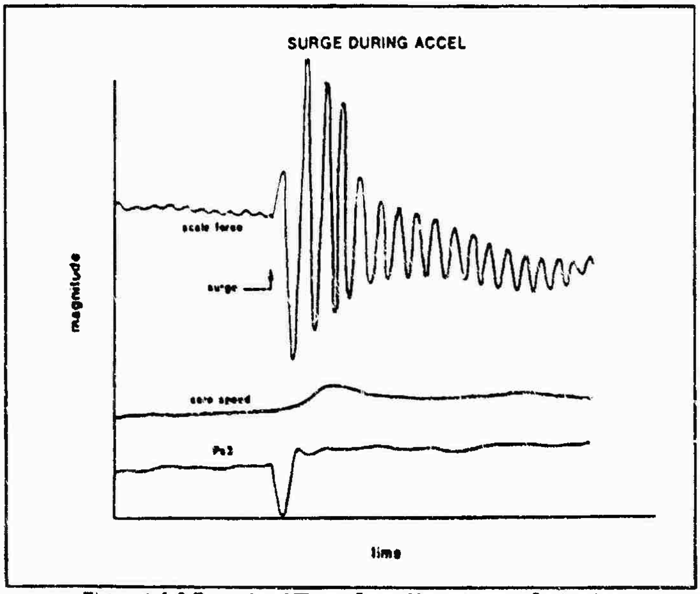
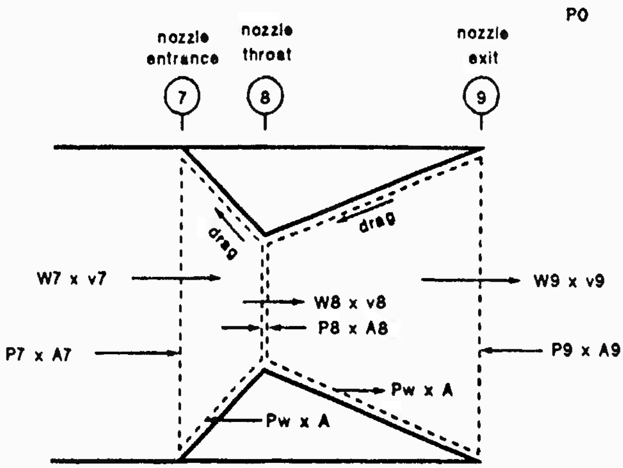


Figure 4.6-5 Example of Thrust Stand Underdamped Oscillation



RAKE POSITION	GROSS THRUST EQUATION
NOZZLE ENTRANCE	$F_g = \int^{A_7} \left(\frac{Wv}{A} + P\right) dA + \int_{A_7}^{A_9} P_w dA - P_o A_9 - \int_{X_7}^{X_9} C_{f_w} dq$
NOZZLE THROAT	$F_g = \int^{A_8} \left(\frac{Wv}{A} + P\right) dA + \int_{A_8}^{A_9} P_w dA - P_o A_9 - \int_{X_8}^{X_9} C_{f_w} dq$
NOZZLE EXIT	$F_g = \int^{A_9} \left(\frac{Wv}{A} + P\right) dA - P_o A_9$

WHERE: F_g = GROSS THRUST
A_7 = NOZZLE ENTRANCE AREA
A_8 = NOZZLE THROAT AREA
A_9 = NOZZLE EXIT AREA
W = MASS FLOW RATE
v = VELOCITY
P_w = WALL PRESSURE
X = DISTANCE
C_{f_w} = SKIN FRICTION COEFFICIENT

- USES COMPUTER CODES TO DEFINE FLOW FIELD PROPERTIES
- PROGRAM INPUTS INCLUDE
  - P
  - T
  - FUEL-AIR RATIO
  - NOZZLE GEOMETRY
  - AMBIENT PRESSURE
- WALL PRESSURES MEASURED OR CALCULATED

Figure 4.6-6 Schematic and Equations for Momentum Balance (Reference 4.6.2)

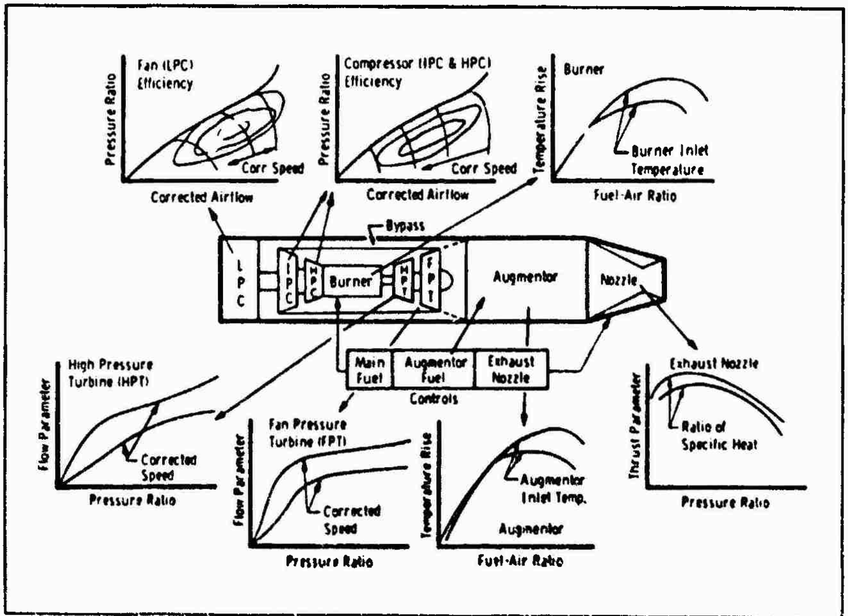


Figure 4.6-7 Schematic of Performance Model

(Reference 4.6.2)

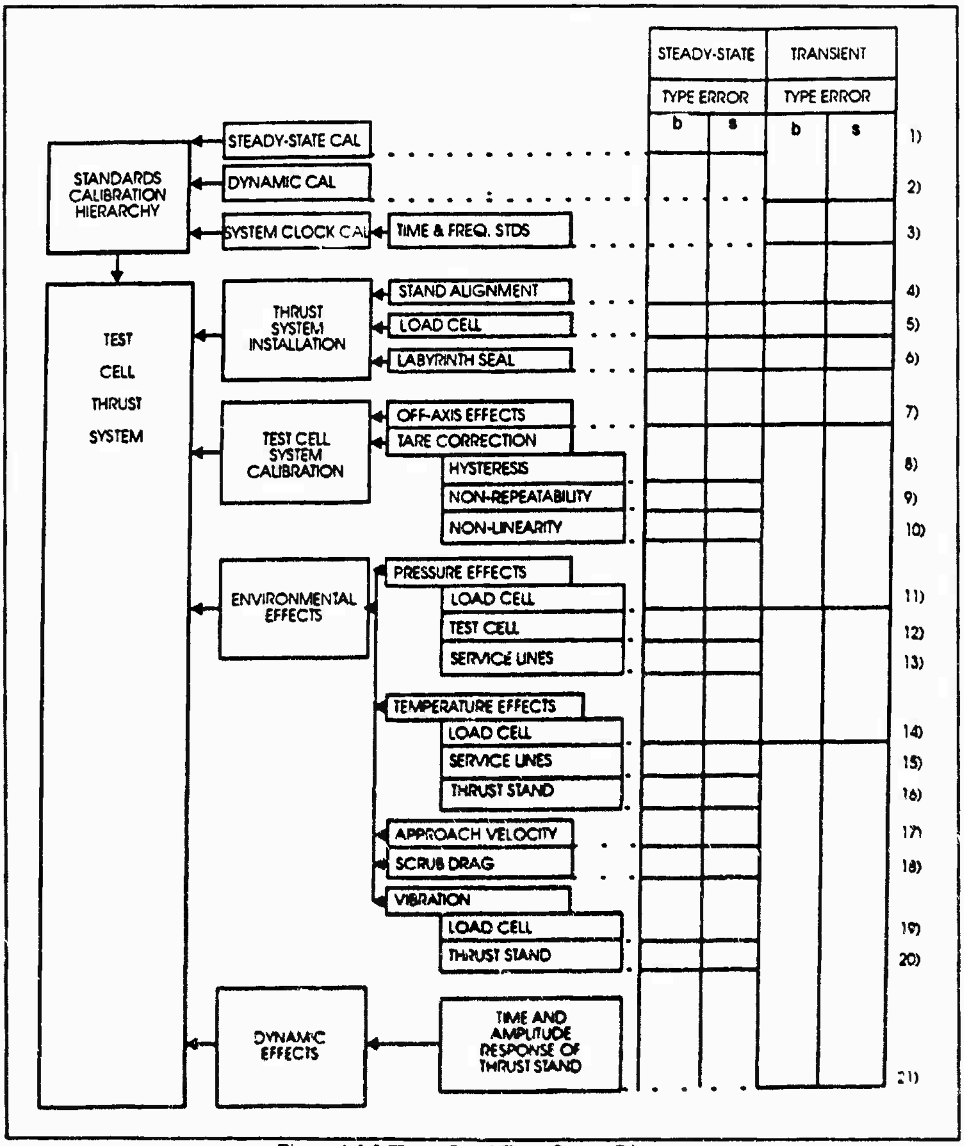


Figure 4.6-8 Thrust Stand Error Source Diagram

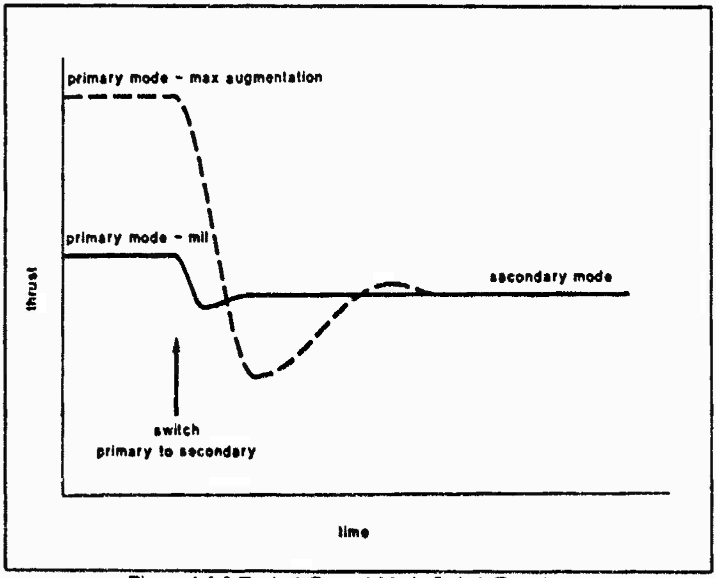


Figure 4.6-9 Typical Control Mode Switch Transients
PLA Constant

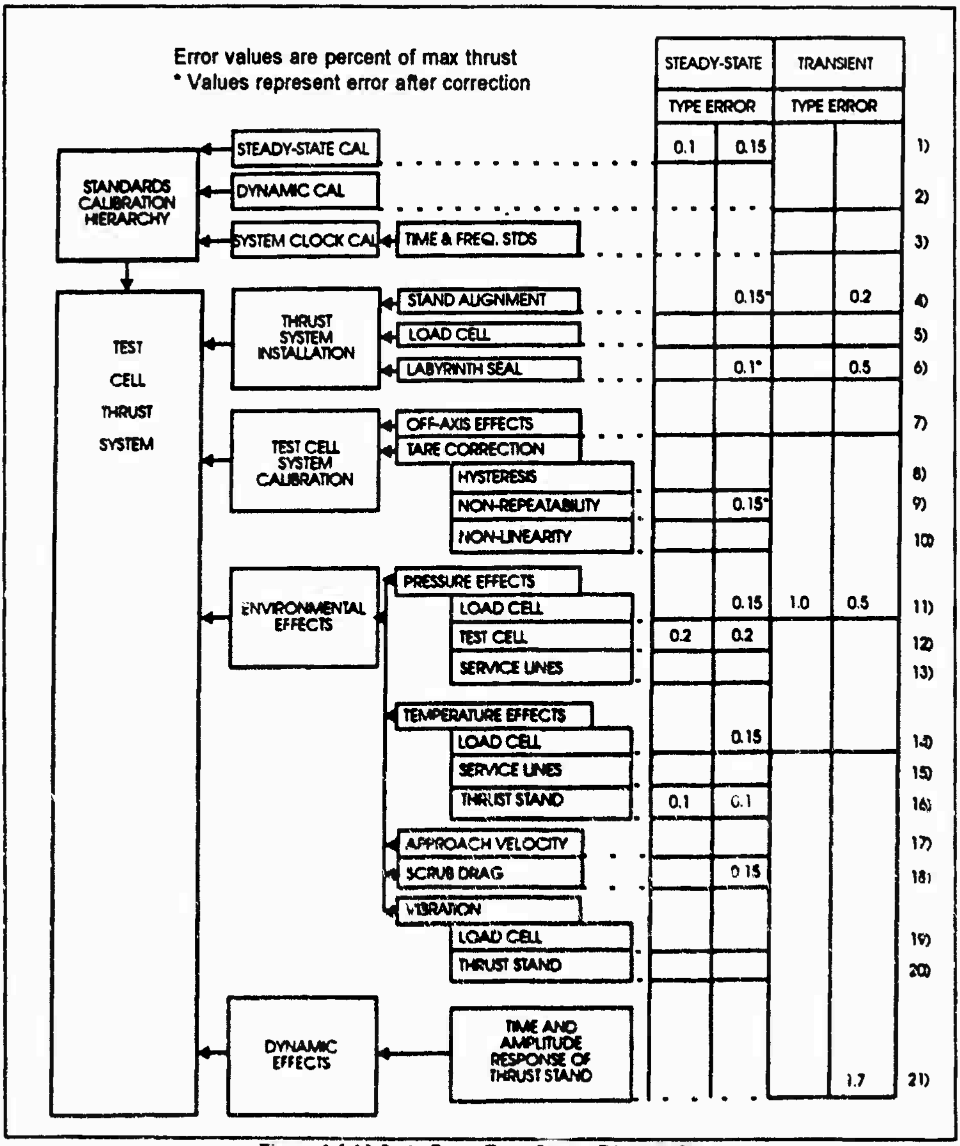


Figure 4.6-10 Scale Force Error Source Diagram for Example Case at Sea Level Static Test Conditions

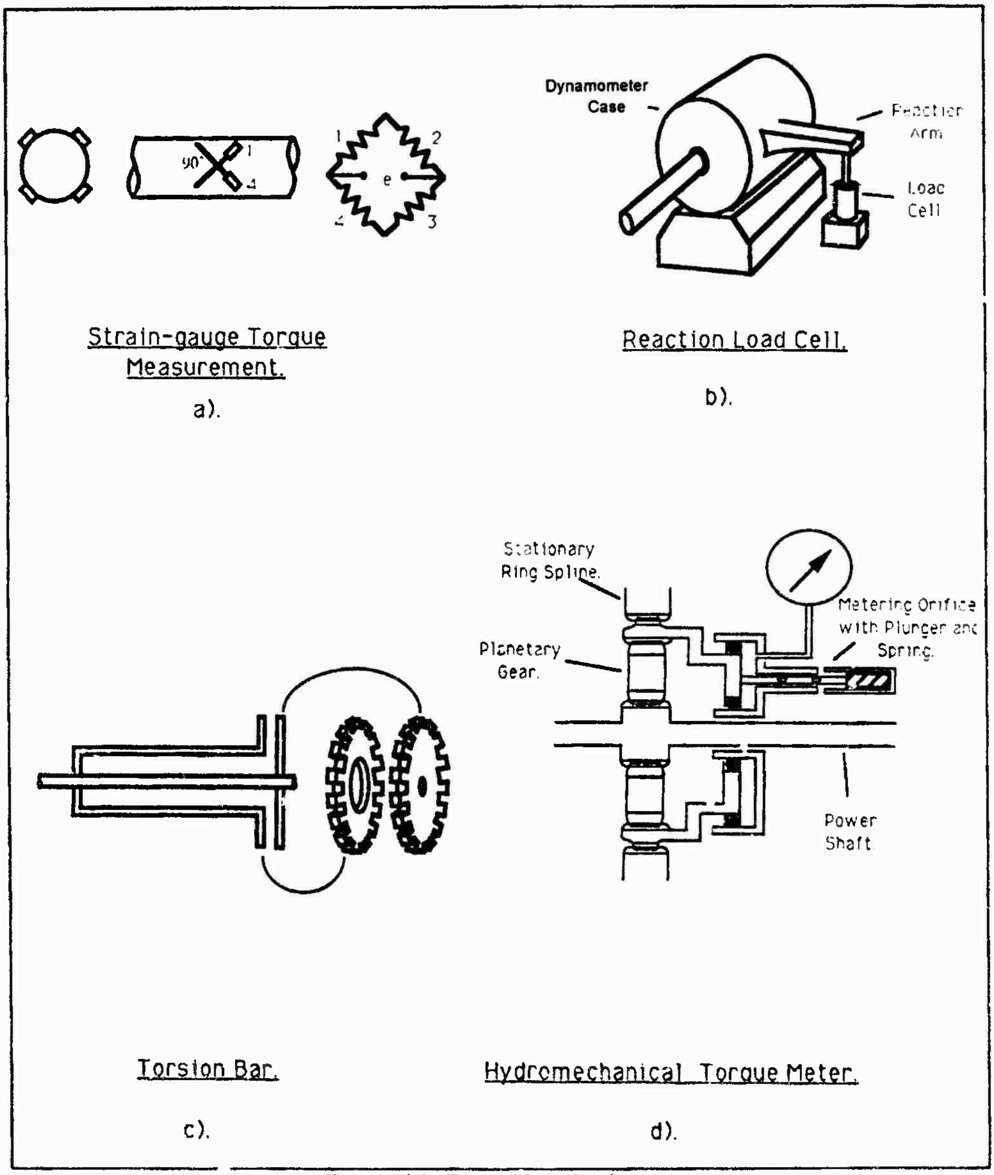


Figure 4.6-11 Torque Measuring Systems

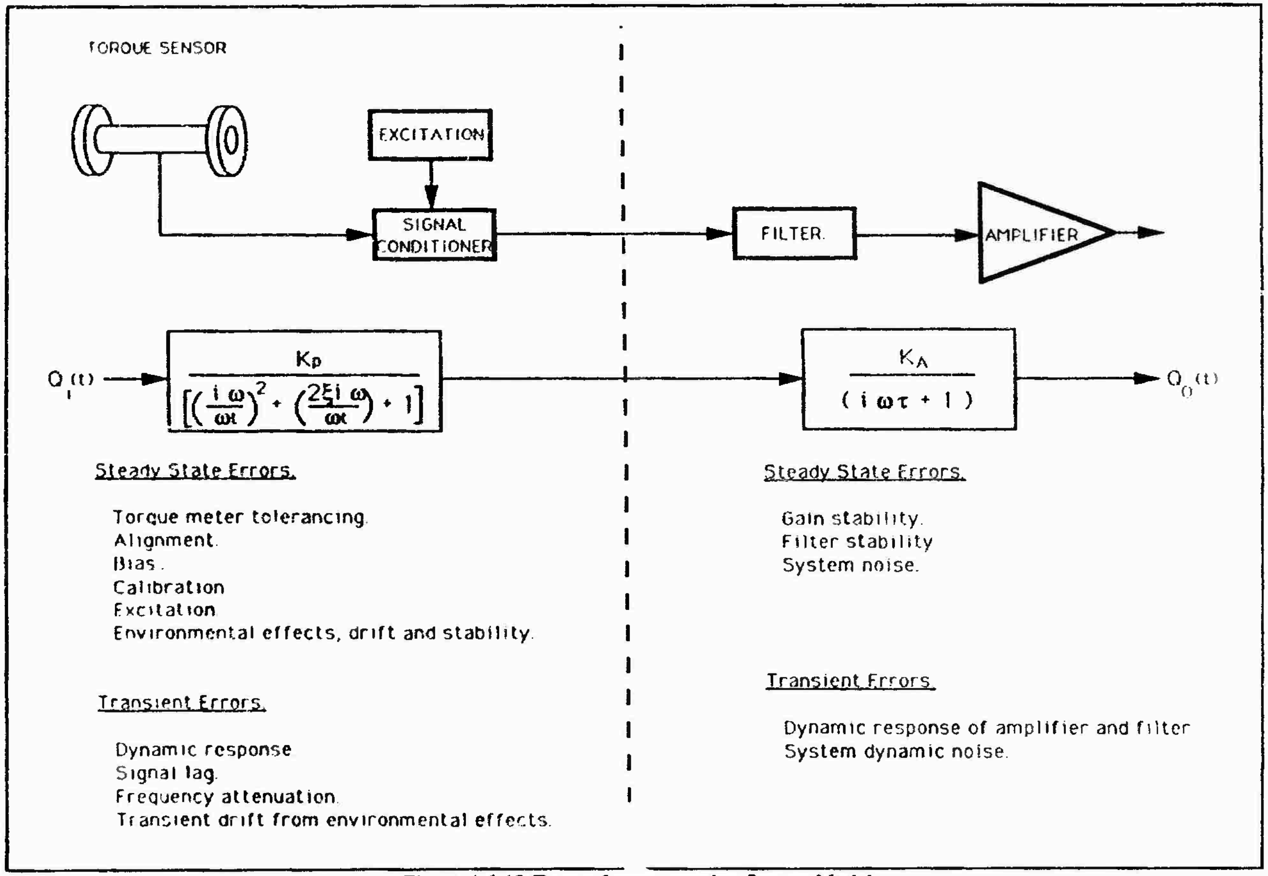


Figure 4.6-12 Torque Instrumentation System Model

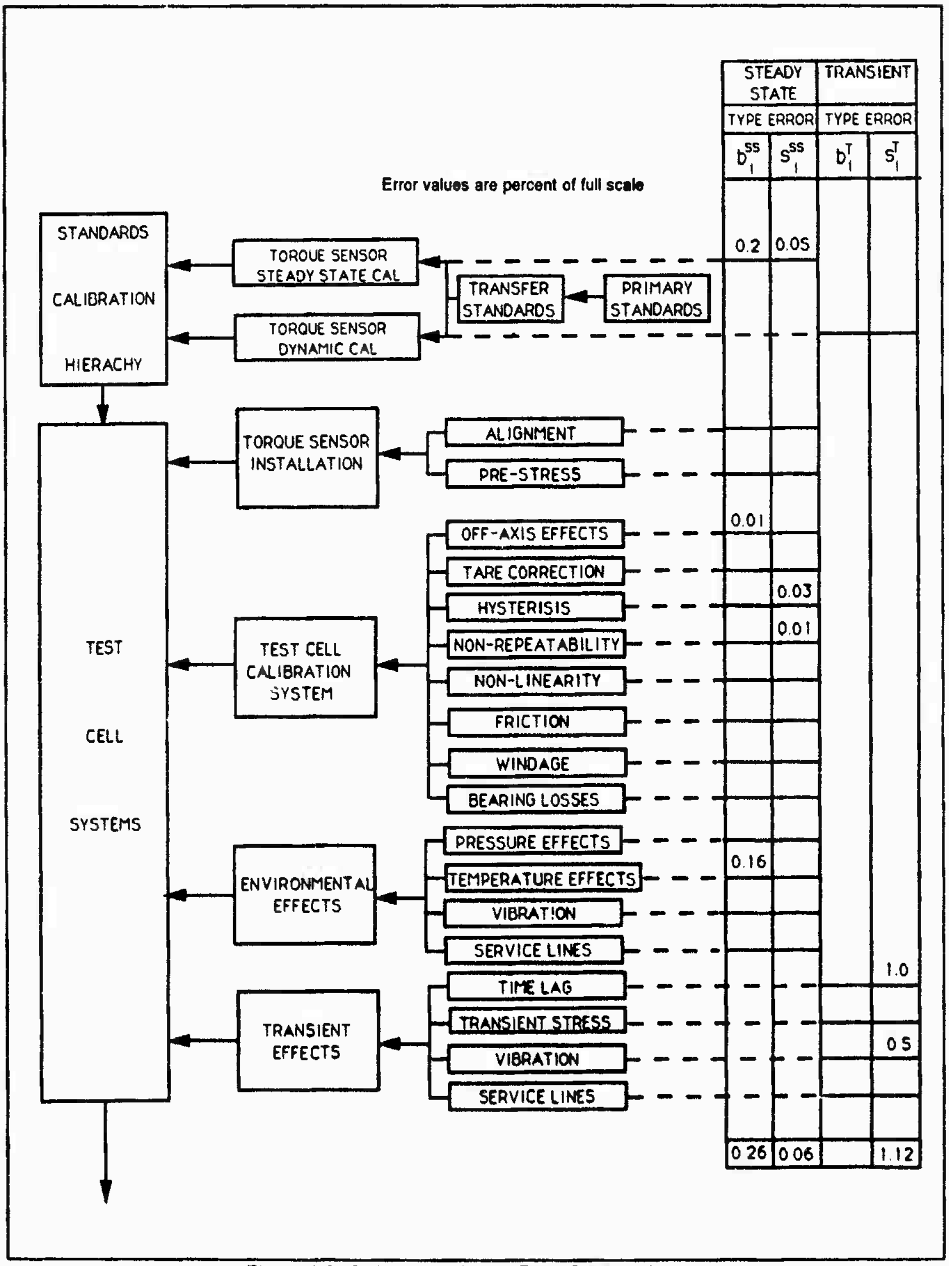


Figure 4.6-13 Transient Torque Error Source Diagram

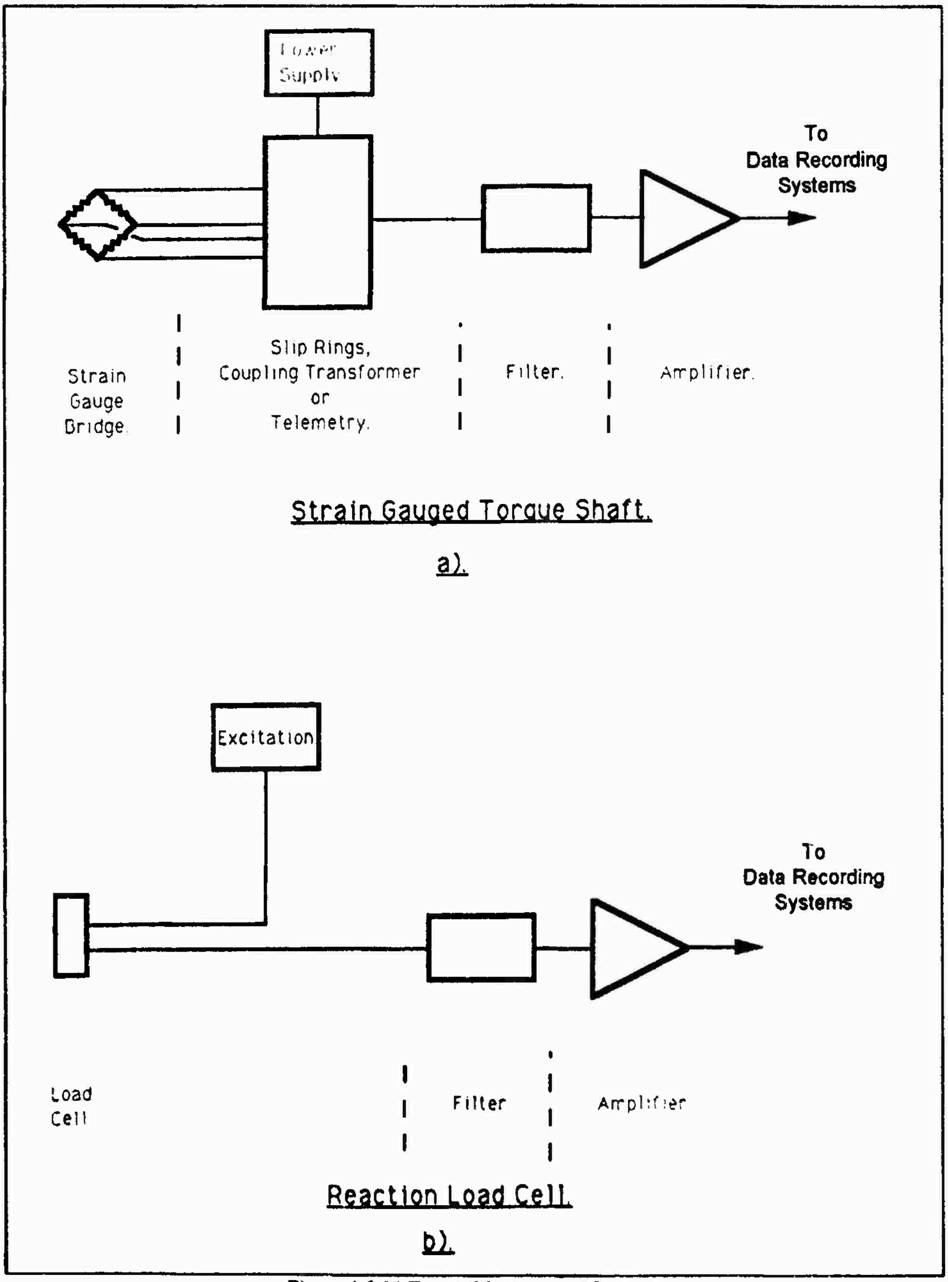


Figure 4.6-14 Torque Measurement Systems

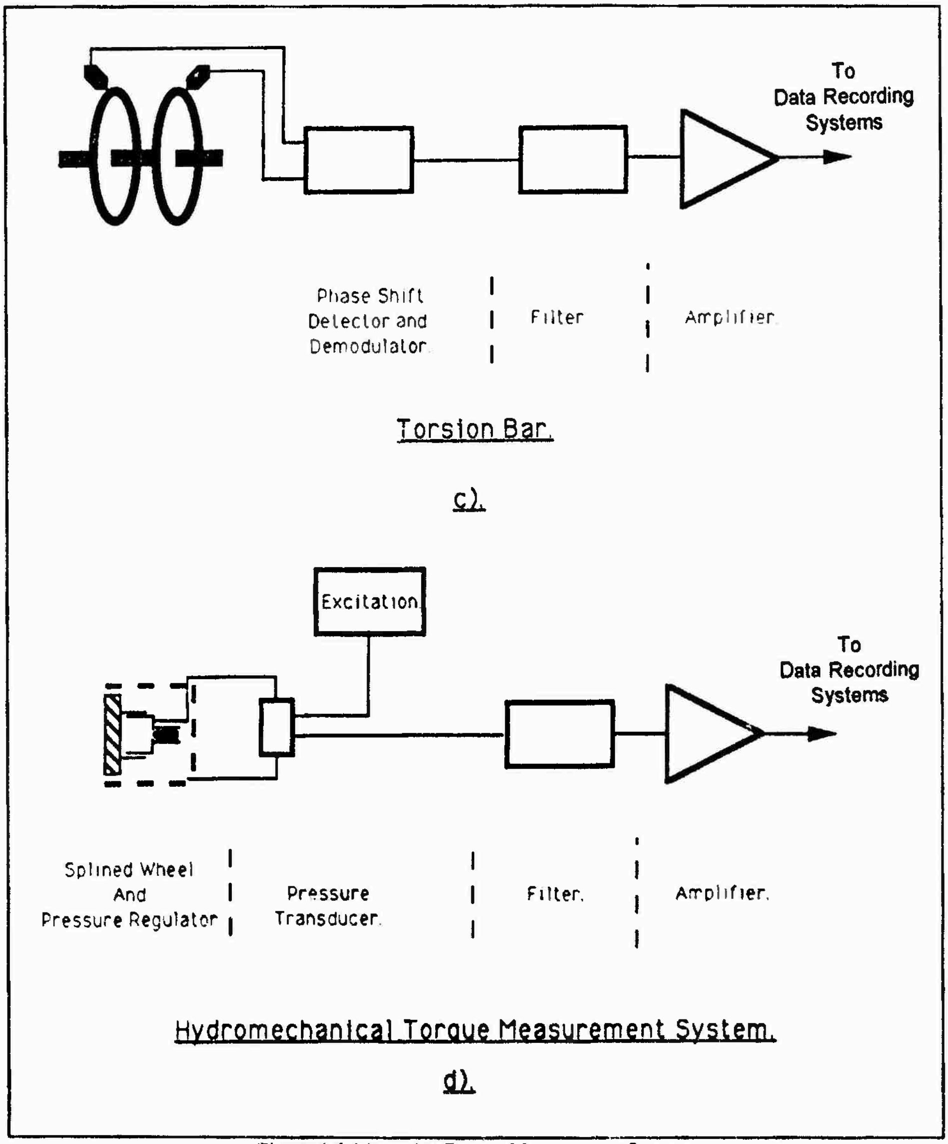


Figure 4.6-14(cont'd) Torque Measurement Systems

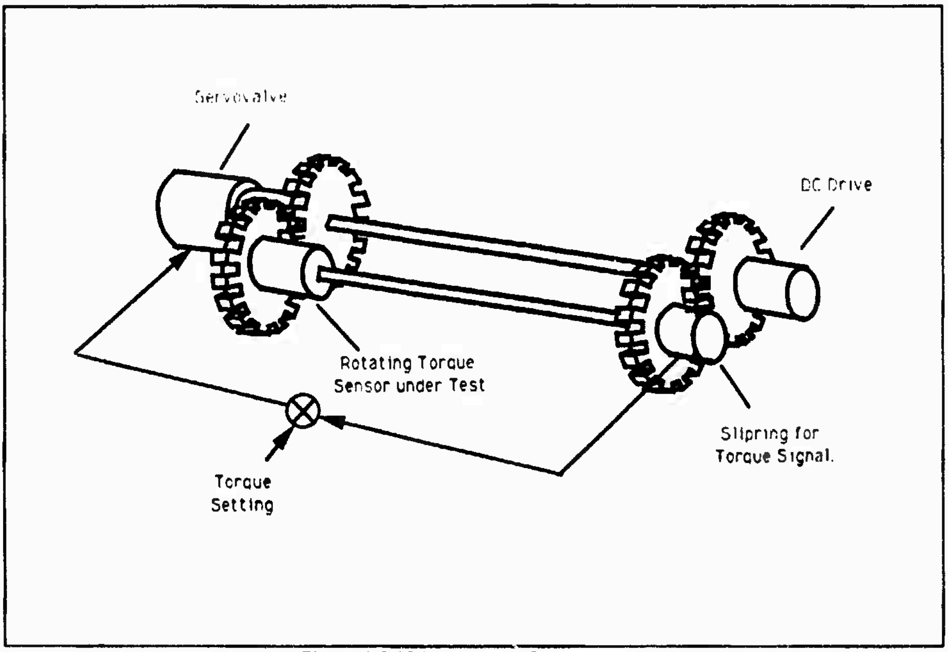


Figure 4.6-15 Four-square Dynamometer

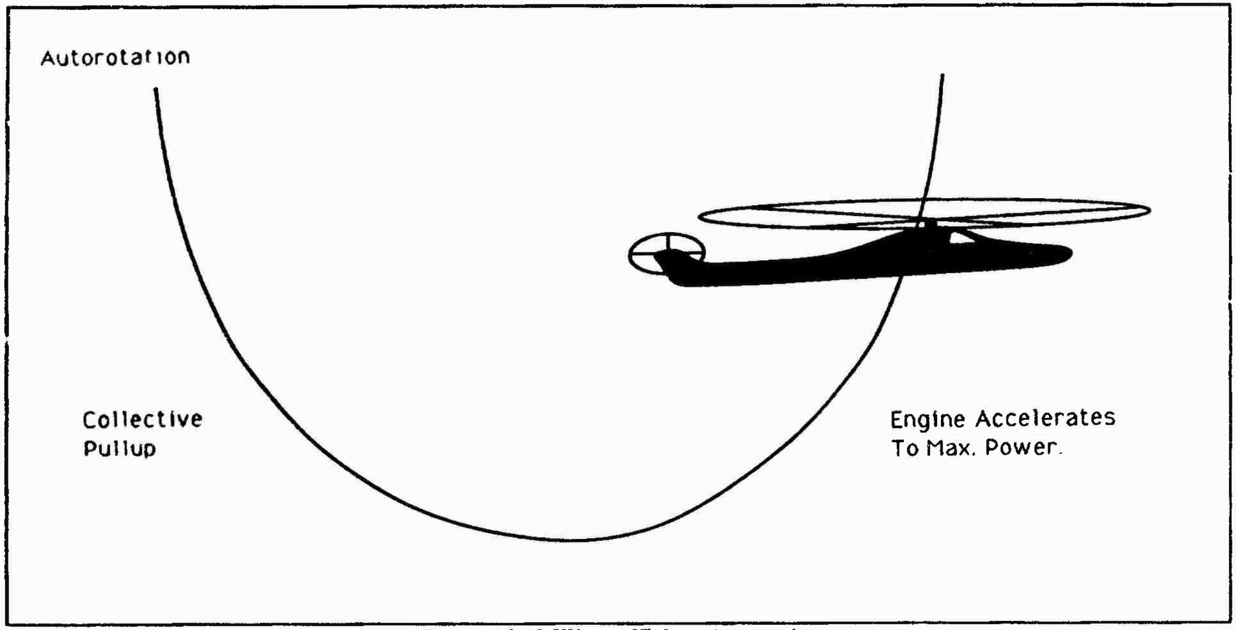


Figure 4.6-16 "Wave-off" from Autorotation

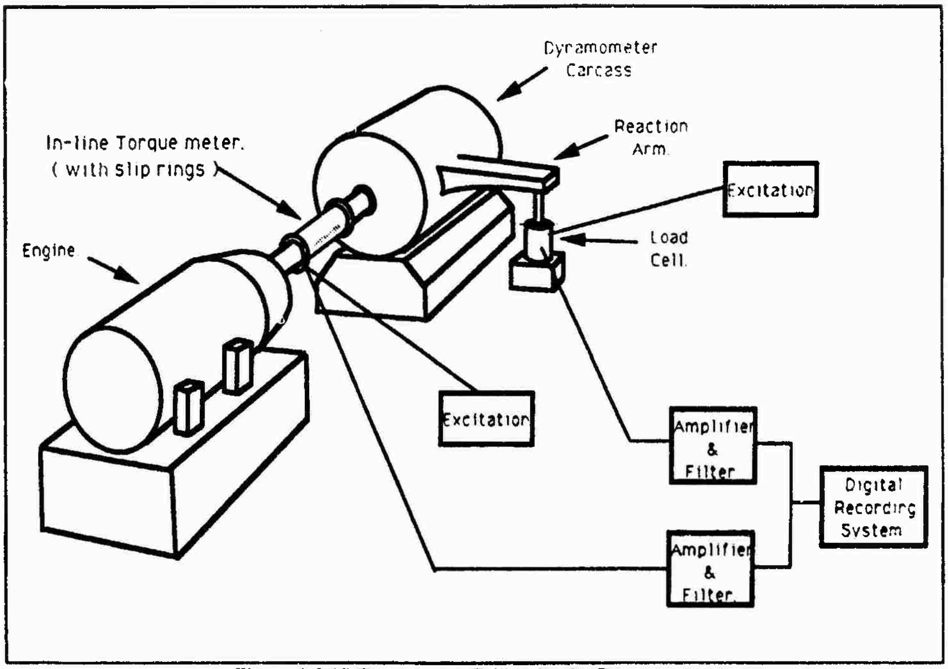


Figure 4.6-17 Torquemeter Calibration by Dynamometer

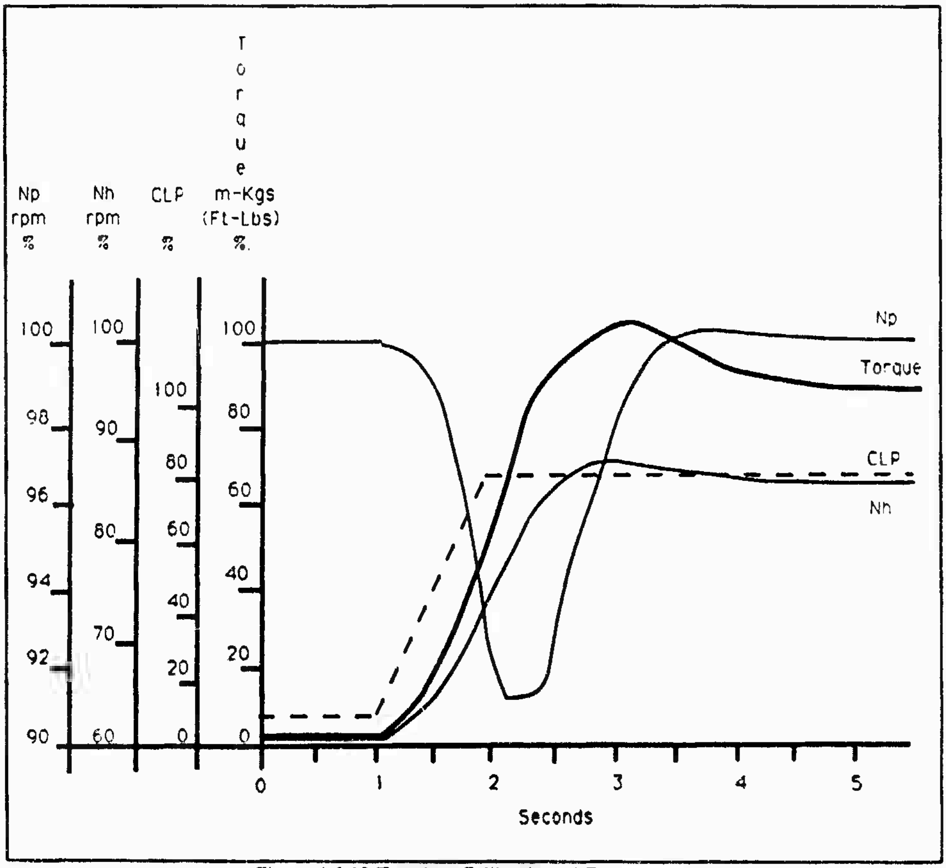


Figure 4.6-18 Transient Calibration of Torquemeter

4.7 CONTROL SYSTEM PARAMETERS[1]

4.7.1 Introduction

The control system monitors engine operation and modulates the controlled engine variables to satisfy demand thrust and to maintain critical parameters within scheduled limits. Most engine transients are either a direct result of control actions or are strongly affected by the response of the control to changing external or engine operating conditions. Any control system consists of a number of sensors which measure specific parameters as inputs to the control, a computing section which embodies the control logic and a number of actuators which control key engine variables. Collectively, the inputs, intermediate variables and the outputs represent a suite of control parameters. Control system parameters can be very important to understanding transient engine behavior.

Occasionally, the performance of the control system itself is of primary interest during the transient tests. It is noted, however, that most gas turbine control systems are strongly partitioned with respect to function. For example, the acceleration schedule is only invoked during large scale accelerations. Similarly, temperature limits may be invoked only during very rapid, high power transients under specific flight conditions. Thus, planning a ground based test to obtain maximum information about the control system requires considerable knowledge of the control strategy used on the engine under test.

Control system parameters are acquired using many of the measurement techniques discussed in other sections of this report, i.e. pressure, temperature, flow, and geometry. As such, the specifics of the various types of measurements will not be repeated here. This section is intended to identify some of the more common control parameters and to assist the user in determining when control parameters are appropriate for transient engine measurement.

4.7.1.1 *Engine Control Systems*

Modern gas turbine engines utilize both hydromechanical and electrical control components. Some control systems are made up entirely of hydromechanical components, while others include analogue or digital electrical units with functions ranging from supervisory power management to full authority. Control system inputs include sensed engine operating parameters, pilot/aircraft control inputs, ambient and flight conditions, and operational status of engine and aircraft systems. Table 4.7-1 lists some of the inputs which are typically received by the engine control. It is evident that many parameters which may be of interest during transient engine testing are control inputs.

The control processes the received inputs and generates output signals which are demand values for the controlled variables. The algorithms relating outputs and inputs are programmed into the control hardware or software. The functionality of controlled parameters often involve intermediate parameters which are generated within the control by modifying or combining inputs in a prescribed manner. These intermediate values can represent corrected or normalized parameters, ratios, differences, or averages of input parameters, or approximations of values which are not sensed directly. Parameters generated within the control are often of interest to the tester since they represent values which are significant to operation of the engine. Typical parameters generated within the control are included in Table 4.7-1.

Examples of controlled variables are also given in Table 4.7-1. The controlled parameters are scheduled or modulated within scheduled limits to drive other sensed or derived parameters to desired values. Control outputs are important to the tester when evaluating system responses or cause and effect relationships during transient engine operation.

4.7.1.2 *Control Data*

If the data are available, the use of the control system as a source of information is frequently quite valuable. Specifically, the large-scale transient schedules of fuel and/or area provide very considerable insight into the performance of the engine. Moreover, the availability of the input measurements from reliable sensors with very good frequency response provide data about the engine itself. It can permit comparison with other

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[1] Tables and Figures for Section 4.7 begin on page 4-255

derived parameters or can be used as a direct means of assessing the engine performance in transient operation. Perhaps of greatest importance, the obtaining of input and output parameters of the control system permits open loop analysis of either the engine or the control or both.

4.7.2 Basic Control Design Concepts

Essentially, gas turbine control systems can be categorized according to the medium of computation.

4.7.2.1 *H· Jromechanical Control Systems*

˜:aditional hydromechanical control systems utilize mechanical analogues of the governing control algorithms or equations. The basic design is such that algebraic relationships are represented by force balances in some convenient combinations of levers, bellows, etc. The computing medium is a force. Transduction of such important ›uts as speed is achieved through simple flyweights whereas pressures require no transduction other than to be applied to a known area to generate a force. Computation of nonlinear parameters is usually achieved by a combination of shaped cams and/or valves. Regardless of the specifics of the control law, each parameter is represented by a force which is imposed on a mechanism, and steady state is achieved when a balance is reached in these forces. A control system block diagram with representative hydromechanical components is shown in Figure 4.7-1.

In terms of measurement, it is clear that use of hydromechanical control systems will require the application of external sensors/transducers to obtain relevant information. There are two major limitations to the successful use of this type of control as a test element.

1) Only certain parameters will be available to which external instrumentation can be applied.
2) The dynamics of the control system must not be altered.

The first limitation is frequently less severe than appears at first glance. Many external ports are available from which to obtain internal control pressures. These can be used in post-test analysis to infer much of the operation of the control.

The second limitation is a serious issue. For the most part, hydromechanical controls are stabilized by various volumes within the system. Introduction of sensors must be very close-coupled and must be capable of very rapid response. Long pressure tubes, for example, are out of the question.

The addition of electronic components to a hydromechanical control system creates a hybrid system with enhanced functionality. The control system in Figure 4.7-1 shows the integration of hydromechanical components with an analogue electrical unit. Such systems usually divide functions between electronic and mechanical components with necessarily more complex interfaces. In this situation, part of the computing medium is voltage and part is force.

Measurements obtained from hybrid control systems must recognize the additional need for external measurements. Once again the primary concern is the application of sensors in a manner which does not affect the operation of the control system.

In the case of the electronic components, they frequently have external test points which enable the measurement of many key internal voltages. Use of these test points implies that the system designers have disclosed (or are willing to disclose) the specifics of the unit design. If so, impedances can be matched properly and the data can be scaled in a meaningful manner.

4.7.2.2 *Digital Electronic Control Systems*

The use of digital electronics in engine fuel control design has created a completely new type of control system where the computing medium is the binary number system. This feature, together with the introduction of a central processor, has permitted the abandonment of the traditional physical analogue representation of control laws. In other words, any linear or nonlinear function can be represented in abstract mathematical form creating great potential for flexibility since non-linear schedules and logic can be represented in software.

The introduction of the digital processor has brought with it an entirely new concept in control. The serial nature of the processor implies that it will have to operate on a time sequence of discrete "snapshots" parameters which are, of course, analogue in nature. This discretization has introduced new control problems associated with the very concept of time sharing of a single processor. Signal aliasing, round-off errors in computation, and the presence of resonant frequencies associated solely with the discrete time representation of continuous data have all represented design challenges to be resolved.

Currently, full authority digital electronic control (FADEC) systems include recognizable components of typical control architectures (Figure 4.7-2). Major components include A/D converters, D/A converters, serial I/O, memory chips and central processors, some of which have sophisticated partitioning of functions to improve speed of execution.

The most important feature of the FADEC architecture is the concept of a data bus. This component permits the sharing of data among components of the control systems and with external systems. It is the concept of the data bus which makes the FADEC an attractive means of obtaining much test information from an engine so equipped.

There are essentially two major bus standards in the industry at the time of writing. The military standard is MIL-STD-1553, whereas the civil standard is ARINC 429.

Obtaining any information from a FADEC requires the test designer to be familiar with these standards and to understand their utilization in the specific control system in question. Both standards represent data highways to other components of a complete avionics suite.

4.7.3 FADEC Systems

4.7.3.1 *MIL-STD-1553*

The MIL-STD-1553 bus is a bi-directional, time sliced multiplexing bus. Its rate of data transfer is 1 MHz.

Access to the bus is through a bus controller from/to a remote terminal point. Thus, from a configuration viewpoint, the FADEC represents a remote terminal point which can place data on the bus or obtain data from other systems within the avionics suite. It must, however, operate with the bus in accordance with the dictates of the bus controller.

All traffic on the bus is controlled by the bus controller. This is achieved through a command word which is a binary bit stream containing the remote terminal (e.g. the FADEC) address, a mode word or word count and sub-address. If the command contains a "mode" word, this signals the remote unit to execute any number of standard functions such as reset, self-test and transmit status. These commands provide the bus controller with vital information on the status of the device at the remote location (i.e. the FADEC).

If the command contains a "transmit data" instruction, the device at the remote terminal receives this information and, if so programmed, will execute a software function which places specific data on the bus. The "status" word contains a remote terminal address and status bit and always precedes data sent by the device at the remote location.

A data word is 16 bits with content and format open to the designers, as is the total content of a message.

In addition to the features described above the bus will permit the broadcast of messages to all devices and provides for a bus monitor which can listen to all data traffic on the bus.

4.7.3.2 *ARINC 429*

The Aeronautical Radio Inc. Specification 429 Digital Information Transfer System Mark 33, 429 is commonly referred to as ARINC 429. It is the basis for digital buses in modern civil aircraft just as MIL-STD-1553 is the basis for digital buses in modern military aircraft.

Requirements for low weight and maximum flexibility drove 1553 to operate at 1 MHz on a bi-directional bus while certification requirements drove 429 to operate at 12 - 14.5 kHz, or 100 kHz on a unidirectional bus. The unidirectional bus is one on which there is only one transmitter, but multiple receivers (up to 20). If a message from one of the receivers is required by the transmitter, a separate bus must be set up with the roles of transmitter and receiver reversed. While this may seem cumbersome, it can be cheaper in certain circumstances and is readily certified. Of greatest significance is the fact that there is no bus controller, remote terminal or bus monitor concepts as there is with the 1553 standard.

Communication on 429 buses uses a 32 bit word format. A low speed bus is used for general purpose, low criticality applications, whereas a high speed bus is used for large quantities of data or where time is critical to flight safety.

Messages on the 429 bus adhere to specifications of the standard. Within the 32 bits, there are 5 recognizable formats possible: 2 for numerical data, 2 for alphanumerical data and 1 for discrete data. All words begin with a label (9 bits). Other bits are used for status and identification. Data can be encoded in either binary or BCD format. Complete messages contain initial, intermediate and final words. In general, initial and final words contain commands, status, handshaking etc., while the intermediate words contain the application specific data. Message content and format is device specific in the ARINC 429 standard.

4.7.3.3 *FADEC Testing*

It is obvious from the foregoing description that the design and implementation of a FADEC must adhere to one or other of the communication standards. To do so requires the following minimum features:

- The FADEC must have been designed with the intention of providing some communication with other devices.
- A controller function within the FADEC must exist for communicating on the external bus. In the case of ARINC 429 this may be restricted to receive or transmit only. If this is the case, the FADEC will likely have very inflexible external communication features.
- Software must exist within the FADEC to enable the device to accept commands and to transmit data to the outside world.

To permit the testing of the FADEC with or without the engine in the loop requires the test personnel to set up an external bus system to which the FADEC can be attached. In addition, the test system will require a programmable device capable of issuing commands, receiving messages, and decoding messages to obtain the control parameters in engineering units. Such an undertaking requires knowledge of the control system design, its protocol for bus communication and the specifics of how messages are to be sent and received. Unless the original designer intended that the FADEC allow such communication, the use of the FADEC as an engine test article is next to impossible. Happily, however, most designers have provided this capability and the FADEC can provide a very powerful "data acquisition" capability for engine testing.

4.7.4 Sources of Control Data

4.7.4.1 *Control Sensors*

Control system sensors represent instrumentation which are permanently installed in the engine. The control manages the engine based on information received from the sensor set (control inputs) including many of the most important and often requested engine measurements. Even more to the point, the control operates the engine in "real time" which requires that most of the sensors be designed for transient capability consistent with normal operation of the engine. The ease with which transient measurements can be obtained from control sensors varies greatly with the type of system and the intended use of the data. A good example is compressor discharge pressure (CDP). Most engine controls have CDP as a sensed input with the typical sensor being a static-pressure tap in the combustor. The pressure signal is transmitted through a pneumatic tube to the outside of the engine and directly to a hydromechanical control unit or to a transducer which converts the pressure to an electrical signal for an electrical control unit. A transducer must be applied to the control pressure sensor tube (using the guidelines presented in Section 4.2) in order to record the CDP signal. With an electrical control, it may also be possible to record the output from the transducer which is part of the control system. In this case the signal being recorded is the input as received by the control. The tester may wish to do both in order to evaluate the characteristics of the control transducer itself.

With a hydromechanical control system it is more difficult to measure the actual CDP signal as it is used by the control. The pressure signal enters the control where it is converted into hydromechanical form for use within the control unit. Application of a transducer within the control unit would be necessary if the tester wished to measure the CDP signal in its hydromechanical form.

There are many cases where control sensors are useful for obtaining transient measurements. Table 4.7-2 lists some typical control sensors and the types of signals they generate. Applied instrumentation will be required to provide electrical signals for recording or display from hydromechanical control sensors. Care must be taken to assure that applied instrumentation does not interfere with normal operation (signal amplitude, time response, or phase) of the control inputs.

Analogue electrical control units often include a special connector for monitoring control parameters. Digital electronic control data can usually be accessed through an interfacing data bus. Considerations when using digital control data are discussed in Section 4.7.4.

4.7.4.2 *Control Outputs and Internal Parameters*

Control inputs (see Table 4.7-1) are received from sources other than just the engine sensors. Inputs are also received from aircraft sensors and control systems and from the flight crew. Calculated parameters are generated within the control from the inputs received using logic contained in the control hardware/software. Outputs are then generated to drive controlled engine variables and to provide data to aircraft systems or cockpit. These internally generated parameters and outputs could also be of interest to the tester when evaluating transient operation of the engine and control system.

Control outputs (controlled variable demand values) are sometimes recorded as approximations of controlled variable positions. A more appropriate use of these data is for comparison with the actual values obtained from applied instrumentation to evaluate control system response and tracking characteristics.

Parameters generated within the control usually include calculated values which are key indicators of engine operating conditions. Corrected rotor speeds, fuel flow/CDP, and engine pressure ratios are primary control variables and can be of great significance to the tester. Internally generated control parameters are relatively difficult to obtain from hydromechanical components requiring special applied instrumentation. As a result, this is done only when necessary to isolate a problem within the control. Electrical control components have made the data much easier to obtain. Control parameters are often recorded in place of applied instrumentation and in many test situations have become the primary source of engine data. The tester must be aware of the response characteristics and limitations of the control system to assure that the data are not misinterpreted and that his needs can be met.

4.7.4.3 *Factors to Consider*

Some items to consider are listed below to alert the tester to the types of things which should be checked prior to making a decision to record control data as an alternative to applied instrumentation.

- o Cost and reliability are very high priorities in the design of control sensors and transducers. The ruggedness required may result in less than optimum time response and accuracy characteristics. This is especially true for temperature sensors.
- o Engine/control system configuration and space constraints may result in limited frequency response of pressure data when long pneumatic tubing lengths or small diameters are installed.
- o Control sensors are designed to provide predictable and correlatable measurements but not necessarily station average values of temperature and pressure.
- o Most control sensors must operate throughout the flight envelope, requiring measurement ranges which meet envelope extremes but are far from optimum at some test conditions. On the other hand, some sensors function only over a portion of the engine operating range. An example is the turbine blade pyrometer signal, which is cut off below a threshold temperature level allowing the sensor to be optimized at high temperature conditions. As a result, no data are available at lower temperatures.
- o The tester should understand exactly how calculated parameters are generated within the control. Computations may be approximated for ease of implementation in hydromechanical or analogue electrical units. Digital controls use tables or possibly simplified equations. Be aware of the source of all control inputs. Sometimes control outputs (demanded values) are used rather than sensed feedback signals from controlled variables to reduce noise in digital systems. Logic may be used to compensate for time lag in input parameters (especially temperatures). Also, the source of a control input may change with time. An example is compressor inlet temperature which is sensed during steady-state operation but calculated during transients.
- o When multiple or redundant inputs are available to the control, the selection logic should be understood. Multiple values may be averaged or the high/low value selected. Logic used to discriminate between valid and invalid input should also be reviewed. Rate and range checks, maximum allowable tolerance between redundant inputs, and "voting" by internally generated (model) values may be used. Parameter substitution schemes and failure modes should be reviewed, and recorded data should include the status of each parameter so that the method of calculation is always known.
- o With digital controls the time relationships of data at the interface bus can be confusing. Update rates of individual parameters may not all be the same. A detailed flowchart of how the data are sampled and how/when values at the interface bus are updated is required.

4.7.5 **Advantages and Disadvantages**

Many of the advantages and disadvantages of the various control parameters have been covered in the preceding paragraphs. Control parameters represent a source of transient data which may often be acquired without the need for supplementary instrumentation or probes within the engine. However, supplementary instrumentation is required to obtain data from hydromechanical sensors and control components. Recording of control parameters during transient testing allows the performance of the control system to be evaluated; schedules, limits, and logic can be developed and problems isolated. Additional transient engine instrumentation will be required to obtain independent data for comparison with control sensors if assessment of control input characteristics is a test objective.

Control systems are designed with response characteristics suitable for normal engine operation. In some cases however, the control sensors or sampling rates of digital controls may not meet the user's frequency response requirements or the accuracy of the system may not be sufficient for the test objectives.

Control system characteristics should be documented in specifications and verified by component and engine testing. Specifications and component acceptance test results should be reviewed relative to the data requirements of the user. Caution should be exercised when the user's requirements are beyond specification values or outside of the experience range where control parameters have been verified against independent engine measurements.

If an operational problem involving control system response is being investigated, it will not be sufficient to record only control parameters. Supplementary transient engine measurements will be required to isolate the problem. For example, the control parameters of core speed, compressor inlet temperature, and variable stator position may be recorded to check how well the variable stators track the nominal schedule during transients. The nominal schedule is a function of speed corrected to compressor inlet temperature and analysis of the recorded control data shows good transient tracking. This proves that the variable stator actuator can follow the position demand generated by the control. An independent measurement of compressor inlet temperature however might show that the control temperature sensor has a large time lag resulting in erroneous input to the control during transient operation. The result is a significant error in stator tracking relative to the desired schedule which could not be identified from control data alone. Control data in conjunction with transient data from applied instrumentation would be required to isolate the problem.

Proper use of control parameters based on a thorough understanding of their characteristics and limitations can frequently meet the user's requirements for transient data. The extent to which control parameters can be used in place of supplementary transient engine instrumentation will depend on the specific requirements of the user, the type of transient tests planned, and the degree to which the control system characteristics are understood and can meet these requirements.

4.7.6 Signal Conditioning

The signal conditioning requirements for recording control parameters will depend on the specific types of measurements as indicated in the preceding Sections. Hydromechanical sensors and components require pressure, geometry, or position measurements covered elsewhere in this report. Signals from electrical control components may require conversion from analogue to digital or digital to analogue. Amplification may also be needed to match signal levels to terminal device ranges. Considerations for sampling, filtering, and recording of electrical signals are covered in Section 4.9.

A primary concern when recording control parameters is to avoid changing the operational characteristics of the control system. Supplementary instrumentation or electrical interfaces must not alter the performance of the control. In the case of electrical interfaces this means that appropriate isolation must be provided. This is necessary both to obtain valid data and to assure safe operation of the engine. The user should review requirements with both Instrumentation and Controls Engineers to determine the proper approach to acquiring the control parameters.

4.7.7 Calibration

Calibration requirements for supplementary instrumentation applied to measure hydromechanical control parameters are as presented in the sections of this report corresponding to the specific types of instrumentation used. The characteristics of control sensors and components themselves should be well documented. System specifications and acceptance test results provide nominal and specific calibration data for control components. In special cases bench testing or in-place calibration procedures can provide additional data for the system.

It is always preferable to correlate the control parameters with data from a more extensive array of instrumentation. Control parameters are often the only common thread between instrumented factory test engines and non-instrumented production engines. It is important therefore that the correlations be established early or whenever appropriate data are available.

Table 4.7-1 Control Parameters

INPUTS	INTERNALLY GENERATED	OUTPUTS
Rotor Speeds	Corrected Rotor Speeds	Control Variable Position Demands
Temperatures	Temperatures	Fuel Metering Valve
Engine Inlet	Averaged	Main
Compressor Inlet	Min/Max Selected	Augmentor
Compressor Discharge	Compensated for Time Lag	Ignition On/Off
LP Turbine Inlet	Pressures	Fan Variable Stators
Turbine Exit	Averaged	Compressor Variable Stators
Pressures	Ratios	Nozzle Area or Flap Position
Engine Inlet	Deltas	Bleed Valves
Fan Discharge	Nozzle Area/Area Ratio	Status Words (Digital)
Bypass Duct Static	Fuel Flow/PS3	Control Mode Selection
Compressor Discharge	Main	Limits
Exhaust Nozzle	Augmentor	Event Counters
Bleed Manifold	Total	Maintenance Flags
Variable Geometry Positions		
Fan Variable Stators		
Compressor Variable Stators		
Exhaust Nozzle		
Bleed Valves		
Fuel Flow		
Main		
Augmentor		
Bypass		
Turbine Blade Pyrometer		
Flame Detector		
Aircraft		
Throttle		
P ambient		
Mach		
Weight on wheels		
Armament Firing		
Bleed Request/Valve Position		
Vector/Reversing		
Angle of Attack or Sideslip		

Table 4.7-2 Control Sensors

PARAMETER	TYPICAL SIGNAL	
	HYDROMECHANICAL	ELECTRICAL
Rotor Speed	Rotational (Shaft)	Frequency
Temperature	Differential Hydraulic Pressure	DC Electrical
Pressure	Pneumatic Pressure	DC Electrical
Variable Geometry	Feedback Cable Position	DC Electrical
Fuel Flow	Metering Valve Position	DC Electrical
Pyrometer	-	DC Electrical
Flame Detector	-	DC Electrical

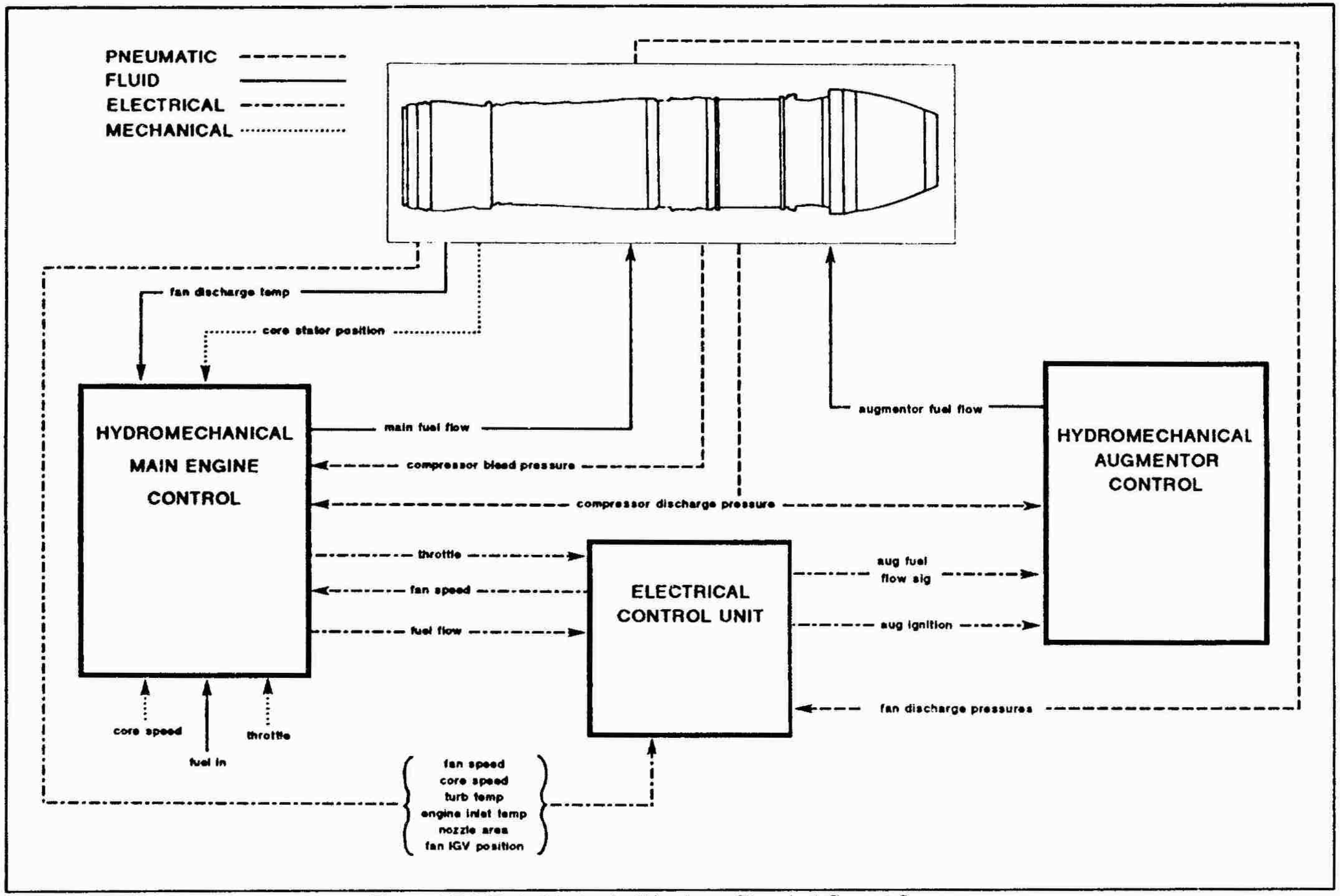

Figure 4.7-1 HydroMechanical/Analogue-Electrical Control System

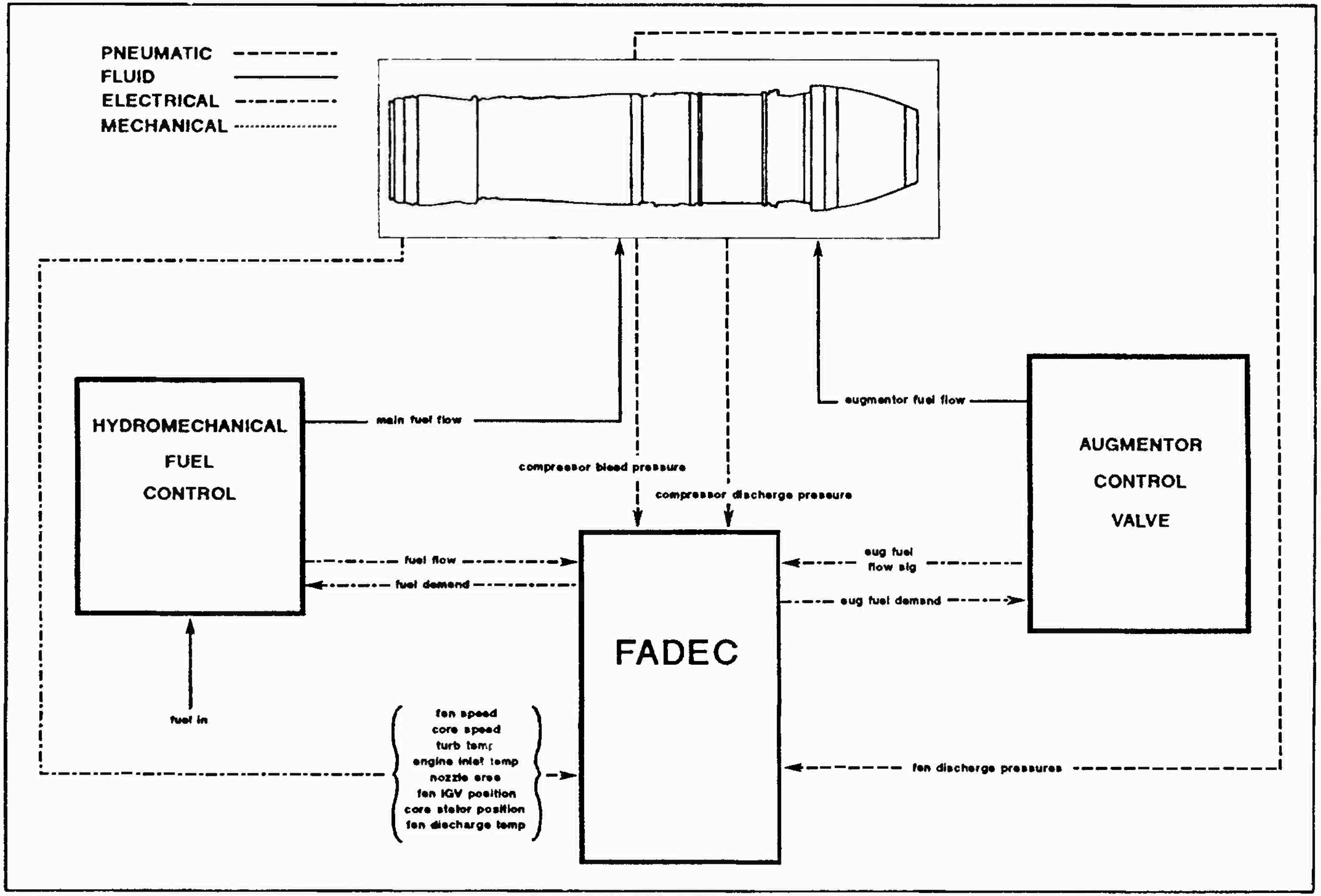

Figure 4.7-2 FADEC System

4.8 MISCELLANEOUS

4.8.1 Flame detection

Flame detection as a means of indicating light-up, flame-out and combustion non-uniformity or instability is often a necessary part of transient testing. For example, the failure of an afterburner to light-up can have serious implications if the final nozzle area is not reset. Thus sensors, sometimes referred to as light-up detectors, are often a feature of production afterburning engines. In practice, these sensors may be designed to detect the direct presence of combustion or some other easily measured secondary parameter, e.g. turbine pressure ratio. Light-up detectors can also be used as a surge indicator by reacting to the presence of flame pulsations at the turbine exit. Information such as this is of value in the development of control and fuel systems.

This section will concentrate on the direct detection of combustion itself but will not consider the accurate measurement of temperature levels or combustion efficiency. For measurement of temperature levels refer to Section 4.3. Further, only those areas in which combustion is designed to take place will be considered, i.e., combustion chambers and afterburners.

As with all transient testing, the response rate will be dependent on the objective of the investigation but in the case of flame detection will normally be less than 1/10 sec.

Sensors can be classified into two main groups: poke-in probes responding to local gas temperature or remote radiation indicators. The poke-in would usually take the form of a thermocouple as described in Section 4.3. Unfortunately, to achieve an adequate response rate the sensor configuration is essentially very delicate and would be unlikely to survive long in the harsh environment of combustion. A poke-in probe more likely to survive is a fibre-optic sensor (References 4.8.1 and 4.8.2) also described in Section 4.3.1.7 of this report. Unfortunately, the present versions of these probes have a response rate ' hich is too slow to meet the needs of the most transient investigations.

The form of radiation detector considered in this second group are those in which the transducer (radiation energy to emf) is mounted external to the combustion zone. Because of this, the transducer can be made both reliable and have a very rapid response rate. For these instruments to act as light-up detectors, they must be focused so that they respond to the radiation resulting from combustion products rather than that from near-by structures. Unfortunately, radiation from the wide range of components which make up combustion products implies a very wide range of radiated wavelengths from the ultra-violet through the visible to the infrared. Which particular groups of radiated wavelengths predominate at any one time will be dependent upon the temperature and composition of the gas upon which the pyrometer is focused (References 4.8.3 and 4.8.4). Also there are a wide range of materials and designs which can be used for the transducer, filters and windows (Reference 4.8.5). It is thus necessary to refer to the makers description to ascertain the wavelengths to which the instrument is most sensitive and to focus on those regions where the instrument response will be most effective. A considerable amount of trial and error to establish the appropriate set up may thus be necessary.

Recent developments in thermal image scanners and data recording methods, including digital and video systems, may provide much more detail of the transient combustion process (References 4.8.6 and 4.8.7).

Perhaps the simplest, and often the most revealing, method of investigating afterburner light-up, combustion stability and uniformity is by observation using a high speed video camera with the recording linked to the common time base and thus to related engine parameters. Such cameras can also be used to indicate surge by displaying the presence of flame pulses at turbine exit or, in some cases, fan inlet.

4.8.2 Accessory Power Extraction

4.8.2.1 *Introduction*

Horsepower is just one of many names given to the more general term "rate of work", which in turn is a force moved over a distance in a given time. Hence:

Horsepower = foot-pounds per minute
= Newton-metres/sec
= etc.

More specifically in the case of rotating machines:

Horsepower = torque x rotational speed.

From the above it can be stated that the provision of a system to extract or apply a horsepower loading to a gas turbine engine can be accomplished by applying the requisite torque at a given rotational speed. The majority of gas turbine engine transient investigations, where development tests are called for, do not include a requirement for a variable time-dependent horsepower extraction test to be performed. The more usual practice is for a horsepower, or shaft power loading to be set at a pre-determined value and then the engine itself to be operated transiently to see how it reacts to supporting the given load. For this more usual case it is relatively easy to set a given shaft power off-take to the pre-determined level via some type of brake or electrical loading machine which has been statically calibrated. However, since this report covers transient behaviour, suggestions will be put forward which would enable the power extraction to be varied over a pre-determined time schedule whilst the engine itself is maintained at a fixed power lever setting. The systems discussed for the extraction of shaft power can be used in both the above cases and therefore the simpler case of fixed loading will not be addressed here.

This section, which describes methods of horsepower extraction, has many common factors with both section 4.6.2 and 4.5 which deal with torque and rotational speed respectively. Reference will be made to the earlier sections to save repetition.

4.8.2.2 *Accessory Power Extraction Systems*

The provision of a transient horsepower extraction system for a gas turbine engine test can be accomplished in several different ways; three methods are outlined below:-

(a) The use of an alternator installed to be driven from the power output shaft or the accessory gearbox output of the engine is one method of extracting power from the engine. The alternator can be loaded by a resistance bank to give the appropriate horsepower rating and controlled to provide the required rate of change or planned variation in loading. The alternator drive system will, however, have some residual loading even when no electrical loading is applied. This residual power loading is generally small and can be determined by calibration. Calibration of the whole drive and loading system can be carried out against a known standard brake system or an inter-connecting shaft can be instrumented to provide a measurement of torque and combined with rotational speed the horsepower can be calculated. Alternative methods of determining torque could use the degree of shaft twist developed in a suitably shaped shaft which enhanced this deflection when loaded.

(b) An alternative electrical method of applying load to the output shafts of the gas turbine could be achieved by an eddy current machine. In the eddy current machine forces are generated by the stator assembly and controlled by the DC power supply fed to the field coil. With this method a wide torque/speed characteristic can be generated for transient horsepower extraction. The power can be calculated from the torque developed by the stator housing. The remarks applying to the calibration and variations in torque measurement mentioned in the alternator method also apply here.

(c) The use of a hydraulic brake using water or other fluid to provide a means of applying a power loading is another alternative method. Here the torque is developed by the interaction of a rotor and stator using the hydraulic fluid as a transfer medium. The torque can be controlled via sluice gates which vary the quantity of fluid between the moving parts. The torque can be measured by the moment developed in the stator casing using a suitable load cell and hence the horsepower can be calculated. With this system there is once again some residual power due to friction within the machine.

Although there are other techniques using mechanical brakes to extract shaft power, these are not ideally suitable for this application. The most elegant method and easiest to install and control is undoubtedly one of the electrical methods described in (a) or (b). These systems can also often be directly coupled to the output shaft avoiding the necessity of installing an additional gearbox with its attendant mechanical efficiency loss.

4.8.2.3 *Advantages and Disadvantages*

For transient horsepower loading applications the alternator loading technique offers the best method since it is relatively easy to configure the control system to provide the requisite resistance load profile with a good response time. The eddy current machine also offers a good response time for transient load application with its DC power control system. The hydraulic dynamometer method on the other hand does not offer as good a response time due to the mechanical features of the control system. All methods suffer to some extent from the sheer bulk of the mechanical parts and so temporal compensation will be needed in all cases. In addition, the transient loading schedule will be limited by the time constant. These features will depend on many factors, most importantly, on the degree of horsepower extraction to be simulated relative to the gas turbine power capability. This in turn, will determine the system mass weight, rotational speed and electronic processing requirements and hence the time constant.

4.8.2.4 *Primary measurements*

As outlined in the introduction the primary measurements for horsepower extraction in a transient simulation are torque, rotational speed and time.

The most direct measurement of torque can be obtained from a torquemeter fitted to the interconnecting shaft between the gas turbine and the loading system. Section 4.6.2 suggests three different methods of torque measurement for this case:

(a) A strain-gauged torque shaft.
(b) A torsion bar torquemeter.
(c) A hydro-mechanical torquemeter.

The strain-gauged torque shaft offers the best response rate since the strain gauges react very quickly to the changes in torsion load. Therefore this system requires virtually no correction for time lag. The response rates for methods (b) and (c) are not so rapid and therefore temporal compensation may be needed. Section 4.6.2 covers this subject in more detail.

The alternative method of measuring torque via the stator reaction and a load cell, although relatively simple, does have two inherent problems. Firstly, the measurement includes bearing friction and windage losses, etc and secondly, the inertia of the system requires significant temporal corrections to be made, particularly in transient operation.

The measurement of rotational speed is relatively straightforward and can be accomplished in a number of ways, many with relatively small time lag characteristics and with a low uncertainty bandwidth. Section 4.5 covers this aspect in detail and should be referred to for specific advice on sensors and signal conditioning.

4.8.2.5 *Calibration procedures*

Calibration of the torque measurement in the transient rotational mode is extremely difficult but may be achieved against the characteristics of a brake and reaction load cell system. Static calibration is somewhat easier, particularly in the case of a torque shaft. Statically the shaft can be loaded with weights at a known position on a calibration load arm and the strain-gauge bridge calibrated. The same principle can be applied in the rotating mode through the dynamometer mechanism, but in this case the extraneous forces of friction and pipe stiffnesses must be representative and constitute part of the calibration. Further details are discussed in Section 4.6.2.4.

4.8.2.6 *Flow Offtake or Injection*

As with horsepower extraction via shaft gearing, power offtake taken in the form of airflow bleed is very often required. Should the bleed be applied rapidly, a transient engine response will be induced.

Flows which are required for external services can be dumped overboard but those required for internal cooling, etc., must remain within the engine and measurements taken such that a minimum disturbance is caused to the bleed flow. Some of the simpler methods of flow measurement described in Section 4.4 could be applicable.

Also, the sudden application of flow injection, e.g., water, will influence the engine in a similarly transient manner.

4.8.4 References

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4.9 DATA ACQUISITION AND PROCESSING SYSTEMS[1]

4.9.1 Introduction

Data acquisition is of major importance in the measurement and understanding of the Transient Performance of Aircraft Engines and Components. If it is not performed satisfactorily, then subsequent analysis will be severely restricted and conclusions erroneous. This section discusses the background to the subject of data acquisition and draws attention to those areas where particular caution should be exercised.

It is extremely important to understand the limitations of measurement and data capture since the validity of the signals which will be processed is dependent on these factors. Too often physical processes are quickly measured and acquired with the mistaken belief that the analysis will compensate for measurement errors. Previous Sections (4.1 to 4.8) have gone through the instrumentation techniques in detail and these must be carried out with sufficient accuracy to meet the objectives of the test proposal. Uncertainty analysis methods have been described in Section 3 for these instrumentation procedures. It should be noted that data acquisition is an additional source of error, though, in many cases, this contribution is small.

In general, transducers can be described as instruments which translate physical quantities into an electrical output signal; other devices convert the electrical signal into digital numbers for subsequent processing. Figure 4.9-1 (also Figure 4.1-1) shows a typical situation where a transducer measures some quantity of interest in the environment and the signal is played into the acquisition system. Data storage from the experiment can take two forms, analogue or digital. In the analogue form this would normally be recorded as a frequency modulated (FM) signal stored on magnetic tape. This could subsequently be replayed into the processing system. In the digital system the analogue signal would be immediately converted into a digital representation by the analogue to digital converter, and then stored in this form. An intermediate form of digital storage is the Pulse Code system where the analogue signal is represented and stored in a pulse coded format (Reference 4.9.1) (see also Section 4.9.3.4). Pulse coded systems are needed to provide efficient and undistorted transmission of data. Pulse coded digital systems are desirable for transmission of data over long distances or for storage of accurate information on magnetic tape. With all digital systems it is particularly important to use a sampling rate which is adequate to capture the signal with acceptable uncertainty.

The type of sensor, transducer, and the installation used is dependent on several factors including the physical quantity to be measured and the environmental conditions under which the measurements are to be made. This subject has already been adequately covered in Sections 4.2 to 4.8 of this document. However, it should be noted that the transducer used must be able to measure the required parameter accurately and, in particular, be able to encompass the frequency range over which subsequent analysis is required.

The analogue voltages from the transducers should, in general, be amplified using signal conditioning equipment (see Sections 4.1 to 4.8) so that they are at a suitable level for digitisation and, if required, recording to an analogue magnetic tape. This section assumes that the signals are at such levels. These analogue voltages are then accepted and stored by the data acquisition system. The arrangement of Figure 4.9-1 shows an antialiasing filter followed by a parallel sample-and-hold element, multiplexer, analogue to digital converter, recorder, processor, and display. The data in this system are also stored in analogue form on magnetic tape. The antialiasing filter is introduced to guard against signal distortion and is briefly discussed in Section 4.9.4. The parallel sample-and-hold system shown in Figure 4.9-1 is discussed in Section 4.9.3.2 where the the alternative sequential sampling system and the related phase correction methods are also discussed. The conversion of the analogue signal to digital form, and its storage, is discussed in Section 4.9.3.1. Calibration factors for the sensor, transducer or total measurement system response can be applied during the data reduction process so that the uncertainty in the output (in engineering units) is minimised.

It is recommended that, wherever possible, on-line indicators (e.g. trace recorders) be provided so that testing may be aborted if the response of the system

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[1] Figures for Section 4.9 begin on page 4-271

appears faulty or inadequate, and also to detect, if possible, impending unsteady events.

Finally, the overall performance of the data acquisition system must be reviewed and the elemental error characteristics be identified with respect to both hardware and software. Included in this assessment should be software error sources related to the interpolation procedures for the instrumentation calibration data supplied, the influence of the test procedure adopted, etc. An example of some of the error sources likely to be present is illustrated in Section 4.9.7.

4.9.2 Time and Sampling Rate

The recording of time is an important requirement in transient or dynamic gas turbine engine tests in order to provide a reference base against which the relationship of detected physical events can be judged. The accuracy of time recording has to be set by a pretest uncertainty analysis based on the sampling rate necessary to capture an anticipated event. This implies that a choice has to be made between recording time with a resolution sufficiently accurate to capture only the features of the engine transient expected, or with a degree of resolution sufficient to detect the instant of a high speed event. Therefore, careful pretest consideration of each situation will always be necessary to establish the sampling rate required to detect and faithfully record the measurand characteristics. In many cases it is desirable to sample at 10 to 20 times the highest frequency of interest associated with the measurand. Surge type tests, where data change relatively quickly, may require that parameters be monitored at rates of up to 500 or 1000 samples per second.

The choice of sampling rate is very important and will depend upon many factors and, in particular, upon the shape of the measurand signal anticipated. Each case must therefore be treated on its merits. An example case for surge pressure ratio measurement is given in Section 5.2.2.5. In that section a Fourier analysis of the anticipated signal is undertaken to derive the highest order harmonic needed to adequately define the measurand. This harmonic is then assumed to be the highest frequency of interest. Alternatively, a guide to the sampling rate necessary could be obtained by examining the response of the filter as described in Sections 4.9.4 and 4.9.7.

The recording of time, either by a quartz based high accuracy clock or by using the clock generator of the data acquisition system, is very accurate and there is no need to be concerned with the errors in such readings. It is usual to record the actual real time at the start of a test (from the computer clock or from an external clock) and record the sampling rate of digitisation. From this any subsequent time can be calculated as:

$$\text{Base Time} + n \cdot \Delta t_s$$

where n = the n^{th} sample, and
Δt_s = the sampling time

Although the accuracy of the sampling time has almost zero error, problems do arise relating to the measurement of time and these are mainly associated with the mechanics of the data acquisition system, the configuration of the instrumentation, the form of signal being recorded and the type of analysis being undertaken.

Although these aspects have already been discussed in earlier sections a short summary is included here as it is a fundamental requirement of all transient testing that all events are related to a single time base.

Transient behaviour can be initiated in several different ways, e.g., steady but rapid throttle shift, geometry change, fuel spike, etc. Precise recording of these input events, which are in effect influenced by the engine control system characteristics, must be properly carried out.

Allowances must be made for system lags. Lags can be defined as the time interval between the input and response. Some examples of lags are:

(a) Delay between throttle movement and fuel pressure rise (say) due to pump or throttle controller characteristics.

(b) Delay due to sensor being remote from point of reaction, e.g. pump flow meter or pressure sensor to spray nozzle.

(c) Delay due to sensor/transducer characteristics, e.g. tubing volume or time constants.

(d) Delays or distortion of recorded signal due to characteristics of acquisition system.

Further, the analysis of an event, rate of change, magnitude, period, etc., will need careful consideration in relation to the chosen or defined time interval. Hence, the time interval over which the event is considered to happen may need careful thought. It may extend over several minutes as a result of changing (stabilization) of thermal gradients.

4.9.3 Analogue to Digital Conversion Methods

Analogue to digital conversion is an important stage of Data Acquisition. If done correctly, errors can be

controlled, but if done without thought, the subsequent analysis may be meaningless.
Major points to be considered are:

- Quantisation error and amplification
- Sampling phase errors
- Calibration

Each of these topics are discussed below.

4.9.3.1 ***Quantisation Error and Amplification***
Analogue to Digital Converters (ADC) usually have 12 or 16-bits capability. For instance, a 12-bit ADC will convert the analogue voltage (say in the range $\pm$10 volts) into 4096 digital sample points which may be in the range either of -2048 to +2047 or 0 to 4096. (A 16-bit ADC will divide the voltage input into 65536 sample points.) Since there are only a finite number of digital sample points, the converted value will not be an exact representation of the voltage data but will be rounded to the nearest digital level. In Figure 4.9-2, point t_1 will be converted to the digital value x_0 but t_2, which lies between x_2 and x_3, will be converted to the nearest level. With certain types of ADC the value may be rounded up or down independent of the position of t_2 between x_2 and x_3. The error in this process is called "quantisation error" or "digital noise error".

An important point to consider is the full scale range of the ADC being used. For example, if the full scale of a transducer signal output of 0 to 10 volts represents a temperature of 0 to 40°C, then the resolution resulting from a 12-bit ADC is 0.01°C. However, if the 0 to 10 volt signal represented 0 to 400°C, then the resolution due to the ADC would be 0.1°C. It is important that as much as possible of the range of the ADC be used. Provided the full range of the ADC is used, this 'quantisation' error is usually small compared with other measurement errors.

It is useful, sometimes, to introduce an offset to the signal to improve the accuracy of conversion. For example, if a signal is always in the range 400 to 500°C but the measuring device creates a signal 0 to 10 volts for 0 to 500°C then it is possible to subtract an offset (e.g. 8 volts) from the signal and amplify the remaining signal (say by 5). Hence, the range of interest is spread over the full 0 to 10 volt range being used by the ADC. The offset and amplification can be taken care of in the calibration process.

In addition, if the acquired signal is low level (i.e. < 1 volt), the signal may be amplified prior to digitisation to enable use of the full range of the ADC. However, the signal will be clipped if it is amplified excessively. Figure 4.9-3 shows that if the analogue voltage exceeds the maximum value of the ADC range then the value given by the ADC will be the maximum (or minimum) value achievable. If this occurs, a true representation of the analogue signal will not be achieved. Care must be taken to ensure that the signal is correctly amplified, particularly when surge tests are being performed.

It should be noted that:

(i) Using a 16-bit ADC as opposed to a 12-bit ADC will mean that there is less need to amplify the signal since the quantisation error is reduced by a factor of 16.

(ii) Some 12-bit ADC systems have gains incorporated in them.

(iii) Some anti-aliasing filters combine amplification with filtering, thereby reducing the need for separate amplifiers.

When digitising data it is often good practice to check both the number of points out of range (i.e. ill defined) and the range of the ADC used. If inaccurate data has been acquired, and if the data is being replayed for analogue tape, then the gain of the amplifiers can be adjusted and the data re-acquired. If the data is being taken on-line, a warning flag should be raised about the possible inaccuracy of the data.

4.9.3.2 ***Sampling Time/Phase Errors***
There are three possible arrangements for installation of analogue to digital converters (ADC) as shown in Figures 4.9-4, 4.9-5 and 4.9-6.

In the sequential sampling system (Figure 4.9-4) each input signal is multiplexed into a single ADC for digitisation. Figure 4.9-7 shows the details of a typical multi-channel sequential sampling digitisation process. During the sampling time Δt_s, a serial sample-and-hold circuit stores the value of the analogue signal over the aperture time A, and the rest of the sampling time is used to convert this value into a digital value.

After the first channel is converted the next channel is selected and sampled. This process leads to a time delay between the sampling of different channels. The speed at which the ADC goes from one channel to the next is called the "burst sampling rate". For subsequent signal processing using single channel statistics this error is irrelevant but, for multi-channel analysis, where an accurate common time base is required and channels have to be combined together, this can lead to errors.
The "Burst Sampling Rate" is dependent upon the ADC used:

- $25\mu sec$ for an ADC running at 40k samples per second
- $3\mu sec$ for an ADC running at 333k samples per second
- $1\mu sec$ for an ADC running at 1000k samples per second

Note that when sampling 31 channels using a 40 kHz ADC the time lag between the first and last channel will be 30 x $25\mu secs = 750\ \mu secs$.

As discussed earlier, data from certain measurement channels may be combined with other channels. Care must be taken that the time interval between such channels is small and significant errors are not introduced in such calculations. This can often be accomplished by using a high speed ADC (e.g. 1000 kHz) and have those channels which are to be combined next to each other in the multiplexing sequence.

It is always important to consider the time varying nature of the parameter. For instance, a delay of 1 millisecond may be acceptable on a slow moving variable such as temperature. If this error is deemed to be significant then it can be corrected by a pre-analysis software process. Interpolation of the time domain data can be done to allow for this delay in sampling. This should be done with caution and only when the data has been sampled at many times (at least 20) the cycle of highest frequency content.

In the example given in Figure 4.9-8(a), 10 parameters were scanned at a rate of 20 times per second with a channel delay of 1/400 sec between measurements. At a later stage it may be required to combine the individual channels and hence it is necessary to have them on the same time (scan) base. To do this, an interpolated value can be calculated as:

$$V_{new} = V_{i-1} + (V_i - V_{i-1}) \times \frac{(\Delta t - \delta t)}{\Delta t} \qquad 4.9\text{-}1$$

where: V_{new} = new interpolated value for point i

V_{i-1}, V_i = values taken interval Δt apart (1/20 in Figure 4.9-8a)

Δt-δt = time from the first sample in the scan.

The calculation can be recognised more clearly from the diagram in Figure 4.9-8(b).

The above assumes a linear variation of measurand within the sampling interval. Obviously, higher order interpolation procedures could be used which would allow a reduction in sampling rate.

The alternative acquisition method is to use a parallel sample-and-hold system such as shown in Figures 4.9-5 or 4.9-6. When a digitisation sequence is initiated a sample of each channel is stored simultaneously for subsequent conversion. This process for the multiplexed system (Figure 4.9-5) is further illustrated in Figure 4.9-9 where A represents the sample aperture time and Δt, the ADC conversion time. The obvious advantage of the parallel sample-and-hold system is that each measurand is sampled at the same instant in time. Other characteristics of these three arrangements are given in References 4.9.1 and 4.9.2

4.9.3.3 *Calibration*

The ADC converts an analogue voltage into a digital number, say in the range ± 2048. The simple equation to convert this into engineering units is:

$$\text{Eng. Units} = \left[\frac{(\text{Digital Value}) \times \text{FACT}}{\text{GAIN}} + \text{OFFSET}\right] \times \frac{1}{\text{CAL}} \qquad 4.9\text{-}2$$

where FACT = is a system constant which converts the digital value into millivolts,

GAIN = is an amplifier gain used before digitising the signal into the system,

OFFSET = is a dc offset in millivolts,

CAL = is the sensitivity or calibration constant in millivolts per unit.

In previous Sections (4.1 to 4.8), methods of calibration of the sensors and transducers have been discussed in detail. Using this calibration information, and any further calibrations of the data acquisition system itself, the acquired digitised data may then be converted to engineering units using a simplified relationship, as above, or through a high (e.g. 5th) order polynomial representation of the calibration. However, in most cases it is preferable to store data in raw digitised form (i.e. prior to conversion to engineering units) as this makes it easier to carry out further analysis at a later date or to revise calibration data should that prove advisable.

4.9.3.4 *Acquisition of Data in Pulse Coded Form*

When data has to be transmitted from one location to another it is best done using a pulse coded format as an analogue signal can become degraded. In some acquisition systems it is this pulse code representation which is recorded; the most popular code being "Pulse

Code Modulation" (PCM) (References 4.9.1 and 4.9.5). Pulse coded tapes can usually be read into the data analysis system using a digital input interface (as opposed to an analogue to digital converter interface).

If this is done, and if this data has to be correlated or combined with the data which was acquired through the ADCs, then a common time code must be recorded on the PCM tape and the analogue recording. In both methods of input (digital or analogue), the system can then time stamp each sample accordingly. This is very important where applying the Sampling/Time phase corrections as described in Section 4.9.3.2.

4.9.4 Filtering

The frequency of interest in transient data will, in many cases, contain frequency components up to 100 Hz, and will have been sampled at 1000 or more samples per second (see Sections 4.9.2 and 5.2.2.5). There are, however, other cases where the maximum frequency of interest will be much lower, and then the sampling rate can be much reduced. The raw data may also contain unwanted noise and other data at higher frequencies than those of interest. It is necessary to remove these from the data before recording. This is usually carried out by the incorporation of a carefully selected low pass filter either incorporated in the signal conditioning components (Sections 4.1.3.3 and 4.2. to 4.8) or in the data acquisition system. Signal processing can also be carried out after the signal has been digitised. The term "digital filter" is used to represent a digital processor which receives a sequence of input values and carries out some preprogrammed digital operation on them which can, in effect, be a filtering process.

The sampling of any signal must be viewed from two main aspects. Consider Figure 4.9-10(a) where sufficient data points have been sampled to correctly identify the frequency of the sinusoid. An increased sampling frequency will improve the fidelity of the digitised signal and provide a more reasonable estimate of its peak amplitude. On the other hand, in Figure 4.9-10(b) the sampling rate is too low and insufficient points are sampled to correctly identify the frequency. The data would falsely appear in a spectrum analysis as being a lower frequency than it actually is but, most importantly for transient data, the peaks of the signal would not be determined correctly. This effect is known as aliasing. The critical frequency, where there are exactly two points per cycle is called the Nyquist, or folding, frequency (f_N) and is equal to half the sampling frequency (fs). This Nyquist frequency is the minimum that can be used if aliasing is to be avoided. However, as stated above, a sampling rate of 10 to 20 times the top frequency of interest is recommended in many transient test programmes. Nevertheless, filters are usually incorporated in the data acquisition system in order to reject (attenuate) those frequency components of the signal which are outside the range of interest and to guard against aliasing.

Selecting a filter is not easy. All filters, whether executed in the analogue or digital domains, alter the signals passing through them in some way and, for any filter characteristic, the effect is strongly dependant on the kind of information contained in the signal. Therefore, it is always important to assess the errors or distortions (attenuation and phase shift) of the measurand that will be introduced by the filter itself.

Many types of filters are available, each offering different characteristics (see, for example, References 4.9.1, 4.9.2 and 4.9.4). Figure 4.9-11 illustrates this for some low pass filters. The elliptic filter, while providing a sharp cut off may have poor fidelity in the pass band and is prone to ringing. At the other extreme, the Bessel filter has a drooping pass band, is unsurpassed for fidelity, and has a short settling time. More details of three of these types of filters are given in Figures 4.9-12 to 4.9-14 (Reproduced with permission of Frequency Devices, Inc.). The main performance features of these filters can be described by:

a) The flatness, ripple or droop in the pass band, its cut off frequency and the attenuation decay rate beyond cut off.

b) The phase shift (between input and output) as a function of frequency.

c) The rise time (. time constant), overshoot and settling time in response to a sudden change of input, e.g., step or ramp.

Butterworth filters (Figure 4.9-12) have a flat response in the pass band, a relatively sharp cut off and a moderate phase shift but a slow rise time and a significant overshoot. They could be the preferred type if the overriding requirement was pass band fidelity.

Bessel filters (Figure 4.9-13) have a linearly increasing phase shift in their pass band and a short rise time with minimum overshoot but a slow droop which extends into the pass band.

Chebyshev filters are designed to have a specific ripple in their pass band. Compared to Butterworth and Bessel filters they (Chebyshev) can achieve a faster roll off but only at the expense of pass band ripple. The example shown in Figure 4.9-14 has a pass band ripple of 0.5 dB.

Cauer-Elliptic filters are designed to achieve maximum sharpness of frequency cut off. However, the pass band is rippled and the stop band descends deeply into one or more notches, returning to a finite level. These filters are specified by the amount of pass band ripple, cut off frequency and required stop band attenuation.

The performance of high pass or band pass filters can be similarly described.

There are thus many factors which must be taken into account when selecting a filter. These will include the input signal characteristics, the frequency content of interest and the necessary behaviour of the filter in terms of freedom from signal distortion, settling time, sharpness of cut off, phase shift, etc. Finally, it is important that all channels, which are to be compared and combined, are put through the same type of filter, otherwise an allowance for phase shift may be required.

Figure 4.9-15 illustrates the response to a step input for three different 4 pole filters each having a cut off frequency of 100 Hz. Figures 4.9-16 to 4.9-18 show the response of the same three types of filter to a saw tooth input. In this case, different levels of cut off frequency, 50 Hz, 100 Hz and 200 Hz are illustrated. In each case, the output signal shows a time delay and a depression in peak output level. The magnitude of the errors is illustrated in the "design example" given in Sections 4.9.7 and 5.

It is possible to minimize some of the errors introduced by the filter by as calculation procedure known as deconvolution. Here the recorded filter output signal is reprocessed, using the known filter specification and characteristics, to reconstitute the measurand. Figure 4.9-19 shows the deconvolution of the solid line (filter output) to the dotted line which to all intents and purposes was the initial measurand.

Even though the above discussion refers only to the theoretical performance of the different types of filters, it is an adequate guide on which to base the choice of filter. For example, the abrupt step used as input in deriving the response curves shown in Figures 4.9-12 to 4.9-15 is unlikely to represent a real world situation which would be better described by a ramp input. Table 4.9-1 shows the calculated percentage overshoots for a range of Butterworth filters (and a single Elliptic filter) subjected to a series of ramp inputs. The significance of these results is that even though real world systems do not precisely simulate a sensor with an ideal step input, for relatively slow rise time inputs (in relation to cut-off frequency) the peak overshoots remain nearly the same as that obtained from an ideal step.

As well as these theoretical performance characteristics, there are other "steady state elemental error sources" inherent in the build of any filter. A typical manufacturer's specification will often refer to the following sources of error: input and output drift with temperature, zero offset (sometimes adjustable to zero), crosstalk, distortion, internally generated noise, gain (can be calibrated out), etc. The magnitudes of these errors can be estimated from the manufacturer's specifications.

4.9.5 Data Manipulation

Advances in the technology of measurement and data acquisition have greatly increased the quantity of information which may be captured from a given experiment. Although an understanding of the physical system may be obtained by examining the data directly, further knowledge is often obtained from manipulated data. When this is held in digital form the processes of display and manipulation become relatively easy to achieve. Calculating derived functions from the data measured, e.g. velocity from acceleration, horsepower from torque and speed, can save considerable time and money either by reducing the number of functions to be measured or by eliminating the need for expensive instrumentation when less expensive instruments are available to measure related functions.

When calculating combined components the time lag between measurements in the physical system should be accounted for as mentioned in Section 4.9.3.2. Also, it is essential to ensure that the uncertainty in the derived parameters, obtained using the methods suggested above, remains acceptable.

4.9.6 Analysis and Processing System

It is not the purpose of this report to describe specific hardware or analysis and processing procedures. However, the basic components of such a system are (Figure 4.9-20):

(a) Computer processor to run the software which analyses the data and controls the peripherals.

(b) An analogue input system (AIS) to acquire the data; this data may also be in digital form.

(c) Graphics display units to output the analysed data.

(d) Disc backing store to store programs and analysed data.

(e) Printer or plotter to get a permanent copy of results.

4.9.6.1 *Analogue/Digital Input System*
The critical area of the analysis system is the acquisition of the data. Relevant points in this area were discussed above.

Analogue signals from the experiment are fed through anti-aliasing filters into the Analogue to Digital Converter (Figure 4.9-21). The ADC is controlled by, and feeds data through, an interface module (IFM) using software drivers and subroutines so that digital information (i.e. a replica in digital format of the measured signals) can be stored in the computer.

4.9.6.2 *What Type of Analysis System?*
Such systems could range from a PC to powerful mini-computer. The requirement is dependent on the input bandwidth of the data and the type of calculation to be done. In addition, the requirement for on-line display of the results during or immediately after the test should be considered. In general, much time can be saved by seeing immediately that good data was acquired from a test.

The type of system and its capacity can only be considered when all the facts about data measuring and output requirements have been defined. This is particularly important when a new system is being designed so that the widest possible use can be made of the facility.

4.9.7 Design Example
This section illustrates the sources of error arising within the DAS for the surge margin measurement example using a fuel spike (see Section 5). In practice, the DAS is usually fixed hardware installed in the test facility, often with fixed operational boundaries and a limited range of adjustment. It will therefore be necessary to determine the uncertainty limitations of the DAS and estimate whether or not the system is capable of acquiring (accepting and recording) the input signals with an adequate level of confidence (accuracy).

The arrangement proposed for pressure measurement is shown in Figure 4.9-22 (i.e. Figure 5.2-9) and consists of a parallel sample and hold system. The pressure signals $(PS31)_o$, $(P25)_o$, $\Delta PS25$ and $\Delta PS31$ are measured. Then $PS31 = (PS31)_o + \Delta PS31$, with a corresponding equation for inlet pressure, $P25 = (P25)_o + \Delta P25$. A correction will be applied to transpose the measured combustion chamber casing static pressure PS31 to an equivalent mean compressor outlet pressure P3 (see Section 4.2.6 and 5.2.5).

A block diagram representing the DAS and Processor and the Error Model is shown in Figure 4.9-23 where the main sources of error are considered to arise in the filter, sample and hold system, A/D converter and data processor. The input levels to the DAS are assumed to be as in Table 4.9-2.

In the filter, distortion will be introduced by the filter transient transfer characteristics and also by its steady state performance specification. It has been assumed that all transient channels have filters with the same specification and hence similar time delays. Also, since peak pressure ratio is the measurement objective, only this error will be considered.

In Section 5.2.2.5, a derivation is presented for the selection of the "highest frequency of interest" and, hence, a justification of the sampling rate referred to earlier. Then follows the selection of the appropriate filter type, its cut-off frequency and related elemental errors. All these filter errors, discussed in Section 5.2.2.5, have been entered in Figure 4.9-23, even though many of them arise in the signal conditioning component. These results are further illustrated in Figure 4.9-24, where the theoretical attenuation over the range of frequencies associated with this example are plotted.

The parallel sample-and-hold system, used in this example to capture the various pressures (Figure 4.9-22), was chosen to effectively freeze the fast moving signals at a series of corresponding instances in time. These frozen (i.e. held) signals would subsequently be digitised through an A to D converter. The input and output from a sample-and-hold amplifier is shown in Figure 4.9-25. The features to be considered in selecting this component are aperture time, settling time, droop rate and the related performance uncertainties. Note that the digitisation process is initiated at the end of the settling time. Further information on sample-and-hold systems can be obtained from References 4.9.1 and 4.9.2 or manufacturers' manuals.

A typical error, obtained from manufacturers' specifications for the sample-and-hold component required for this example, would be ± 5 mvolts in a ± 5 volt range (i.e. $\pm 0.1\%$ FS).

There are a wide variety of current designs for analogue to digital converters; more information is available in References 4.9.1 and 4.9.2. The various types differ in speed, accuracy, cost, etc. and manufacturers' specifications should be referenced for this data. For the surge margin example being considered here a 12 bit A to D converter, with a conversion time of 12 μsec, was chosen. Typical bias and σ precision errors of such a component would be of the order of 0.03% FS in both cases (see also Section 8.2 of Reference 4.9.3).

In both the sample-and-hold system and the A to D converter it is assumed that the full operating range is used and thus the error in reading relates to the full scale (FS) error limit.

Data reduction by the processor consists of converting the digital recordings to engineering units via calibration curves. It is assumed for this example that uncertainties introduced by the processor (e.g. calibration curve interpolation process) result in a σ precision error of $\pm 0.03\%$ FS (see also Section 8.2 of Reference 4.9.3).

The above elemental errors have been entered in Figure 4.9-23 (exit pressure) where it will be seen that the overriding error component results from the peak response of the filter. Similar percentage errors can be anticipated in the varying inlet pressure (P25), so care must be exercised in relating inlet and outlet pressures to a common time base with the appropriate allowances for signal delay.

Typical uncertainties that would be introduced by the data system into the measurement of T25 are summarized in Table 5-6.

4.9.8 References

4.9.1 Rangan C.S., Sarma G.R & Marie V.S.V, *Instrumentation Devices and System*, McGraw-Hill, 1983

4.9.2 Doebelin E.O., *Measurement Systems: Application and Design*, 4th Ed., McGraw-Hill, 1990

4.9.3 *Recommended Practices for Measurement of Gas Path Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components*, AGARD Advisory Report No.245, 1990

4.9.4 Huelsman L.P. and Allen P.E., *Introduction to the Design of Active Filters*, McGraw-Hill, 1980

4.9.5 Bendat, J.S. and Piersol, A.G., *Random Data, Analysis and Measurement Procedures*, Wiley-Interscience, 1971

Table 4.9-1 Percentage Overshoot Caused by Different Filters for Variable Input Ramp Rise Times

Ramp Rise Time (sec)	Butterworth				Elliptic
	2 pole	4 pole	6 pole	8 pole	8 pole 6 zero
0.0	4.34	10.87	13.83	15.58	20.18
0.1	4.34	10.86	13.80	15.74	20.17
0.2	4.33	10.84	13.76	15.69	20.16
0.5	4.30	10.74	13.65	15.61	20.01
1.0	4.17	10.39	13.24	15.13	19.52
2.0	3.70	9.06	11.60	13.40	17.70
5.0	2.00	3.63	4.25	4.98	7.60
Filter cut-off frequency (f_c) = 1 Hz					

Table 4.9-2 DAS Error Source Diagram Requirements - Example of Section 4.9.7

Parameters	Frequency	Signal	Range	Impedance	Electrical Interface
ΔP25	<75Hz	mV	0-100	500 Ω	2 wide + shield
ΔPS31	<75 Hz	mV	0-100	1000 Ω	2 wide + shield
P25	steady-state	mV	0-100	1000 Ω	2 wide + shield
PS31	steady-state	mV	0-100	1000 Ω	2 wide + shield
T25	5 Hz	mV	0-20	low	2 wide + shield
N_H	digital (1553)	12-bit	0.020 sec update	bus	bus

Notes:
* Systems for pressure measurement - see Sections 4.2.6, 5.2.3.2 and 5.2.3.3.
* Air flow is inferred and error data are described in Sections 4.4.7.6 and 5.2.3.6.

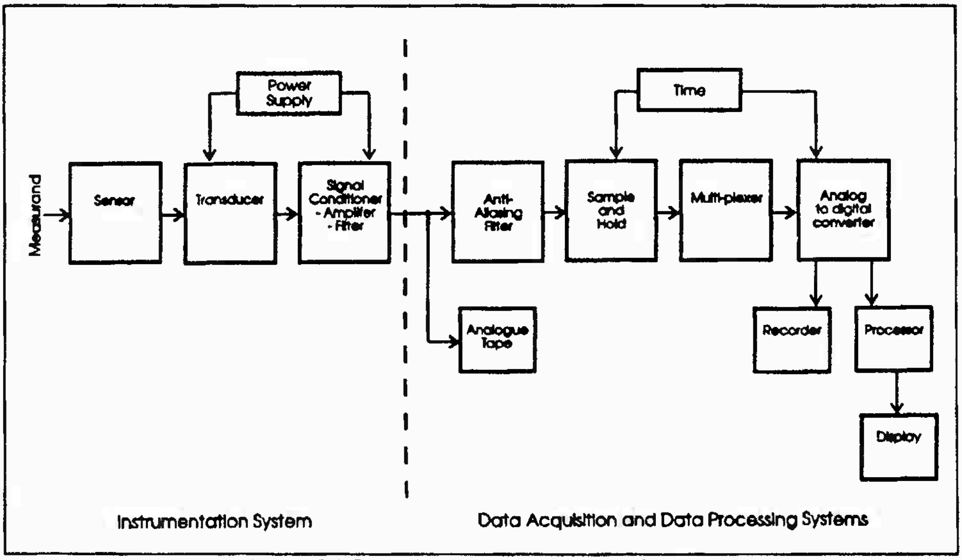


Figure 4.9-1 Generalized Measurement System Schematic

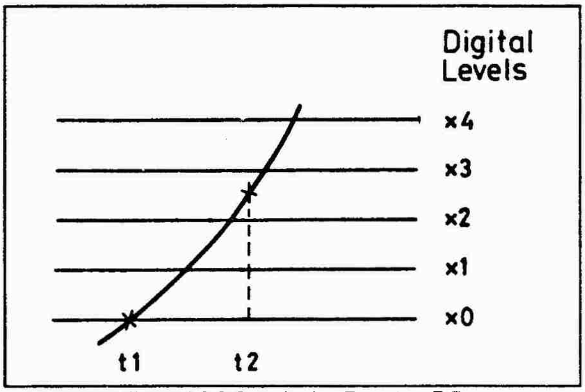


Figure 4.9-2 Quantisation Error in ADC

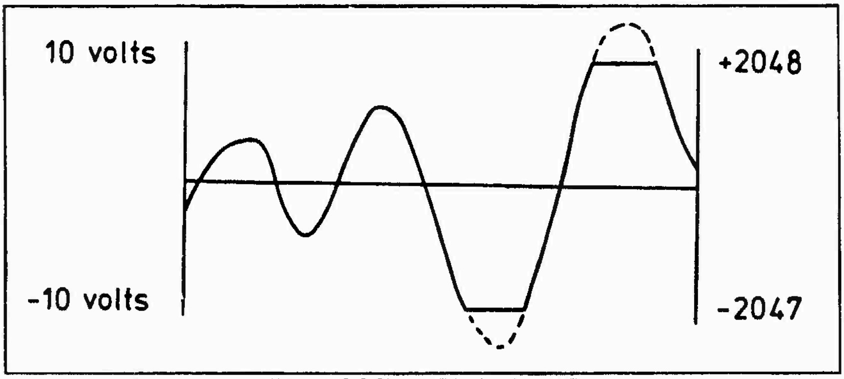


Figure 4.9-3 Signal Clipping in ADC

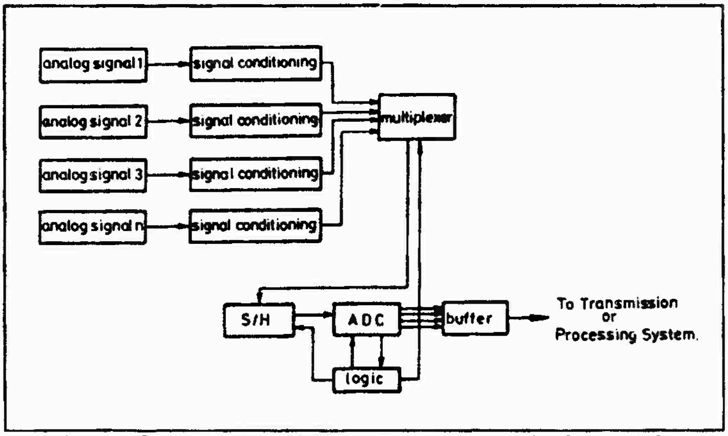


Figure 4.9-4 Multi-channel Data Acquisition System Using Single ADC - Sequential Sampling

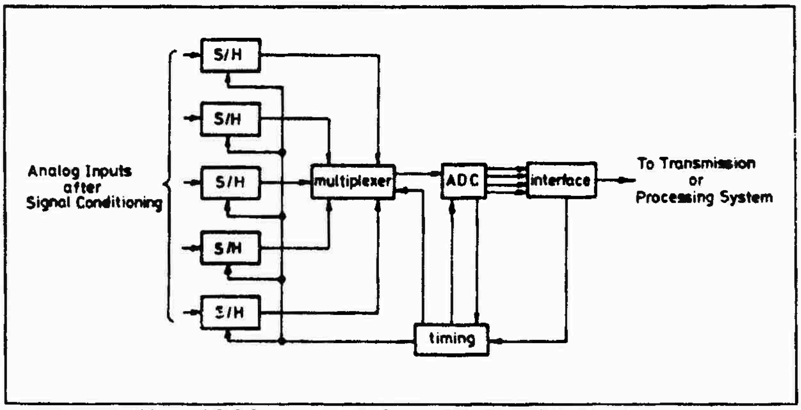


Figure 4.9-5 Simultaneously Sampled System with Multiplexer - Parallel Sampling

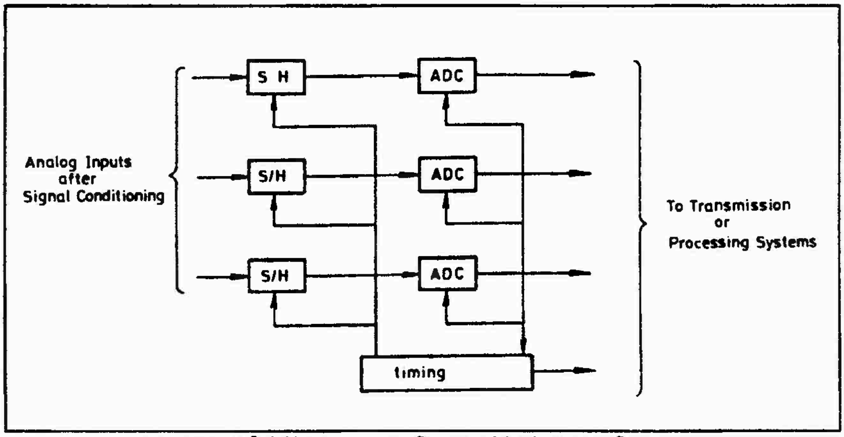


Figure 4.9-6 Simultaneously Sampled Multi-channel System
- Parallel Sampling

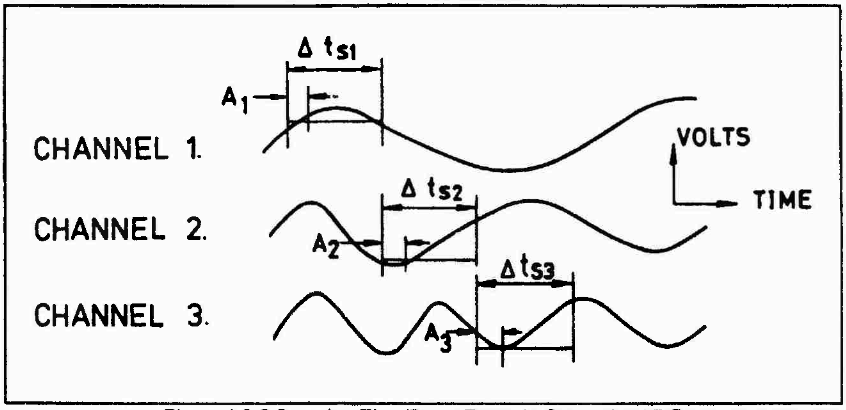


Figure 4.9-7 Sampling Time/Phase Errors in Sequential ADC

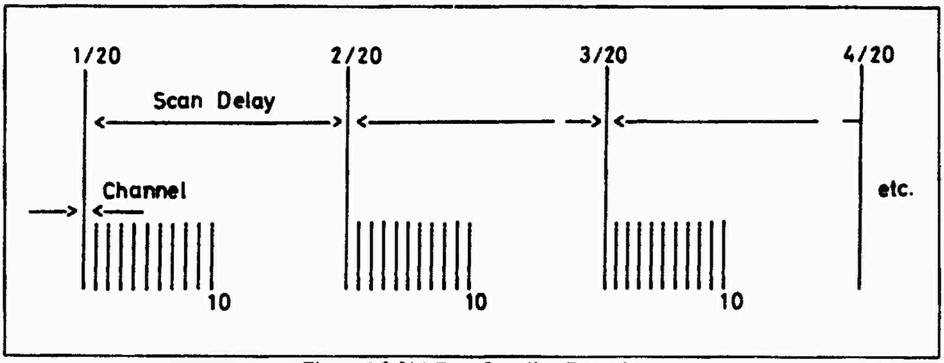


Figure 4.9-8(a) Data Sampling Example

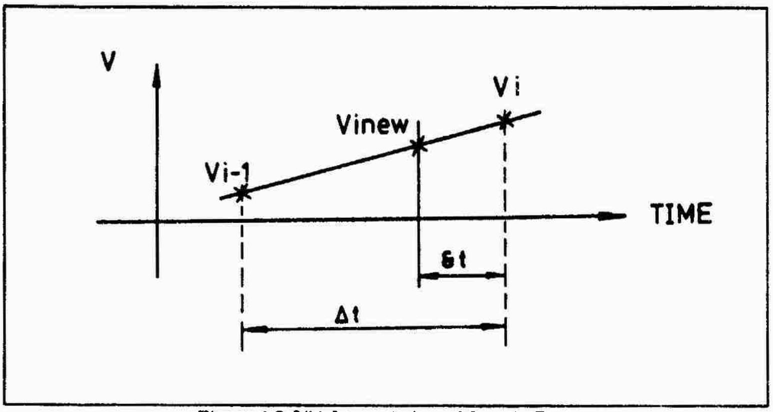


Figure 4.9-8(b) Interpolation of Sample Data

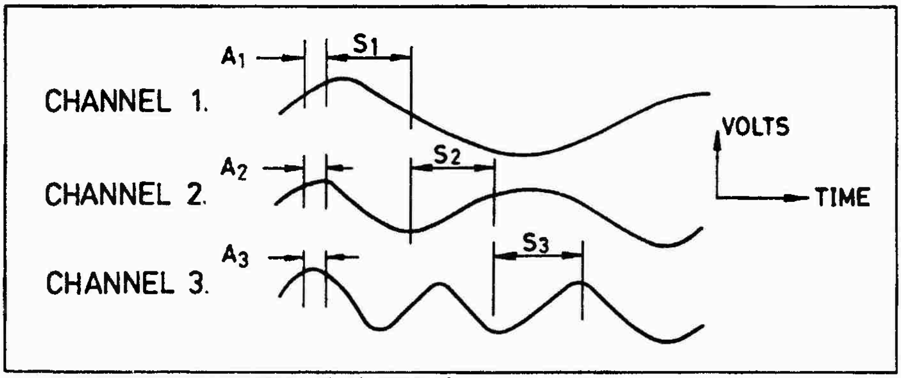


Figure 4.9-9 Parallel Sample and Hold ADC

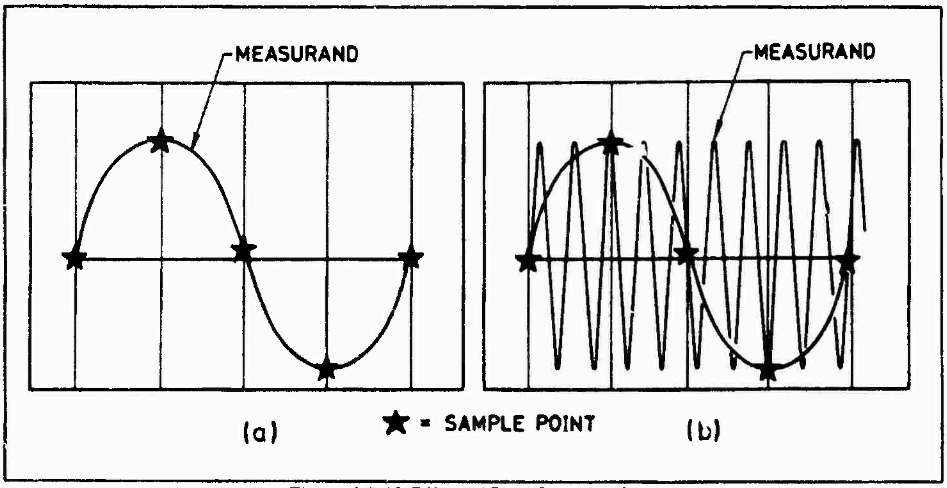


Figure 4.9-10 Effect of Data Sampling Rate

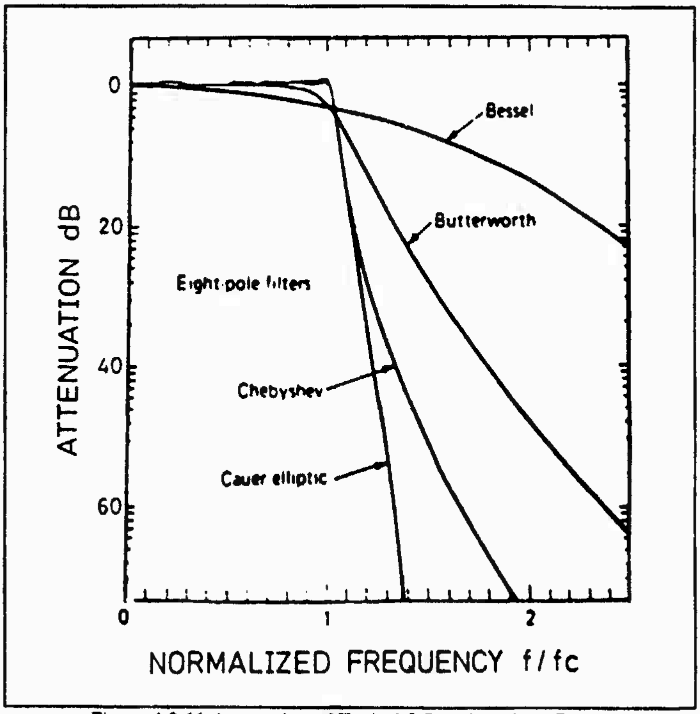


Figure 4.9-11 Attenuation of Typical 8-Pole Low Pass Filters

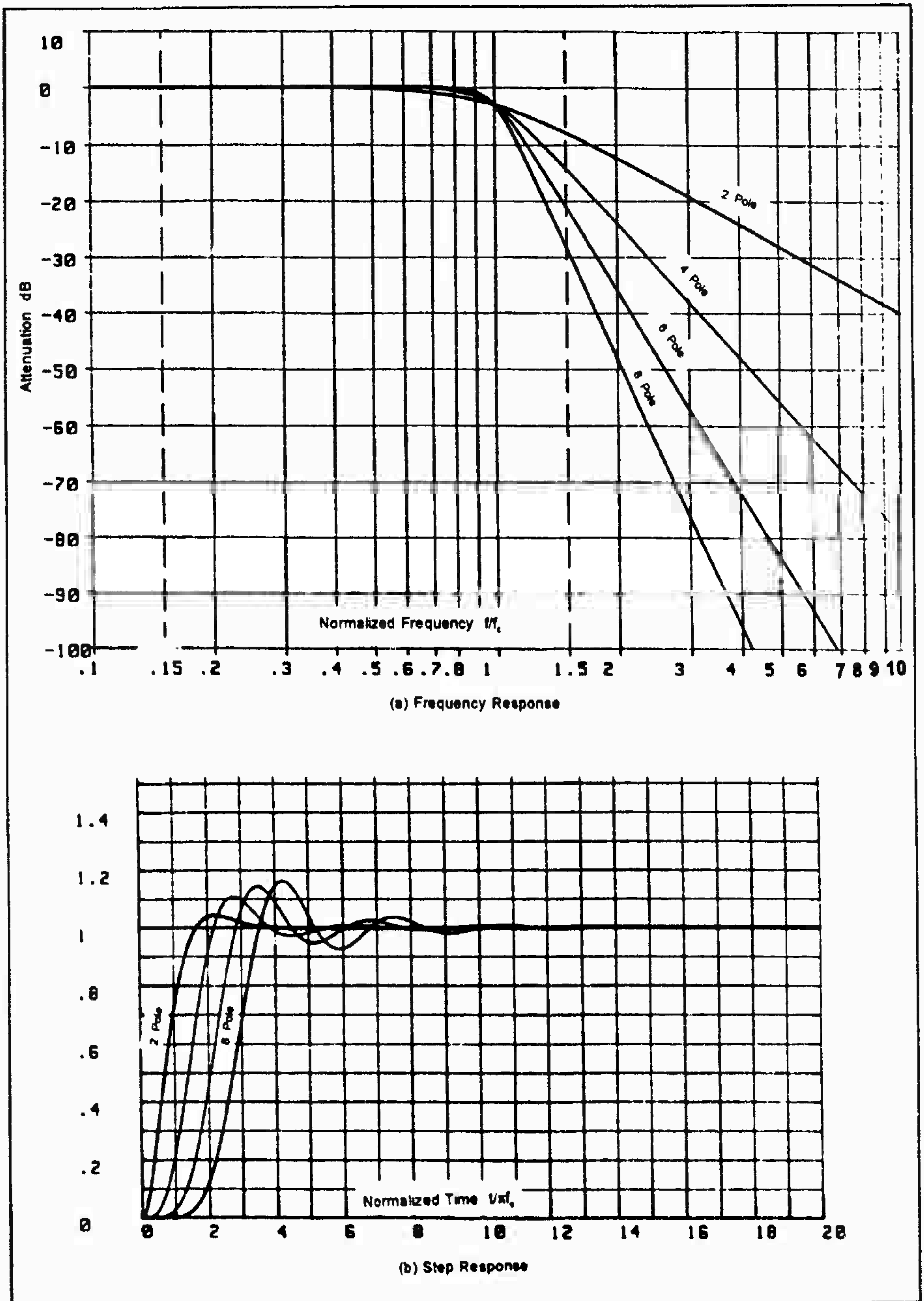


Figure 4.9-12 Theoretical Response - Butterworth Filters
(Published with Permission of Frequency Devices, Inc.)

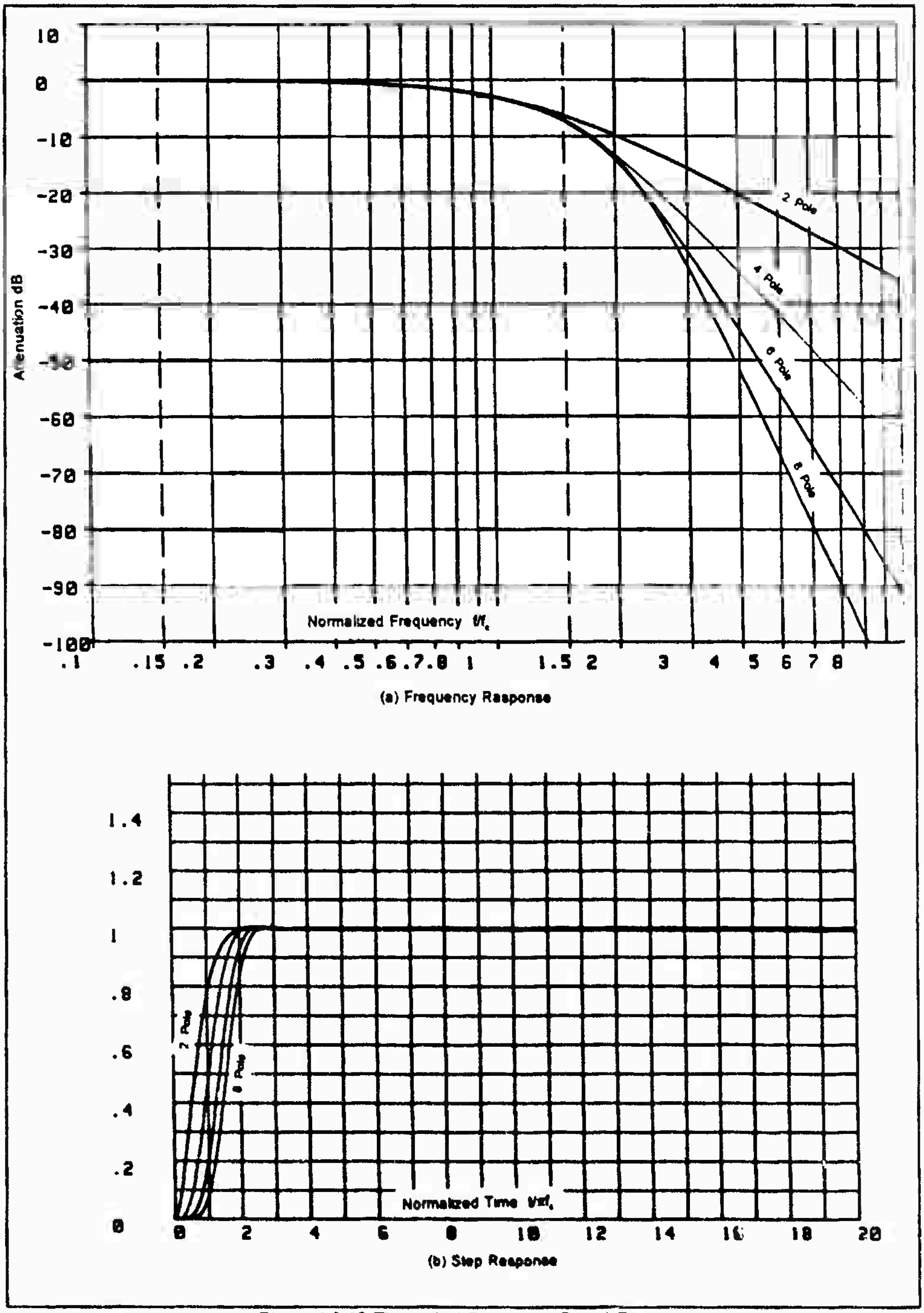


Figure 4.9-13 Theoretical Response - Bessel Filters
(Published with Permission of Frequency Devices, Inc.)

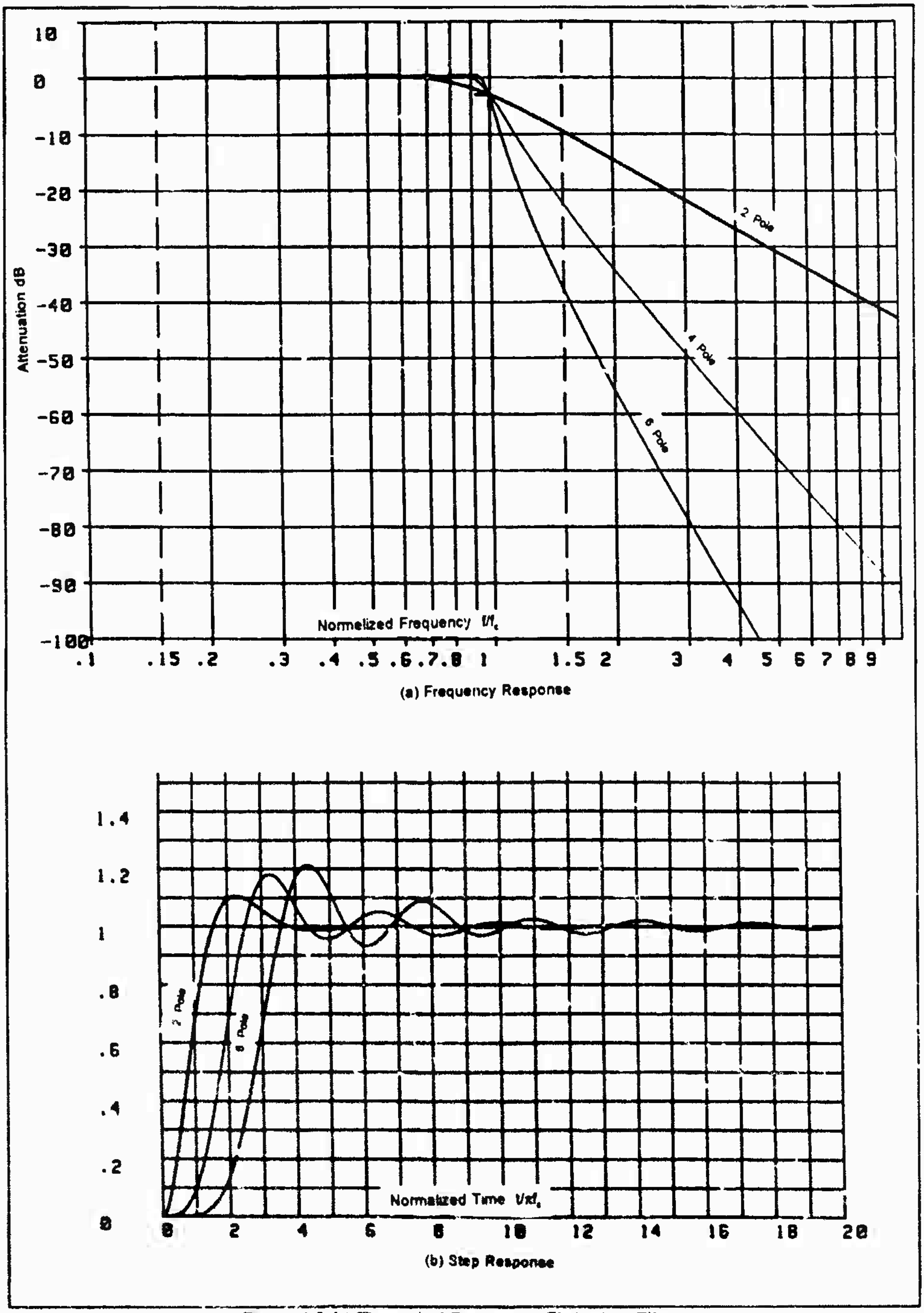


Figure 4.9-14 Theoretical Response - Chebyshev Filters
(Published with Permission of Frequency Devices, Inc.)

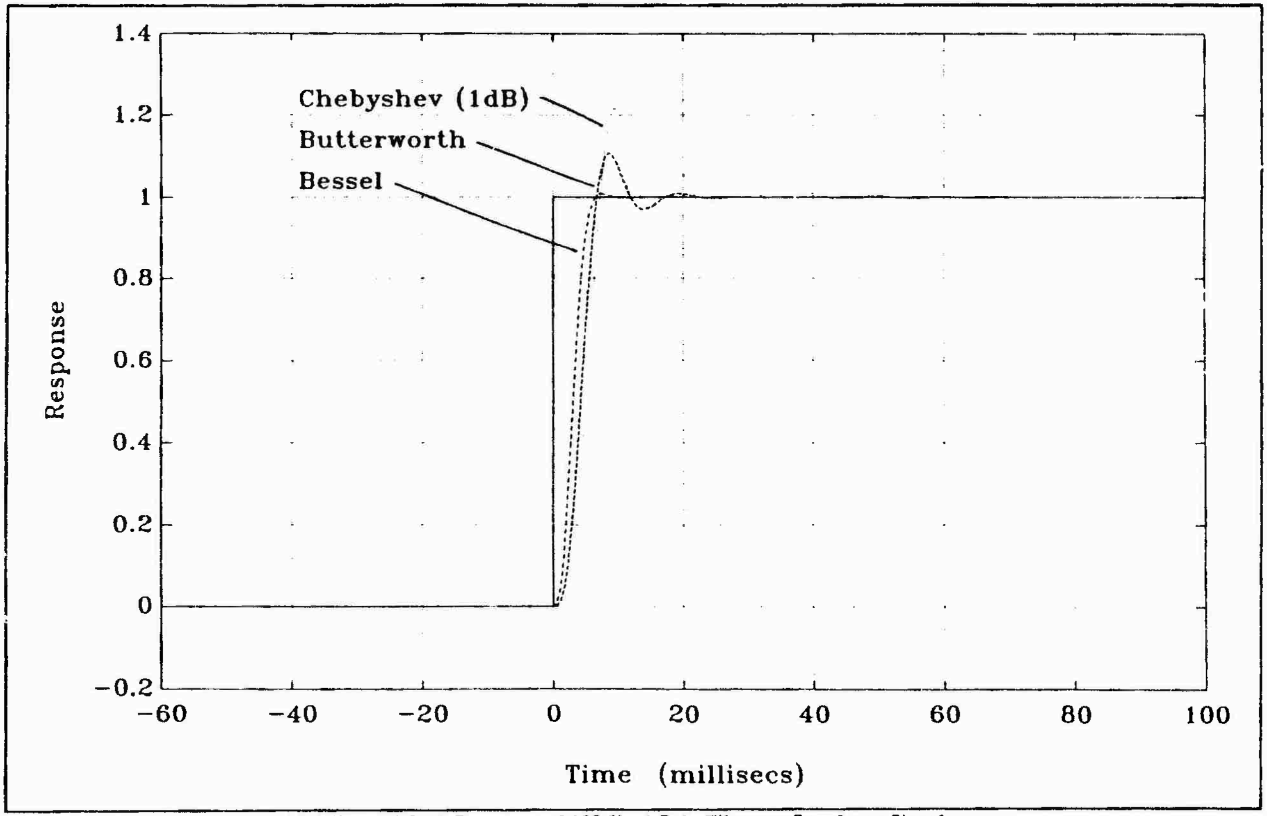


Figure 4.9-15 Response of 100 Hz 4-Pole Filters to Step Input Signal

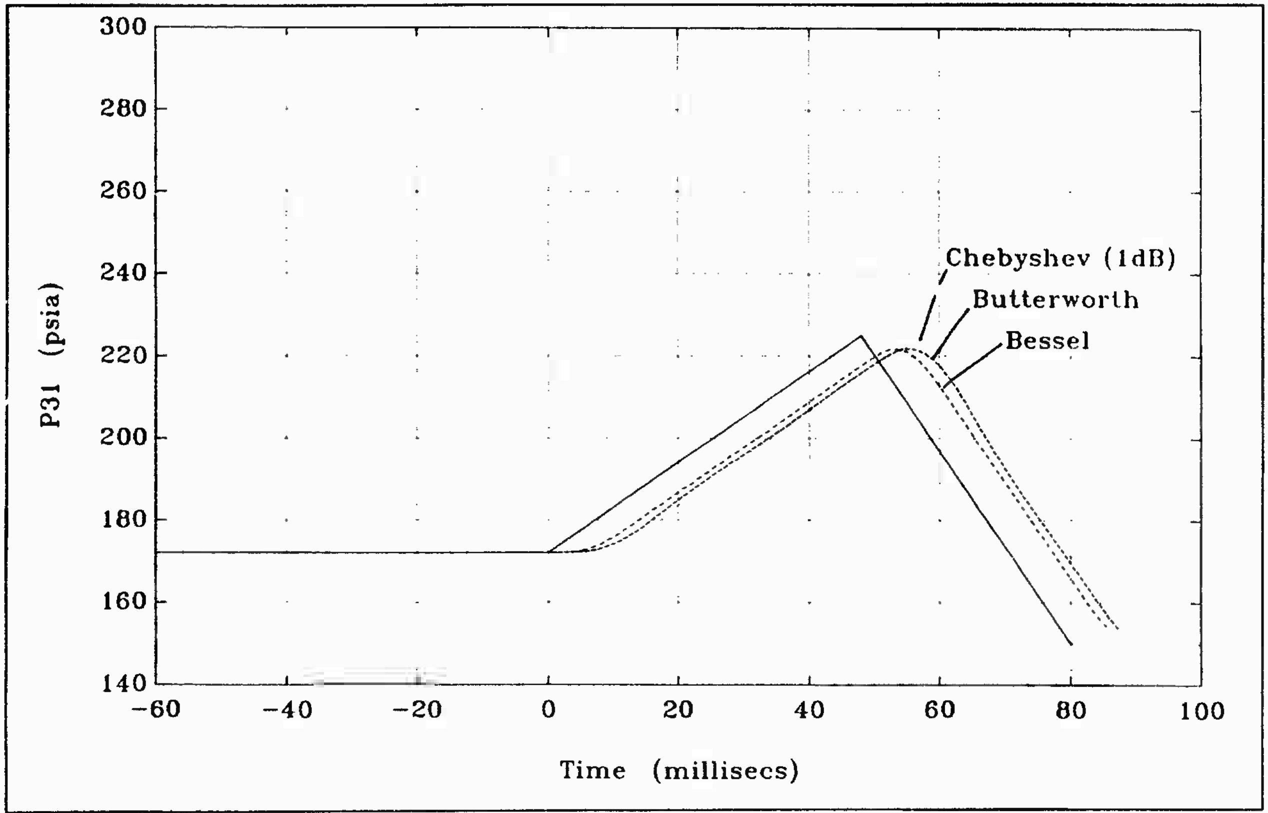


Figure 4.9-16 Response of 50 Hz 4-Pole Filters to Triangular Input Signal

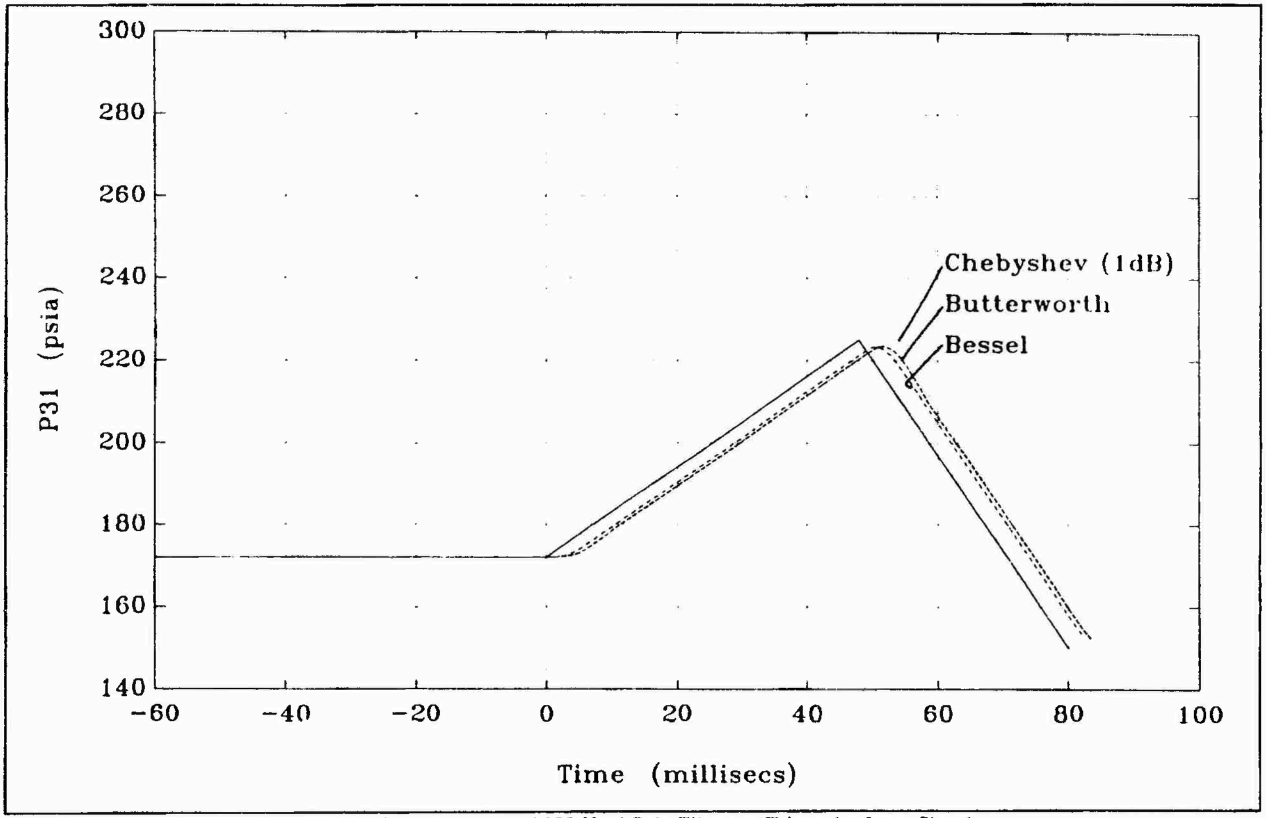


Figure 4.9-17 Response of 100 Hz 4-Pole Filters to Triangular Input Signal

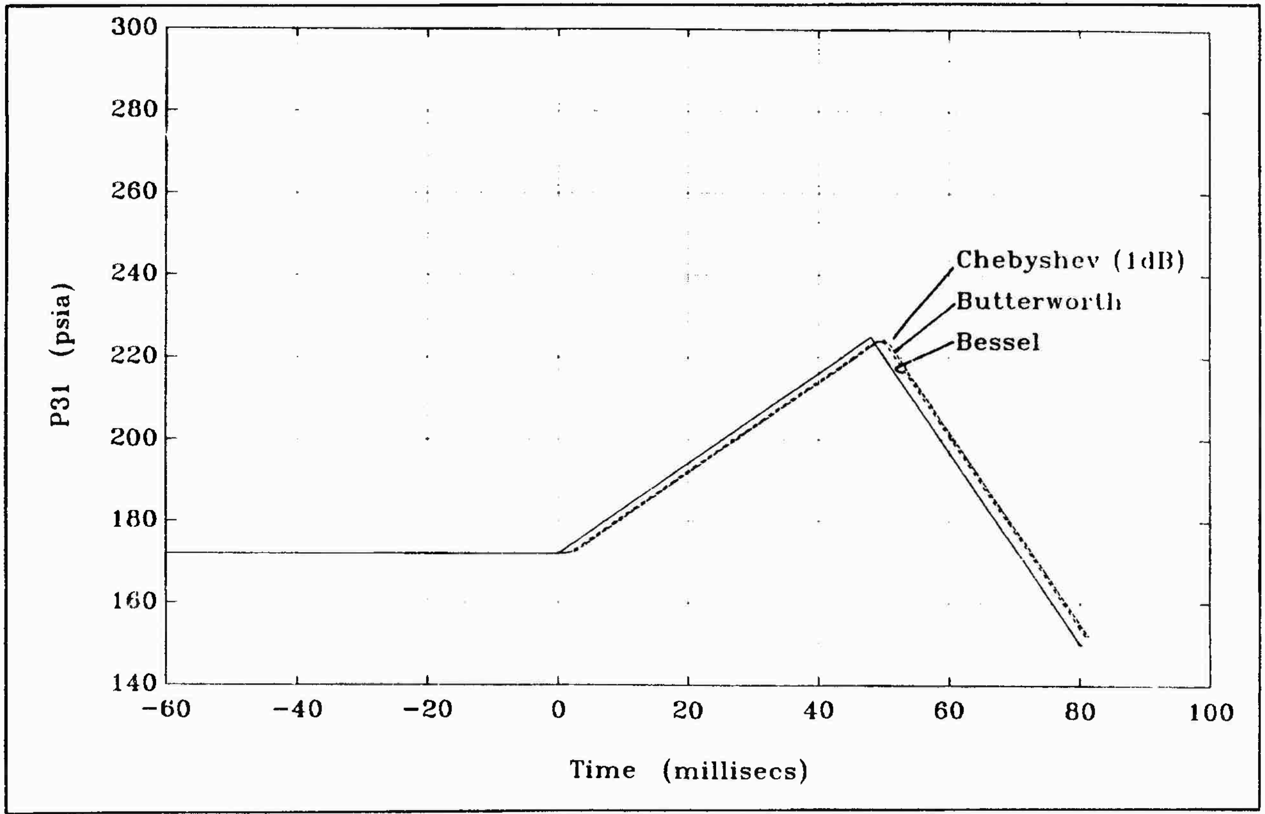


Figure 4.9-18 Response of 200 Hz 4-Pole Filters to Triangular Input Signal

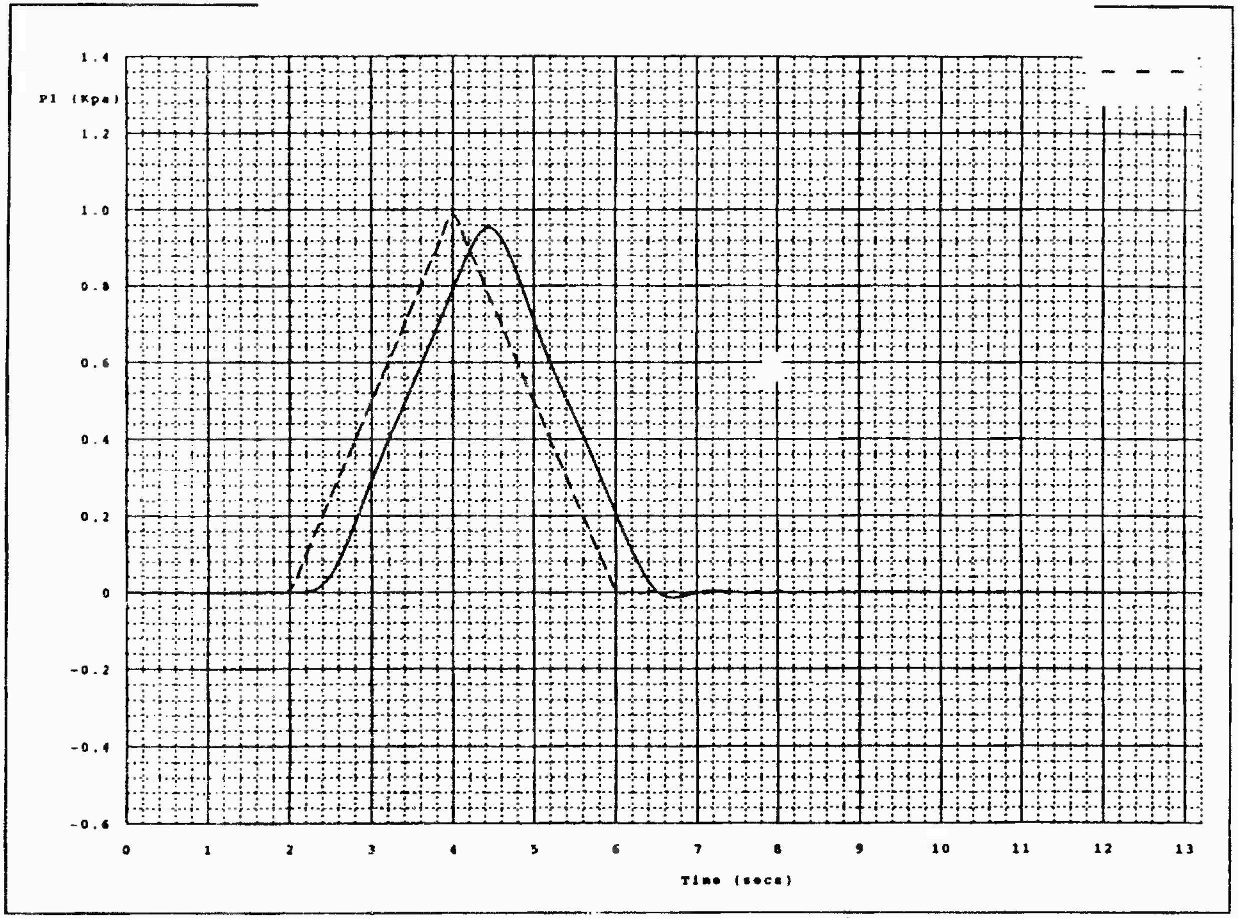


Figure 4.9-19 Deconvolution of Filter Output Signal - (see text Section 4.9-4)

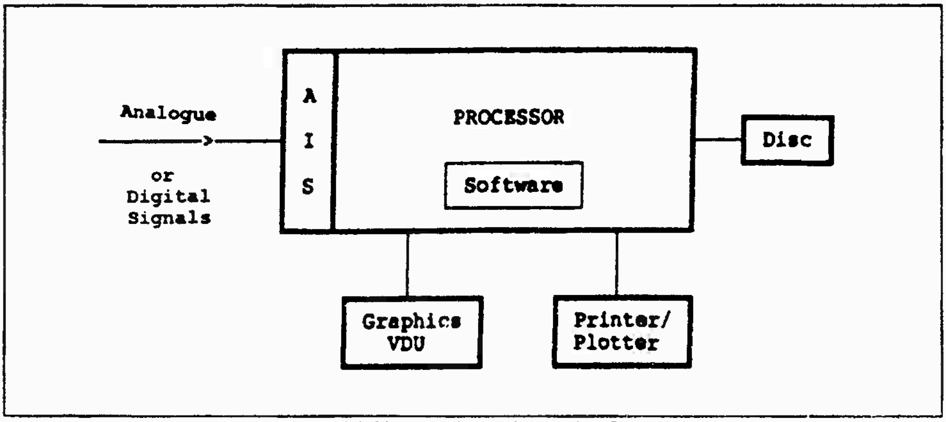


Figure 4.9-20 Analysis and Processing System

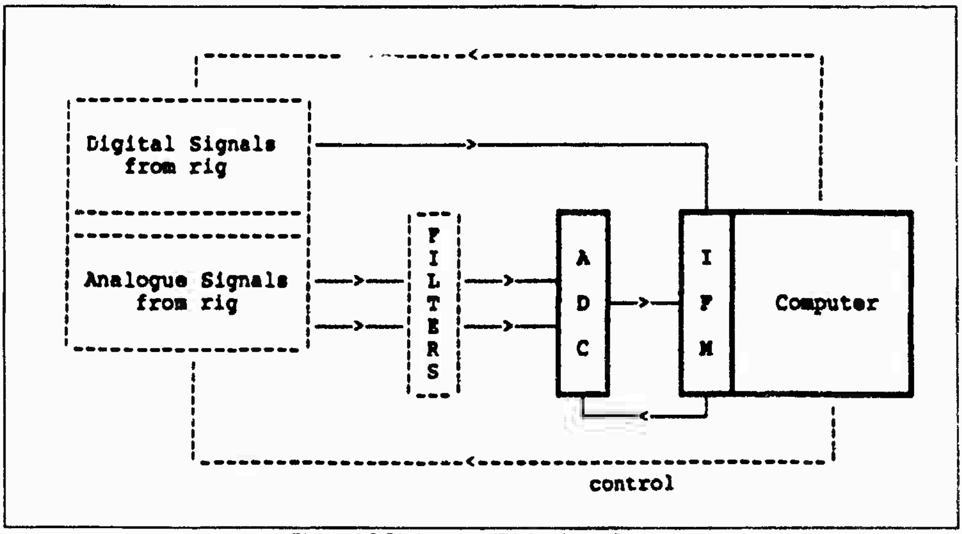


Figure 4.9-21 Analogue/Digital Input System

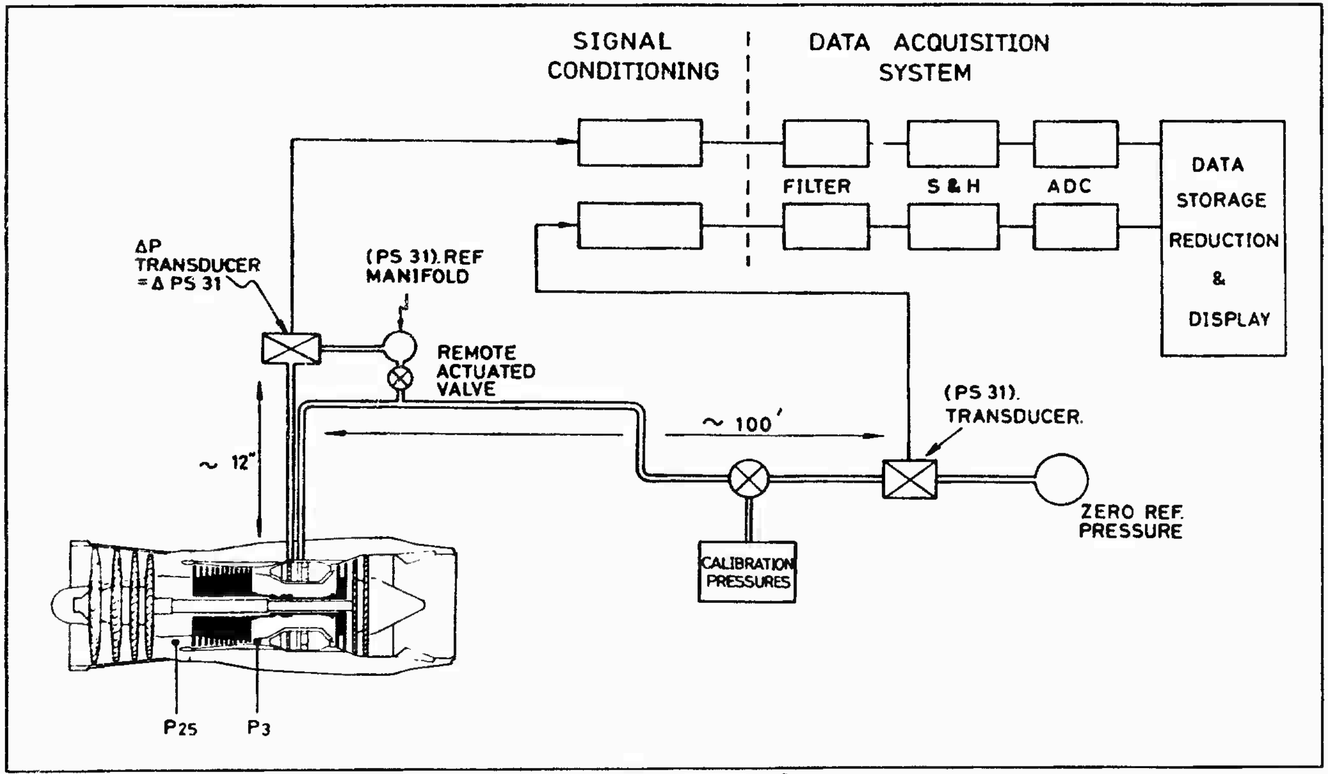


Figure 4.9-22 P3 Measurement System

Error Values are percent of transducer full scale

Data System Acquisition and Processing

	$PS31_o$		$\Delta PS31$				
	Steady		Steady		Transient		
	±b	±s	±b	±s	+b	-b	±s
Filter	Neg	Neg	Neg	Neg	Neg	-3.8	±.39
Sample & Hold	±.1	Neg	±.1	Neg	+.1	-.1	Neg
A/D	±.03	±.03	±.03	±.03	+.03	-.03	±.03
Data Processing	Neg	±.03	Neg	±.03	Neg	Neg	Neg
RSS	±.1	±.04	±.1	±.04	-.1	-3.5	±.39

Figure 4.9-23 Error Source Diagram for Maximum (Surge) Pressure PS31

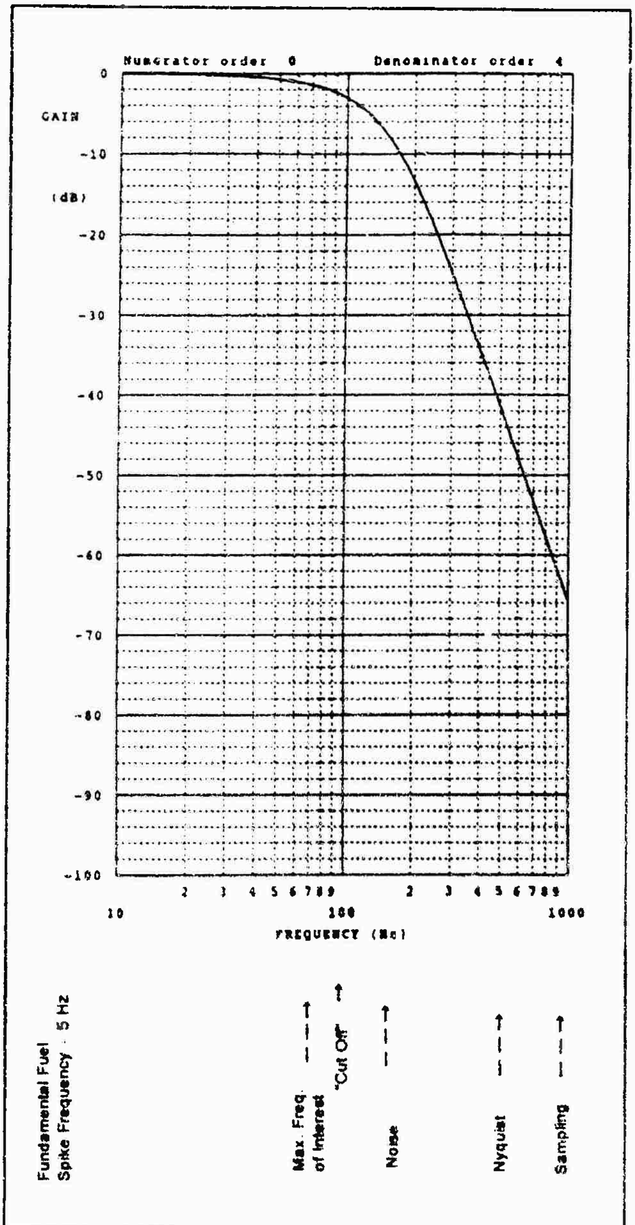


Figure 4.9-24 Summary of Filter Performance for Example of Section 5.2

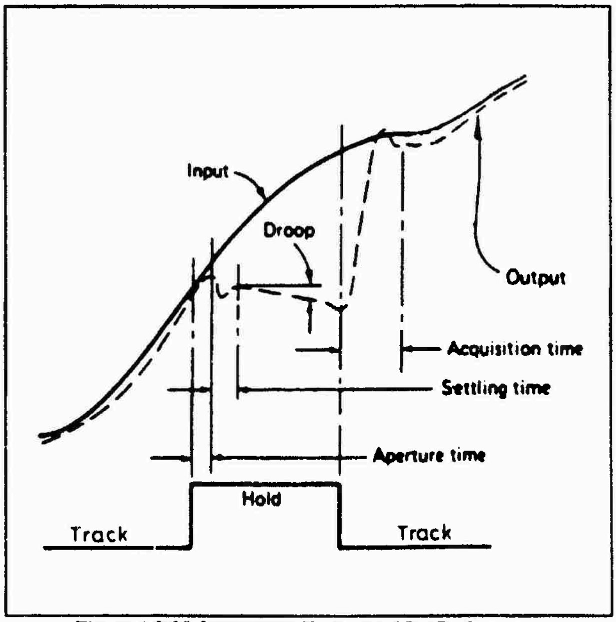


Figure 4.9-25 Sample and Hold Amplifier Performance

5. EXAMPLES OF A MEASUREMENT SYSTEM UNCERTAINTY ANALYSIS FOR TWO TEST CASES[1]

5.1 SELECTION OF EXAMPLES

In this section two examples of pre-test uncertainty analysis will be developed in order to illustrate the application of the principles of transient measurements described in this document. Since the document envisions a wide spectrum of users from engine operators and overhaul and repair personnel through engine developers, the first example represents a complex test that requires special instrumentation and is normally done only by the engine developer, and the second example represents a very common test procedure of universal interest employing standard instrumentation. The tests selected are:

1. Compressor Pressure Ratio and Air Flow at Surge - Engine developer test for surge margin assessment.

2. Accel Time from Idle to 100% Rated Engine Thrust - Typical final acceptance test after engine overhaul.

5.2 MEASUREMENT OF COMPRESSOR PRESSURE RATIO AND AIR FLOW AT SURGE

5.2.1 Description of Test

5.2.1.1 *Test Objective and Method*

The test objective in this example case is to determine the pressure ratio and airflow at the time of surge in a sea level test with a clean, undistorted inlet flow in a large medium bypass military engine.

Pressure ratio is a derived parameter which is calculated from the measurement of compressor discharge pressure (P3), and compressor inlet pressure (P25). Air flow is inferred via a compressor analytical model which, for any input pressure ratio (P3/P25), uses compressor inlet temperature (T25) and rotor speed (N_H) to calculate air flow. The time of surge is defined either as the time P3 peaks or the time that a rapid rise is observed in P25, whichever occurs first.

Figure 2-2 in Section 2 shows a map of compressor operating characteristics in which pressure ratio vs. corrected air flow is plotted. Both the design steady-state operating line of the compressor and the "steady-state" surge line are shown. The nominal "steady-state" surge line represents the locus of points at which the compressor would be expected to surge if its operating point moved from a steady-state design point to the point of surge under quasi-steady conditions. When testing a compressor as a separate component this quasi-steady state change is accomplished by throttling, and the surge line is determined using a series of steady-state data acquisitions along a constant speed line until the surge event occurs. When the compressor is installed in an engine it is not always possible to induce a surge in this way and other expedients must be used. One common approach is to use a fuel spike.

The fuel spike technique requires the use of special equipment to rapidly inject excess fuel through the combustor nozzles. This causes the pressure to rise rapidly at the compressor discharge, at approximately constant rotor speed, until surge occurs. Since under normal conditions most engines will not surge by rapid throttle movements alone, the alternative technique frequently requires that the engine fuel control be temporarily adjusted to modified acceleration and bleed schedules with higher rate limits on fuel flow, temperature rise and rotor speed. Alternatively an auxiliary system which bypasses the main fuel control can be used to inject the excess fuel. In addition the compressor operating line can be raised by in-bleeding high pressure air.

Figure 2-2 also depicts transient operating lines for acceleration and deceleration using normal throttle settings. Figure 2-9 illustrates surge lines which are lowered due to steady-state effects such as Reynolds number changes, blade tip erosion, and also surge line degradation which occurs during transients due to rapid changes in temperature, clearance and the like. The transient operating line is the trajectory on the compressor performance map during an acceleration or deceleration transient and the transient surge line is the locus of points at which the compressor would be

[1] Tables and Figures for Section 5 begin on page 5-14

expected to surge with the engine operating in the transient condition.

5.2.1.2 *Specific Parameters to be Measured.*

For a typical surge margin test in a two spool turbofan engine, the required psrameters to be measured are shown in Table 2-4. For this specific example, using a fuel spike, the additional parameters to be measured are shown in Table 5-1.

The uncertainty of these transient parameters is described in the sections of this document indicated in the table and this information will be used to estimate the total uncertainty. The remaining parameters are needed to establish the initial steady-state operating point, and their time dependence during the transient is not critical.

5.2.1.3 *Test Technique - Fuel Spike from Steady State*

This test is normally carried out beginning with the engine stabilized at a preselected design operating point. Steady-state data are acquired for all the parameters listed in Table 2-3 and for the additional parameters in Table 5-1 which are unique to the specific transient test.

At the same steady-state condition, the calibration of all pressure transducers to be used in both the steady state and transient data acquisition should be checked. The "steady-state" transducers are generally mounted some distance from the engine through tubes that can be 30 m long or more and they are consequently slow in response and not adequate for transient measurements with bandwidth requirements of greater than about 1 Hz. The pressure transducers used for the transient data acquisition are close coupled where "close", as explained in Section 4.2, means the connecting tubing is short enough so that the transient response of the tubing does not produce excessive uncertainty in the measurement. Since the remotely mounted steady-state transducers are normally in a well controlled environment, and since they can be calibrated in situ against absolute standards, they are used as references to check and adjust the calibration of the transient transducers during steady-state data acquisition which precedes the transient. They are rechecked after the transient.

After the steady-state point is recorded, and the data are reviewed to ensure that the engine is at the selected condition, a controlled fuel spike is introduced. The trajectory on the compressor map is approximately along a constant speed line toward the surge point. This is depicted in Figure 5.2-1 which shows the specific test that will be reviewed in this example.

The transient measurements required to define the surge point on the compressor map are: P3, P25, T25, N_H, and W_A. The corrected air flow W_A is inferred from these measurements as described in Section 4.4. In addition, the transient fuel flow must be measured to insure that the specified flow rate spike was achieved. This is essential in order to achieve reproducible results, however high absolute accuracy is not required since only repeatability of the fuel flow is needed for repeat tests. Figure 5.2-2 shows an example of the fuel flow during the fuel spike. The system is designed to inject the full increment of fuel in less than about 80 milliseconds, with the first half introduced in about 30 milliseconds.

The transient excursions that are anticipated in PS31, P25, T25, W_f and N_H are shown in Figures 5.2-2 to 5.2-6. The time of surge is defined by the time at which the combustor pressure PS31 peaks and starts to decrease since this occurs slightly before the rapid rise in P25. The HPC pressure ratio at that time is (P3peak/P25), where P25 refers to the pressure at the time at which the peak in P3 occurs and just before the rapid rise in P25. The corrected airflow will be determined for this same instant in time.

5.2.2 Measurement Requirements

5.2.2.1 *Number, location and orientation of measurements*

The details of each primary measurement system needed in this example are covered in Section 4. The locations of the stations for these measurements are shown in Figure 2-3.

The probe location for station 31 is a single static tap in the combustor case. Since the Mach No. at this location is very low, this measurement is very close to the total pressure at the HPC discharge. The correlation with P3 steady-state data is described in Section 4.2.6.

Since both the station 25 probe and the combustor pressure tap described in 4.2.6 are used for transient measurements, they must be "close coupled" to their transducers, i.e. the line lengths and sizes have been selected so as to achieve the desired accuracy given the expected time behavior of the input signal.

5.2.2.2 *Relationship to Station Averages*

Since the transient pressure probes sample the flow at a limited number of points, the relationship between the points they measure and the station averages must be determined. This is usually done, as explained in Section 4.2, by steady-state comparisons between the transient probes and the steady-state probe arrays that are used for performance calibration of the engine.

5.2.2.3 *Range of Measurements*

The measurement systems required for transient testing must be capable of covering the complete range of the measured parameters needed to satisfy the test objectives. In surge margin testing it is not always desirable to use the same instruments over the whole range of the compressor operating conditions because, for example, a transducer which is designed for the high pressure regime will be operating near the low end of its range at idle conditions and therefore may not satisfy the accuracy requirements for this condition. In some cases separate instruments may have to be provided for the low and high ranges of the measurements. One means for overcoming this problem is discussed in Section 4.2 on pressure measurements. In the technique described there, the transient measurements are all differential pressure measurements referenced to the initial steady-state condition and therefore only the transient overpressure is measured by these systems. The typical ranges required for these parameters in a sea level test stand for a large, medium bypass military engine are shown in Table 5-2. The magnitude of the expected overpressure is approximately the difference between the operating line pressure and the pressure at surge.

5.2.2.4 *Uncertainty Requirements*

In this example the target for total uncertainty will be based on the recommendations in Aerospace Recommended Practice 1420, Reference 5.2. For stability measurements of the type covered in this example, ARP 1420 calls for measurement of steady-state absolute pressures with an error not to exceed ±0.5% and unsteady pressures with an error not to exceed ±2.0%, both defined as two standard deviations, and the unsteady pressure is to include information up to "the highest frequencies of interest". The next section discusses the problem of determining frequency response requirements.

Since the uncertainty of P3 and P25 will combine as the root-sum-square, 2% uncertainty in each is equivalent to a 2.8% uncertainty in pressure ratio. The objective for total uncertainty in pressure ratio for this test was therefore set at 3%. The uncertainty objective for air flow was set at 4%.

5.2.2.5 *Frequency Response Requirements*

A major potential source of error in transient testing is the uncertainty caused by the time response limitations of the measurement systems themselves. One objective in planning most transient tests is to avoid, if possible, the necessity of applying corrections for known bias of the measurement systems. This means that the magnitude of the transient corrections must be estimated and that the systems must be designed such that the corrections are small and therefore can be incorporated in the total estimated uncertainty. The range and time scale of the measurands has been defined for the example case in the above table and in Figures 5.2-2 to 5.2-6. We can now investigate what the frequency response of the measurement systems will have to be to satisfy the above objectives. To do this we will use P3 as the principal example since this parameter varies most rapidly and its accurate measurement is critical to the objective of the test. Fuel flow also changes very rapidly but its measurement is not part of the defined test objective and is used only to insure repeatablity of the fuel injection system.

The expected behavior of P3 (PS31) is shown in Figure 5.2-3. Prior to the test we do not know what the precise time behavior of the signal will be, but from prior testing we know that it will be similar to that shown in Figure 5.2-3 and lie somewhere between two extreme approximate forms, the sawtooth pulse and the terminated sinusoid shown in Figures 5.2-7 and 5.2-8. Analytical solutions to the response of first and second order measurement systems can be obtained using methods such as those described in Reference 5.3. These methods allow the magnitude of the transient bias corrections to be estimated for systems that can be approximated as linear systems. Figures 5.2-7 and 5.2-8 also show examples of the response of first order linear systems to the sawtooth and the terminated sinusoid.

The transient response of the measurement system shown in Figure 5.2-9 is dominated by two of the system components. First, the pneumatic tubing which connects the static tap in the combustor to the transducer which measures the transient overpressure and, second, the low pass filter in the signal conditioning or data acquisition system.

The tubing to the transducer is made as short as possible consistent with the available space and the need to maintain the transducer in a very stable thermal environment. Its transient response can be approximated as a second order lightly damped system (Section 4.2) and is therefore describable by a resonant frequency f_R

and a damping constant ξ which is small (see Section 4.2.6 for this example).

In order to minimize noise in the signal, the low pass filter cut-off frequency is set to as low a value as possible consistent with passing the "highest frequency of interest" in the signal, assuming that the highest frequency is known. Since in this example no specific frequency of interest can be defined a priori, an alternative strategy can be used. Once a sharp discontinuity at the peak amplitude is assumed, as with the sawtooth and the terminated sinusoid, a very broad frequency spectrum in the signal would be expected. We then ask what frequency limit is necessary in describing the pulse in order for the peak amplitude to be reproduced with less than the prescribed uncertainty defined in the uncertainty requirements for the test.

First consider how much error is allowed. The peak pressure (P3)p is the adjusted sum of two measurements, the initial pressure, $(P3)_o$, and the adjusted peak overpressure, from (ΔPS31)p.

$$(P3)_p = (P3)_o + C_{\Delta p}(\Delta PS31)_p \qquad 5\text{-}1$$

where $C_{\Delta p}$ is the correction of the pressure rise observed at station 31 to station 3, based on the correlation of steady state measurements at those locations as described in Section 4.2.6 (see Figure 4.2-33).

Since the required relative uncertainty in $(P3)_p$ is 2% (at 95% confidence), and there will be uncertainty in both the $(P3)_o$ and the $(\Delta PS31)_p$ measurements as well as in the estimated correction $C_{\Delta p}$, we will assume that the total allowed uncertainty in $(P3)_p$ is distributed among these three terms. From Figure 4.2-33 we see that the precision error due to the correction factor is approximately 0.25%. If we assume that the allowable contribution to the uncertainty in $(P3)_p$ from the $(\Delta PS31)_p$ measurement is 1%, this leaves an additional 0.75% error as the allowable contribution from the measurement of $(PS31)_o$. Expressing the allowed error as a percentage of $(\Delta PS31)_p$ this yields:

Total Uncertainty in $(\Delta PS31)_p$ = about 4.5% of rdg.

Setting the Data System Filter Characteristics and Sampling Time

The method for determining the filter characteristics and sampling rate required by the data system when applied to this example case can be summarized as follows (see References 5.4 and 5.5 for further discussion of this subject.):

1. Determine the "highest frequency of interest" in the measurand using the estimated waveform of the pressure pulse and calculate the upper frequency limit in the Fourier representation of the signal which will reproduce the peak amplitude to within the allowed uncertainty limit specified for the measurement process. The total uncertainty allowed in $(\Delta PS31)_p$, as discussed above, is found to be about 4.5%.
2. Select a filter with flat response up to the "highest frequency of interest" in the measurand. Decide on the filter type and roll-off rate based on the anticipated noise spectrum in the signal by requiring that the additional uncertainty due to noise passing the filter be tolerably small compared to the total required uncertainty in peak pressure. The noise present will include broadband electrical, mechanical and aerodynamic noise plus noise at discrete frequencies from the power line, the rotors and the resonant pressure sampling tube.
3. Set the sampling frequency of the digital data acquisition system based on one or both of the following criteria:

a) The requirement that high frequency noise passing through the filter produce negligible distortion in the filter pass band due to aliasing.

b) The requirement that the sampling rate yield sufficient samples in the vicinity of the peak amplitude to allow the peak to be determined to within the specified uncertainty limit.

The frequency content of the sawtooth and the terminated sinusoid which approximate ΔPS31(t) are shown in Figures 5.2-10 and 5.2-11. It is difficult to tell from the spectra alone what maximum frequency of interest should be selected. To display this more clearly, the error in the peak of the sawtooth and the terminated sinusoid is shown in Figures 5.2-12 and 5.2-13 as a function of the upper frequency limit which is used in its Fourier representation. The sawtooth wave form can be seen to be much more demanding than the terminated sinusoid in terms of its frequency content. For this waveform, if the peak distortion is required to be no greater than 4.5% , then frequencies of at least 14 times the fundamental must be passed by the measurement system with little attenuation. Since the 50 msec rise time is one quarter wave of the approximate wave form, the fundamental frequency is 5 Hz. The nominal filter cut off frequency should therefore be equal to or greater than 14 times 5, or approximately 70 Hz. Since the true transient signal is likely to be between a sawtooth and a truncated sinusoid, error estimations based on a sawtooth form will represent an upper limit on the uncertainty in peak amplitude arising from the filter. The nominal upper limit of the "frequency of interest" of the measurand will therefore be set at 70 Hz and the filter characteristics selected by examining how various types of filters would perform with this measurand. The filter is chosen to remove as much noise as possible and still produce negligible distortion of the frequencies of interest. We first look at how the filter affects the noise free signal, and then estimate its response to noise.

The responses of the several filters described in Section 4.9.4 to the noise-free sawtooth pressure pulse are shown in Figures 4.9-16 to 18. The attenuation of the peak in each case is given in Table 5-3.

The 50Hz Chebyshev (1 dB) filter and all the filters with cut off frequencies above 70 Hz meet the criterion that peak attenuation is less than 4.5%. We select a 4 pole Bessel filter for this example because it satisfies our uncertainty requirement and will produce less distortion of the overall wave form of the pressure pulse. We next need to estimate the amount of noise which passes through this filter.

From prior tests of similar type in which some very fast response pressure measurements were made, an estimate of the amount of noise to be expected in this test can be made. The power spectrum of the expected noise is shown in Figure 5.2-14. The spectrum shown with the engine shutdown is the electrical noise which can be seen to approximate white noise with higher amplitude spikes at 60 Hz and its harmonics. This noise is due to internally generated noise in electrical components, cross talk and common mode voltage and, as shown in the figure, is one to two orders of magnitude below the noise present when the engine is running. The broadband mechanical and aerodynamic and the discrete rotor-related noise, which is present when the engine is running and passes through the filter, is the principal contributor to the transient random error in the measurement.

We can calculate the rms amplitude of the noise, $NOISE_{RMS}$, which is transmitted by the filter, using the following expression (see Reference 5.6):

$$(NOISE_{RMS})^2 = \int G(f)\,|H(f)|^2 df \qquad 5\text{-}2$$

where $G(f)$ = Power Spectral Density of Noise with engine running - (pressure)^2/Hz
$H(f)$ = Sinusoidal Frequency Response Transfer Function of the filter.

Carrying out this calculation for a 4 pole Bessel filter yields:
RMS noise transmitted by the filter = 1.38 kPa (0.20 psi)
We can equate this with the transient precision index, s_{N1}, arising from the noise transmitted by the filter and set,

$$s_{N1} = \pm\ 1.38 \text{ kPa } (0.20 \text{ psi})$$

or, in terms of % of peak amplitude of ΔPS31,

$$s_{N1}\ \% = (\pm 1.38/365) \times 100 = \pm\ 0.38\ \%$$

The next data system characteristic that must be selected is the sampling frequency, f_S. As the calculation above shows, a significant amount of noise is transmitted by the filter and this includes noise above the nominal cut-off frequency of the filter. How much noise is above the cut-off depends on the filter roll-off characteristics. One method (criterion "a" above) for setting the sampling frequency is to specify a limit on how much distortion can be tolerated in the filter pass band due to aliasing. If we require that the additional distortion due to noise above the filter pass band be 0.1% (60 db) or less, then the sampling frequency can be calculated as follows (Reference 5.4):

$$f_N^* = 1/2(f_C + f_C^*)$$

where f_N^* = the folding frequency
f_C = the filter cut-off frequency
f_C^* = frequency at which the filter attenuation is 60 db

The sampling rate, f_S, must be twice the folding frequency:

$$f_S = 2f_N^* = (f_C + f_C^*)$$

From Figure 4.9-13 we see that, for the 4 pole Bessel filter:

$$f_C^*/f_C = 8.5$$

Since f_C = 100 Hz

$$f_S = (100 + 850) = 950 \text{ Hz}$$

and we can conclude that the sampling rate must be equal to or greater than 950 Hz in order to eliminate the additional uncertainty that could be caused by aliasing.

The above criterion for selecting a sampling frequency is most appropriate for frequency domain analysis of a signal, however other considerations imply that a high sampling rate is required in a time domain analysis as well (criterion "b" above). First, since the noise free signal is rising at a rate of about 0.4% per msec near the peak, a sampling interval of 1 msec could produce as much as 0.2% error in capturing the peak.

Second, since there is a residual rms noise level of 1.38 kPa (0.20 psi) in the signal (i.e. s_{N1} = 1.38 kPa (0.20 psi)), a number of samples are needed in the neighborhood of the peak in order to permit reducing the uncertainty of the peak amplitude due to noise by smoothing of the output signal near the peak. From Figure 4.9-18 the duration of time in which the output signal is within 13.8 kPa (2 psi) (i.e. ~ 4%) of the peak is about 4 msec. Several samples need to be recorded during that time in order to allow a curve fit in the neighborhood of the peak and a post-test estimate of the error of the curve fit. (See Section 3.2.3)

On the basis of the above arguments we select a sampling rate f_S = 1 kHz.

In summary, we select a 4 pole Bessel filter with nominal cut-off frequency of 100 Hz and use a sampling rate of 1 KHz. This filter satisfies the peak attenuation, noise rejection and anti-aliasing requirements and will be used on all transient channels so that the time delay in all channels will be essentially identical (see also Figure 4.9-25).

The uncertainties arising from these choices are then:

Bias due to filter attenuation of the peak:

b_a = 0 to -3.8% in $\Delta P31_P$

Precision index due to noise passing through the filter:

$s_{N1} = \pm 0.38$ %

Precision error due to aliasing of high frequency noise:

$s_{na} = \leq \pm 0.1$%

5.2.2.6 *Time Correlation and Sampling Rate*

Since in the fuel spike method the several primary measurands used to derive compressor pressure ratio and airflow vary rapidly in time, the measurement systems must be designed to allow correlation of the measured parameters in time and the sampling of the signal must be fast enough so that the change in amplitude between samples is small and consistent with the uncertainty objectives. In the last section we examined the effects of the time responses of the measurement systems.

The data system recommended for use for transient measurements (Section 4.9.7) samples all the transient channels simultaneously at a rate of 1 kHz. Since all these channels use low pass filters with the same specifications, the filter time delays are equal in all channels and no time skew errors are caused by the data system. We can now briefly review whether the sampling rate would be adequate to satisfy our requirement to correlate the measurements at the time of the surge event.

The correlation must be based on careful analysis of the requirements of the user of the data to insure that the measurements are compatible with his analytical needs. The basic issues are as follows:

The objective of the test is to determine the compressor's maximum sustainable pressure ratio prior to surge. This aerodynamic stability limit is defined for quasi steady operating conditions but, in the fuel spike type of test, conditions are changing rapidly with time. In this example the transient quantities of primary interest are the measurement of HPC discharge pressure P3 and the measurement of HPC inlet total pressure P25. The questions are: At what instant in time did the surge event occur, and at what points in time should the values of P3 and P25 be taken for computing the pressure ratio at surge?

Using the planar wave description in References 5.7 and 5.8, the surge event generally begins at one stage in a multi stage compressor, and the pressure disturbance propagates upstream and downstream at the speed of sound plus or minus the convection velocity of the air flow (see Figure 5.2-15). Depending on which stage stalls first, the disturbance can arrive at either station 25 or 3 first, although, since the downstream propagation velocity is roughly 460 m/sec (1500 ft/sec) while the upstream is 150 m/sec (500 ft/sec), station 3 or P3 is more likely to see the event first. For a compressor that is roughly 1 m (3 feet) long, the delay times are as shown in Figure 5.2-16. The maximum delay time is 1.5 msec.

The pressure at P3 would be expected to continue to rise for a short time depending on which stage stalls, since excess fuel continues to be injected into the combustor. The magnitude of this error for the P3 measurement can be estimated from the rate of pressure rise anticipated near the peak as shown in Figure 5.2-3 and the time delay as follows:

Time Delay Error = $1/P_3$ x dP_3/dt x td

= 0.4%/msec x 1.5 msec

= 0.6%

At the upstream location, station 25, the delay would be also be no greater than 1.5 msec and, since the pressure rise at this location is not being driven directly by the fuel spike, the rate of pressure rise prior to the arrival of the surge disturbance is much slower than the rate of rise of P3 and, consequently, the time delay error is negligible.

It can be concluded, therefore, that the errors due to time delay effects might be as much as 0.6% in P3 and negligible at P25. Notice also that this bias error in P3 would be positive, that is, the measured pressure would tend to be somewhat higher than the pressure that was present at the time of surge and this is the opposite in sign from the error due to measurement system time lag discussed in the previous section.

Since the data system, employed for this test, samples and holds all channels simultaneously at a rate of 1 kHz, there are negligible time skew errors due to the data system.

In addition to the time delays due to the propagation of the surge in the compressor, there is an additional time delay in the measurement of P3 and P25 which is due to the difference in propagation time of the pressure disturbance in the P3 and P25 probe tubing. The effect of the tubing on the value of these signals was evaluated in Section 4.2.6 above. The effect on the correlation in time could also be significant if there was a large difference in the lengths of these tubes. In this case, using the data in Section 4.2.6, the delay time for P3 is 1.2 msec and for P25 is 0.5 msec. Since the rate of change of P25 is only some 0.03% per msec, this difference in time will not add significantly to the error in pressure ratio at surge.

5.2.3 Analysis of Total Uncertainty

5.2.3.1 *General*

The detailed design, uncertainty model and lists of error sources for each measurement required in this test are covered in the individual sections of this document as indicated in Table 5-1. This section (5.2.3) will summarize and reference those results and use them to develop a total uncertainty estimate for this test case.

For steady-state testing it is feasible to use UADD (99% confidence) for the total uncertainty. For transient testing it is reasonable to accept URSS (for 95% confidence level); this has been done for the calculations of total uncertainty in this chapter.

5.2.3.2 *Compressor Discharge Pressure*

The total pressure at station 3, P3, is not measured directly but is inferred from the measurement of static pressure, PS31, in the combustor dome. A simplified block diagram of the system is shown in Figure 5.2-9 which emphasizes the components which dominate the time response. The inference is derived from steady-state testing as explained in Section 4.2.6. In this example the predicted values at point A in Figures 5.2-1 and 5.2-3 are P3 = 1277 kPa (185 psia) and PS31 = 1190 kPa (172 psia). The initial steady-state value of PS31 is measured by the steady-state instrumentation. Prior to the initiation of the transient, the transient measurement system is initialized (zeroed) by correlation with the steady-state reading. The transient system measures only the transient overpressure and the transducer is selected to accommodate the maximum predicted overpressure. This improves the accuracy of the measurement considerably over that which would be possible with a transient transducer that had to accommodate the total pressure.

The pressure measurement required by the defined test objective is the peak total pressure at the high pressure compressor discharge, which, as shown in Equation 5-1, consists of the measurement of the initial pressure at station 3 $(P3)_o$, the overpressure at 31 $(\Delta PS31)_p$ and the application of the correction factor $C_{\Delta p}$. The uncertainty of the P3 measurement is summarized in Table 5-4 using data from Section 4.2.6, Section 4.9 and Section 5.2.2.

The bias due to the resonance of the underdamped pressure tubing was estimated in Section 4.2.6 to be $\pm 1.5\%$ of $(\Delta PS31)$, which is equivalent to 0.33% of $P3_p$. Since this error would occur at the tube resonant frequency of 205 Hz, it would be significantly attenuated by the 100 Hz filter (-13 dB), giving only about $\pm 0.02\%$ as the uncertainty contribution from this source.

As anticipated, the transient error dominates the uncertainty in this kind of test. To combine this error into total bias, B, total precision, S, and total uncertainty, U, we will use the approach suggested by Abernethy, Reference 3.13, for unsymmetric biases. We will also assume that the amount of data used to estimate the S's is 30 or greater so that the Student t factor, t_{95}, can be set equal to 2 and combine the bias and precision by root-sum-square of the error source term, given in Table 5.4.

$$B^+(P3) = +10.1\,\text{kPa}\,(1.46\ \text{psi})$$

$$B^-(P3) = -14.0\ \text{kPa}\,(2.03\ \text{psi})$$

$$S(P3) = \pm 6.0\,\text{kPa}\,(0.87\ \text{psi})$$

$$U^+(P3) = \sqrt{[B^+(P3)]^2 + [2S(P3)]^2}$$

$$= 15.7\,\text{kPa} = 0.94\%$$

$$U^-(P3) = \sqrt{[B^-(P3)]^2 + [2S(P3)]^2}$$

$$= -18.5\,\text{kPa} = -1.11\%$$

5.2.3.3 *Compressor Inlet Pressure*

The compressor inlet transient pressure is measured using a system identical in concept to that used for PS31. The steady state pressure immediately prior to the initiation of the transient is used as the reference for the overpressure measurement and the total pressure is then the sum of the initial pressure $P25_o$ and $\Delta P25(t)$. Since the overpressure at 25 does not change much prior to the surge, the transient term is much smaller than that for P3. The transient biases due to both the tube resonance and the time delay are negligible. However, there is a significant sampling error term which must be estimated from correlations obtained during steady-state testing with probe arrays as shown in Figure 4.2-33. The uncertainty is dominated by the steady state error.

The total uncertainty in P25 is therefore:

$$\pm B(P25) = 0.27\,kPa \qquad S(P25) = 0.54\,kPa$$

$$U(P25) = \pm\sqrt{[B(P25)]^2 + [2S(P25)]^2}$$

$$= \pm 1.12\,kPa = 0.58\,\%$$

5.2.3.4 *Compressor Inlet Temperature*

This measurement is required only to permit calculation of corrected air flow and rotor speed. It contributes to the total uncertainty only through this correction as shown in Section 5.2.4. Because T25 undergoes only a very small change prior to the surge, transient uncertainty is negligible. The estimated uncertainty in T25, obtained from Sections 4.3 and 4.9.7, and summarized in Table 5-6, is as follows:

$$\pm B(T25) = 0.43\,°C \qquad S(T25) = 0.21\,°C$$

$$U(T25) = 0.60\,°C$$

5.2.3.5 *Rotor Speed*

Rotor speed also does not change very much prior to the surge. Its uncertainty contributes to the uncertainty of the inferred air flow immediately prior to the surge. The estimated uncertainty from Section 4.5.2 is:

$$B(N_H) = 12 \text{ rpm} \qquad S(N_H) = \pm 50 \text{ rpm}$$

$$U(N_H) = \pm 100 \text{ rpm}$$

5.2.3.6 *Air Flow*

This measurement is inferred via an air flow model in which, for a given pressure ratio, the air flow is determined from the measurement of N_H and T25 as described in Section 4.4. The change in airflow prior to the surge is not very great and therefore the uncertainty is dominated by the steady-state measurements which occur in the interval immediately prior to the surge. The greatest contribution to uncertainty comes from the uncertainty in the airflow model itself since it involves assumptions, many of which are based on data obtained under steady-state conditions. For this reason a potential bias of 3% has been assumed to account for the uncertainty in the model.

The uncertainty in W_A is estimated as follows (where the partial derivatives are determined from steady-state flow maps):

$$\frac{\partial W_A}{\partial N_H} = 0.006 \text{ kg/sec/rpm}$$

$$\frac{\partial W_A}{\partial T25} = 0.050 \text{ kg/sec/C°}$$

Est. Bias in model, $B(M) = 3\% = 0.523$ kg/sec

$$B(W_A) = \sqrt{\left[\frac{\partial W_A}{\partial N_H}B(N_H)\right]^2 + \left[\frac{\partial W_A}{\partial T25}B(T25)\right]^2 + B(M)^2}$$

$$= 0.527 \text{ kg/sec}$$

$$S(W_A) = \sqrt{\left[\frac{\partial W_A}{\partial N_H}S(N_H)\right]^2 + \left[\frac{\partial W_A}{\partial T25}S(T25)\right]^2}$$

$$= 0.12 \text{ kg/sec}$$

$$U(W_A) = \sqrt{[B(W_A)]^2 + [2S(W_A)]^2}$$

$$= \pm 0.58 \text{ kg/sec} = 3.3\%$$

5.2.3.7 *Fuel Flow*
The fuel flow measurement in this test is done only to assure reproducibility of results. The uncertainty in the fuel flow does not directly affect the uncertainty of the measurement since it was demonstrated in prior testing that, once the excess fuel introduced by the special pulsing equipment vs time was repeatable within several percent, the pressure ratio measured at surge was independent of the exact shape of the fuel pulse.

5.2.3.8 *Pressure Ratio*
The uncertainty of a single measurement of surge pressure ratio, as shown for example as the transient trajectory from point A to point X in Figure 5.2-1, can be found from the information in the sections above which give the uncertainty for each of the primary measurands, P3 and P25, from which P_R is derived. In addition, since the test objective is to plot the derived pressure ratio as a function of the inferred air flow, we have to consider the possible effect on uncertainty if the derived and inferred parameters have any primary measurands in common (see Section 3.2.3). In this case they do not. Pressure ratio is derived from primary measurands P25 and P3. For any given pressure ratio the model through which air flow is inferred requires only the input of the primary parameters of rotor speed, N_H, and compressor inlet temperature, T25. We can therefore use the following expressions for the computation of precision and bias:

$$S(P_R) = \sqrt{\left[\frac{1}{P25}\, S(P3)\right]^2 + \left[\frac{-P3 \times S(P25)}{(P25)^2}\right]^2}$$

$$= 0.040$$

$$B^{+}(P_R) = \sqrt{\left[\frac{1}{P25} B^{+}(P3)\right]^2 + \left[\frac{-P3}{(P25)^2} B(P25)\right]^2}$$

$$B^{+}(P_R) = 0.083 \qquad B^{-}(P_R) = 0.096$$

$$U^{+}(P_R) = 0.115 = 1.3\%$$

$$U^{-}(P_R) = 0.125 = 1.5\%$$

5.2.4 Summary and Conclusions
The above analysis indicates that the measurement of pressure ratio and air flow using the methods described in this report can be carried out with acceptable uncertainty. The uncertainty in P3 (+0.94 to -1.11%) is dominated by transient errors due to the time response characteristics of the filter and the noise transmitted by the filter. It would have been possible to reduce that uncertainty by deconvoluting the signal (see Section 4.9.4); however, as the uncertainty is already acceptable, that was not necessary. The oscillatory error that could potentially arise due to tubing resonance (f_R = 205 Hz) is significantly attenuated by the 100 Hz filter so it makes only a minor contribution to the total uncertainty. The uncertainty in P25 (±0.58%) is primarily due to steady-state error sources arising from the transducer calibration stability.

The uncertainty estimated for the airflow measurement (±3.3%) was based on propagating the uncertainty in rotor speed, N_H, and HPC inlet temperature, T25, through the air flow model. Both N_H and T25 are slowly varying during the time immediately prior to surge and can therefore be measured with relatively small uncertainty. The uncertainty in corrected air flow is therefore dominated by the uncertainty in the airflow model.

5.3 ENGINE ACCELERATION TIME

5.3.1 Description of the Test

The engine acceleration test is a typical engine pass-off test following engine overhaul. It is normally a part of a series of tests for the given engine type as described in Section 2.5.7. In this example, the uncertainty analysis for an acceleration test that applies to a small afterburning or augmented military turbine engine will be described.

The test consists of an initial stabilization of the engine for 5 minutes with the power lever set at ground idle followed by a rapid motion of the power lever to a prescribed high thrust setting. In this example the high thrust setting is 100% and corresponds to military rated thrust. The initial throttle motion is specified to occur in 0.5 seconds or less. The required elapsed time between initiation of the throttle motion and the time at which the nozzle position reaches minimum area is recorded. The test specification requires the nozzle reach a position between 7 and 9% in less than 8 seconds.

The time behavior of several significant parameters, including nozzle position, for this kind of a test are shown in Fig.5.3-1. [Note: There was a known bias of -7% in exhaust nozzle position in the test shown in the figure. All Nozzle Position Indicator (NPI) readings should have 7% added]. These data were obtained in a fully instrumented test bed which allowed thrust and airflow measurements. These measurements may not all be available in a field test and for this reason the maintenance manual for this engine requires the recording of only the more readily available parameter, nozzle position. The nozzle position is a good measure of the engine's transient acceleration capability.

The test can be carried out using strip chart recorders to record the data, or using entirely manual and visual data recording methods. The uncertainty for both approaches will be described.

For the manual method, the test operator is assisted by a person who times, reads and records the data. After stabilization, when the operator announces all is ready, the timer gives the voice command "start". At this time the operator slams the power lever to the 100% setting and at the same time the timer starts the stop watch. The timer observes the nozzle position indicator and stops the watch when the preselected reading is reached. He then records the elapsed time.

5.3.2 Measurement Requirements

In this test a full set of readings are normally required at the end of the 5 minute stabilization time. These are steady state readings and normally consist of the following:

Rotor speed	N
Exhaust Gas Temperature	T5
Fuel Flow	W_F
Inlet Air Temperature	T1 or T2
Turbine Discharge Pressure	P5
Oil Pressure	P_{OIL}
Oil Temperature	T_{OIL}
Fuel Inlet Pressure	P_F
Nozzle Position	NPI

For the transient test, the measurands required to satisfy the test objectives are nozzle position (NPI) and time (t). The nozzle position measurement is described in Section 4.5.3.6. The plots in Figure 5.3-1 show typical results when recorded on a strip chart recorder.

The typical ranges of acceptable uncertainty for both the automated (strip chart) and manual measurements are given in Table 5-7.

5.3.3 Instrument Definitions

Nozzle Position Indicator

The nozzle position indicator is described in some detail in Section 4.5.3.6. The nozzle position is transmitted mechanically via a cable or link rod to a resolver which is calibrated to generate an electrical signal corresponding to nozzle area. (Figure 4.5-24). The static calibration is shown in Figure 4.5-26 and the read-out meter in Figure 4.5-27.

The time response of all components of the nozzle position indicator are rapid compared to the motion of the nozzle components themselves and therfore the mechanical links and resolver do not contribute to the transient uncertainty of the test. If the NPI signal is recorded with a galvanometric oscillograph or one of the digital data acqisition systems now available, the parameters of the recording system should be set up such that the transient errors from the recording system are also negligible. Using the data from Figure 5.3-1 we can estimate the most rapid rate of change to be expected in the NPI signal and then use the results shown in Figure 3-9 of Section 3 to estimate the time resolution required in the recorder in order to achieve the desired uncertainty objectives. The most rapid rate of change is a 75% area change per second during the period just before reaching minimum area. In the example shown in the figure, the minimum area is reached in about 2.3 seconds after which the NPI is approximately constant for about 0.6 seconds at which time further changes occur due to augmentor light off. The input signal therefore behaves approximately like a descending ramp which terminates at constant value which, in this case, is the minimum nozzle area. This simplified model can be used to set the dynamic response requirements of the automated recording system.

The magnitude of the correction for a ramp input to a damped second order system is:

$$C_2 = \frac{2\xi}{\omega}\frac{\partial Q}{\partial t} \qquad 5\text{-}3$$

where C_2 = correction for a damped second order system

$\partial Q/\partial t$ = rate of change of measurand

ω = natural frequency of the 2nd order system (rad/sec) = $2\pi f(Hz)$

ξ = damping constant (dimensionless)

If a galvanometric oscillograph were used for the read out, it would be set up for ideal damping, and the damping constant would therefore be ξ =0.65. The error at the time the ramp reached minimum is equal to C_2 as calculated above. Following that time, the error due to system time response would decrease exponentially with a time constant approximately equal to $1/(\xi\omega)$. If we conservatively require that the maximum error in NPI at the time the ramp terminates be no greater than 0.5%, we can calculate the frequency response requirements by setting C_2 = 0.5% and calculate f.

$$f = \frac{\omega}{2\pi} = \frac{2\xi}{2\pi C_2}\frac{\partial Q}{\partial t} = 30 \text{ Hz}$$

This frequency response is easily achieved with current oscillographs and transient digital recording systems. The uncertainty in time as measured by this method is therefore about 1/f or U(Oscillograph) =.03 sec.

The ability to time events using a manual stop watch has been studied for applications such as timing sporting events. The results of these studies show that, given some training, a timer can achieve a precision of about ± 0.05 sec and that positive and negative biases occur, with a negative bias of approximately 0.10 sec being typical due to what is evidently a strong psychological tendency to anticipate the completion of the event being timed. We can conclude from this that, although manual timing would not be adequate to determine the instant at which a certain NPI occurred during the period of rapid change, it is more than adequate to determine the time at which NPI reached a minimum and that this time could be determined with an uncertainty of

$$U(t)\text{manual} = \sqrt{[B(t)]^2 + [2S(t)]^2} = 0.14\text{sec}$$

An important source of uncertainty in determining the elapsed time, using manual read out, is the readability of the dial indication on the NPI meter. The contribution of the uncertainty in NPI to the total uncertainty in the elapsed time measurement is discussed in the next section.

5.3.4 Analysis of Total Uncertainty

The defined result of this test is the measurement of the time for NPI to reach 9% and the requirement that the minimum reached after this time be between 7 and 9%. In order to estimate the total uncertainty in elapsed time we can use the results of Section 3.2.3 where the case of two functionally related measurands is treated.

The uncertainty of the NPI measurement system is given in Section 4.5.3.6 and is summarized in Table 5-8.

The total uncertainty in the NPI measurement is therefore;

$$U(NPI) = \sqrt{\Sigma B^2 + [2 \times \Sigma S]^2}$$

and U(NPI) using oscillograph = 1.6%

U(NPI) using Visual = 4.5%

These results show that the measurement objective which requires that the minimum area be between 7 and 9% cannot be achieved with the visual system because of the poor readability of the meter. The oscillograph readout is also marginal although feasible.

As discussed in the above, the uncertainty in the measurement of time itself is relatively small for both the automated (oscillograph) and the visual manual method of read out. The uncertainty in the NPI measurement could significantly influence the uncertainty in time however as a consequence of the propagation of error for functionally related measurands. Since the measurands, time and nozzle position have no common measured parameters the total uncertainty in the time measurement can be estimated using the equivalent of Equation 3-6 which for this case is:

$$[U(t)]^2_{Total} = \left[\frac{\partial t}{\partial(NPI)} \times U(NPI)\right]^2 + U(t)^2$$

where:

$[U(t)]_{Total}$	=	Total Uncertainty in Elapsed Time
$\partial t/\partial(NPI)$	=	Slope of time vs NPI curve
U(NPI)	=	Total Uncertainty in NPI
U(t)	=	Uncertainty in the time measurement

Table 5-9 summarizes the magnitudes of the terms needed to calculate total uncertainty in time,t. Using these results, the uncertainty in the measurement of the elapsed time by the two techniques is:

Oscillograph	$[U(t)]_{Total}$	=	0.04 sec
Visual/Manual	$[U(t)]_{Total}$	=	0.14 sec

With either method, the uncertainty in the measurement of elapsed time for the NPI measurement to reach the minimum area is small compared to the specified 8 second limit. In this particular test the time to reach minimum is well within the 8 second limit and the time measurement would present no difficulty.

The requirement that the minimum area NPI reading be between 7 and 9% would be impossible to determine with the manual method however. Not only is the dial readability inadequate for an operator to resolve this limit but the time available for the reading is only 0.6 seconds (see Figure 5.3-1) so while the stop watch could be activated within the estimated uncertainty in time, the value of %NPI read by the operator would be no better than ± 4.5%.

The oscillograph method is a much better choice for the measurement. The uncertainty in time is well within the desired limit. The measurement of %NPI at the minimum is still rather marginal however. The estimated uncertainty at the 95% confidence level is seen above to be ± 1.6% which is extremely close to the 2% tolerance objective for the minimum %NPI measurement. This means that there would be a high probability that the test would appear to fail the 7 to 9% criterion, even when the true value of %NPI was within the limits, due to random error alone. The uncertainty in the %NPI measurement should be reduced to approximately 1/10th of the 2% limit in order reduce the incidence of test failure from random error to acceptable limits. It would therefore be advised that an improved data acquisition system, with digital recording capability, be employed for the measurement since, as shown in Table 5-8, the largest source of uncertainty is the readability of the oscillograph readout.

5.4 REFERENCES

5.1 *Recommended Practices for Measurements of Pressures and Temperatures for Performance Assessment of Aircraft Turbine Engines and Components*, AGARD Advisory report No. 245, June 1990.

5.2 *Gas Turbine Inlet Flow Distortion Guidelines*, SAE Committee S-16, ARP 1420, March 1978.

5.3 Doebelin, E.O., *Measurement Systems: Application and Design*, McGraw-Hill, 1990.

5.4 Taylor, J.L., *Computer-Based Acquisition Systems: Design Techniques*, 2nd Ed., Instrument Society of America, 1990.

5.5 Bendat, J.S. and Piersol, A.G., *Random Data: Analysis and Measurement Procedures*, Wiley-Interscience, 1971.

5.6 Dvorak, S.D., Hosny, W.M., Steenken, W.G., Taylor, J.H., *Dynamic Data Acquisition, Reduction, and Analysis for Identification of High Speed Compressor Component Post-Stability Characteristics*, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, Paper No. AIAA 87-2089, 1987.

5.7 see for example: Gretzmeyer, Alley and Tipton, *Track and Field Athletics*. C.V. Mosby Pub. Co., 1974.

Table 5-1 Specific Parameters to be Measured

Steady-State Parameters	Symbol	# Channels	Range/Units	Output	References
Total Pressure - HPC Inlet	P25	15	100-415 kPa	0-100 mV	5.1
Total Pressure - HPC Exit	P3	15	240-1635 kPa	0-100 mV	5.1
Static Pressure in Combustor	PS31	15	240-1725 kPa	0-100 mV	Section 4.2.6
Transient Parameters	**Symbol**	**# Channels**	**Range/Units**	**Output**	**Sections**
Total Overpressure - HPC Inlet	ΔP25	1	35 kPa	0-100 mV	4.2.6
Static Overpressure - Combustor	ΔPS31	1	350 kPa	0-100 mV	4.2.6
High Rotor Speed*	N_H	1	5-15,000 RPM	4200 cps	4.5
Fuel Flow*	W_F	1	$.02\text{-}2.2 \times 10^{-3}$ m^3/sec	0-2000 Hz	4.4.2
Total Temperature - HPC Inlet*	T25	15	15-175 °C	1-10mV before amp.	4.3

* These parameters may be recorded at a lower rate than pressure during the transient.

Note, as explained in Section 4.2, the transient measurement of P3 is not made directly but is inferred from the combustor static pressure PS31.

Table 5-2 Range of Measurements

Measurand	90% N2	
	Op. Line	Surge
P3 kPa (psia)	1276 (185)	1670 (243)
P25 kPa (psia)	190 (27.5)	194 (28)
PR	6.7	8.6
T25 °C (°F)	82 (180)	~83 (~184)
W_F kg/sec (lb/hr)	0.27 (2100)	1.64 (13000)
N2 (rpm)	11700	~11700

Table 5.3 Peak Attenuation

Filter Type (all 4 pole)	Cut-off Frequency f_C		
	50 Hz	100 Hz	200 Hz
BESSEL	-5.9 %	-3.8 %	-1.9 %
BUTTERWORTH	-5.5 %	-3.5 %	-1.8 %
CHEBYSHEV (1 dB)	-3.8 %	-1.9 %	-1.7 %

Table 5-4 Uncertainty of $P3_p$ ($P3_p = P3_o + C_{\Delta p}(\Delta PS31)_p$)

Error Sources (All % refer to the absolute value of $P3_p$)		$P3_o$		$(\Delta PS31)_p$				
		Steady-State		Steady-State		Transient		
		±B	S	±B	S	+B	-B	S
Pressure System (Section 4.2)	%	.04	.04	.01	.27[1]	.02[2]	.02[2]	.21[3]
	kPa	.66	.66	.17	4.51	.33	.33	3.51
Data System (Section 4.9)	%	.08	.03	.02	.01	.02	-.83[4]	.08[5]
	kPa	1.28	.51	.34	.17	.33	-13.86	1.34
Time Delay (Sect.5.2.2.6)	%					.6[6]		
	kPa					10.0		

Notes on some dominant terms in the error sources

[1] Steady state calibration of ΔP31 transducer. See p. 4-32 and Fig. 4.2-35
[2] Pressure tube resonant response attenuated by 100 Hz filter. See p. 5-7 and Fig. 4.2-35
[3] ΔP31 transducer random error due to temperature drift. Fig. 4.2-35
[4] Uncertainty in attenuation of peak by 100 Hz filter p. 5-6
[5] Noise passing the 100 Hz filter. p. 5-6
[6] Error due to propagation time in the compressor. p. 5-6

Table 5-5 Uncertainty of P25

Error Sources (All % refer to the absolute value of $P25_p$)		$P25_o$		$(\Delta P25)_p$			
		Steady-State		Steady-State		Transient	
		±B	S	±B	S	±B	S
Pressure System (Section 4.2)	%	.051	.045	.01	.26		.09
	kPa	.10	.09	.02	.50		.17
Data System (Sect 4.9)	%	.10	.04	.02	.01	.08	.01
	kPa	.19	.08	.04	.02	.15	.02

Table 5-6 Uncertainty in T25

Error Sources		Steady-State	
		±B	±S
Temperature System	% Reading	0.44	0.20
	Deg. C	0.37	0.17
Data System	% Reading	0.26	0.12
	Deg. C	0.21	0.10

Table 5-7 Recommended Uncertainty Objectives

Total Uncertainty		
Measurand	Automated Recording	Visual Manual
Nozzle Position	±1.0%	±2.5%
Time	±0.05 sec.	±0.20 sec.

Table 5-8 Uncertainty of Nozzle Position (% NPI)

	STEADY-STATE UNCERTAINTY	
Error Sources	Bias (B)	Precision (S)
Mechanical Cal.	0.5	0
Electrical Cal.	0.3	0
Oscillograph Readout	1.0	0.5
Visual Meter Readout	4.0	2.0

Table 5-9 Uncertainty in Elapsed Time Measurement

Type of Readout	∂t/∂(NPI)	U(NPI)	U(t)
Oscillograph	(1/75)(sec./%NPI)	1.6%	0.03 sec.
Visual/Manual	(1/75)(sec./%NPI)	4.5%	0.14 sec.

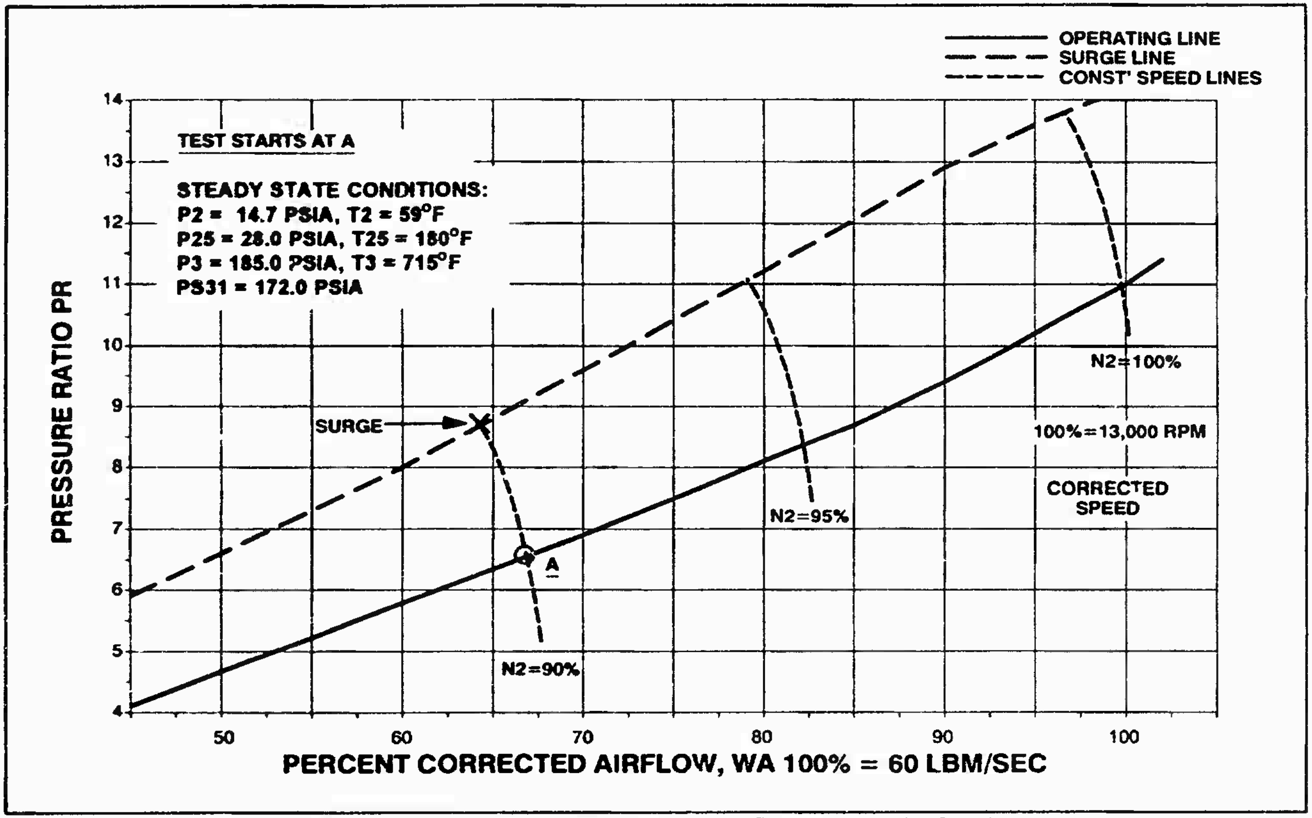


Figure 5.2-1 Performance Map - High Pressure Compressor (Design Intent)

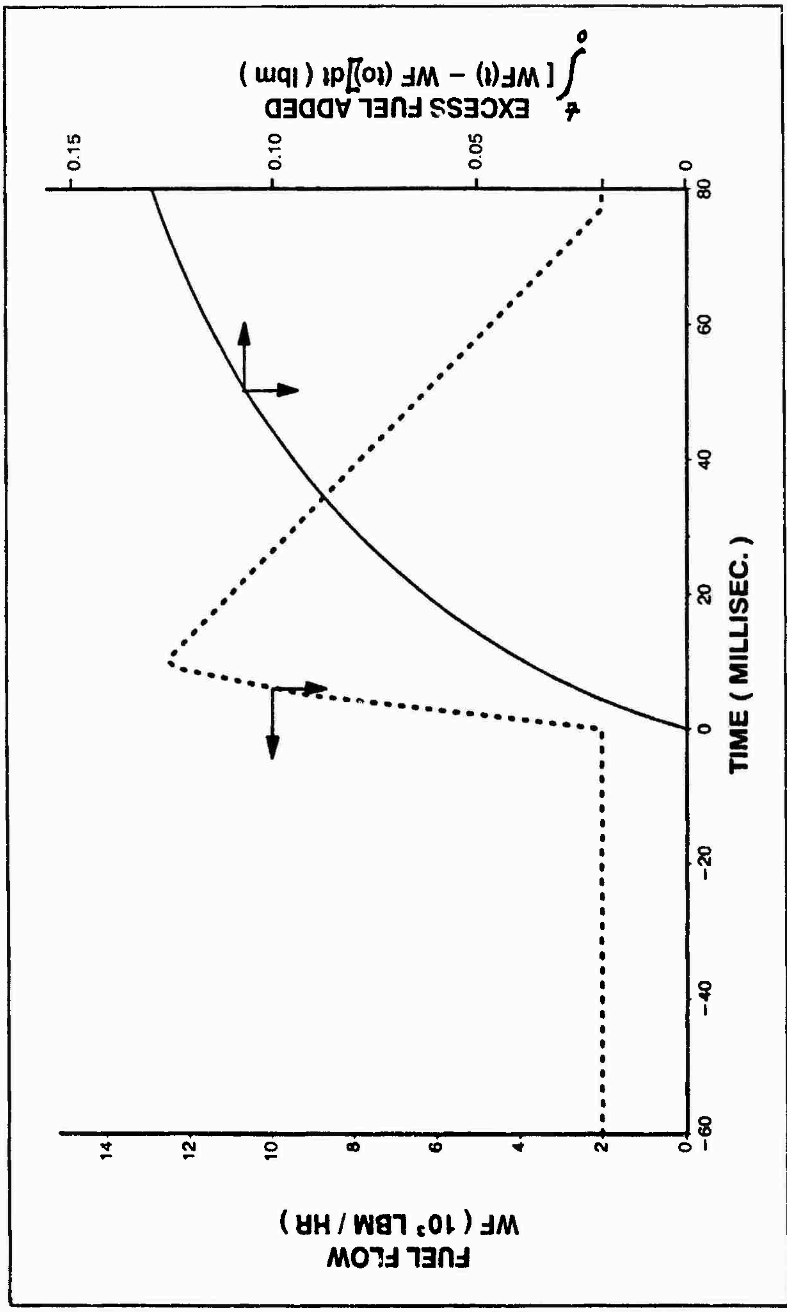


Figure 5.2-2 Fuel Flow and Excess Fuel Added in the Spike

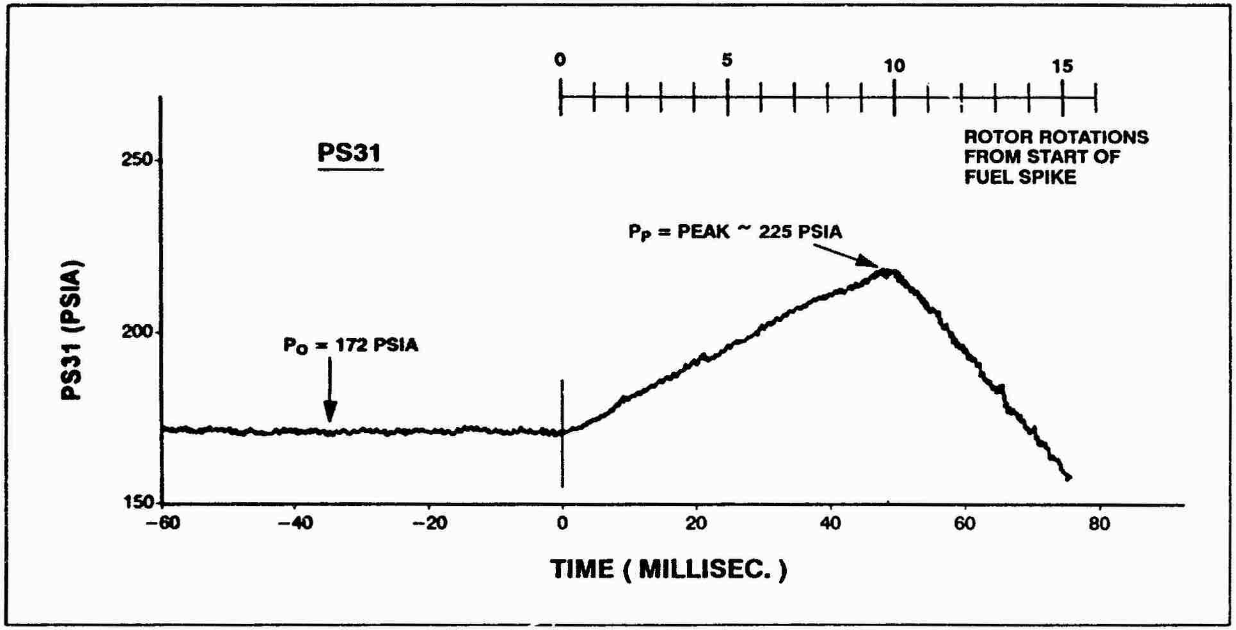


Figure 5.2-3 Combustor Static Pressure

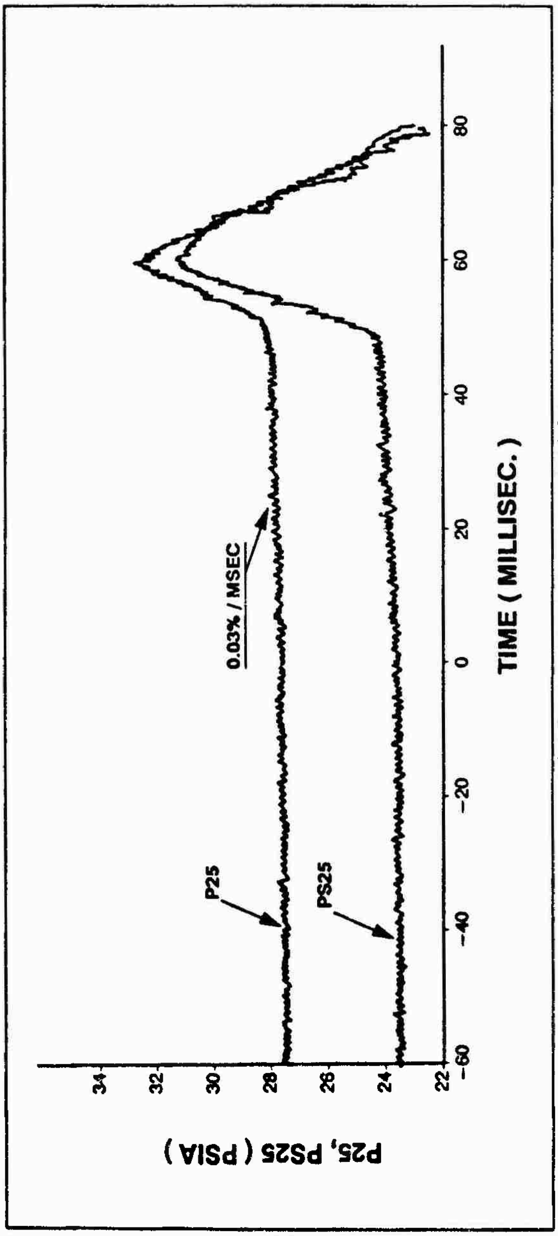


Figure 5.2-4 Total and Static Pressure at HPC Inlet

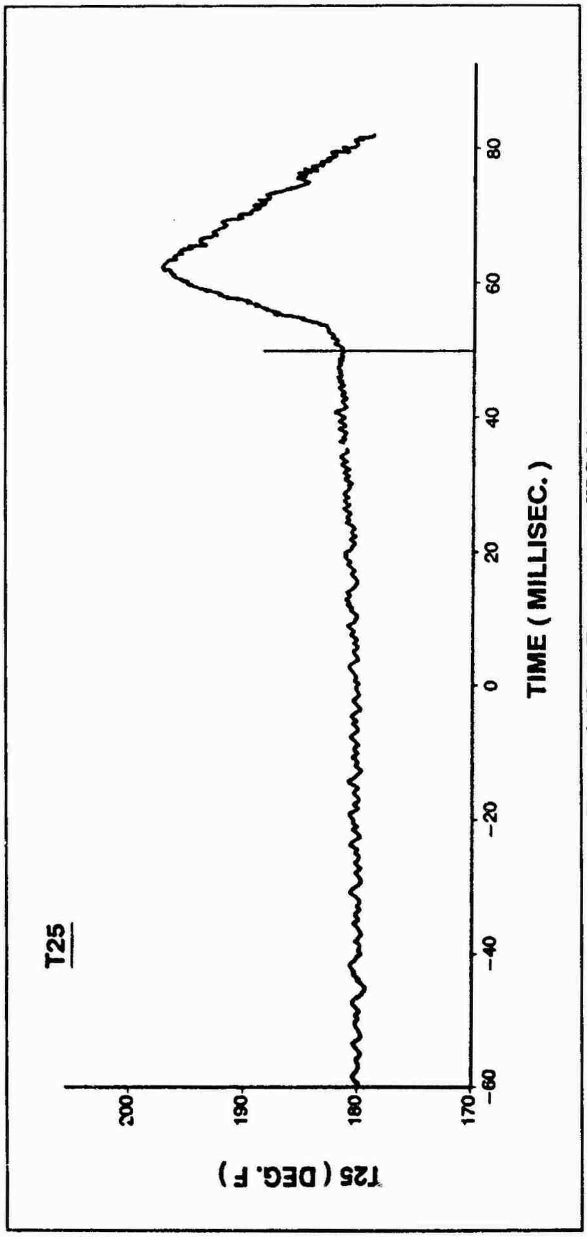


Figure 5.2-5 Total Temperature at HPC Inlet

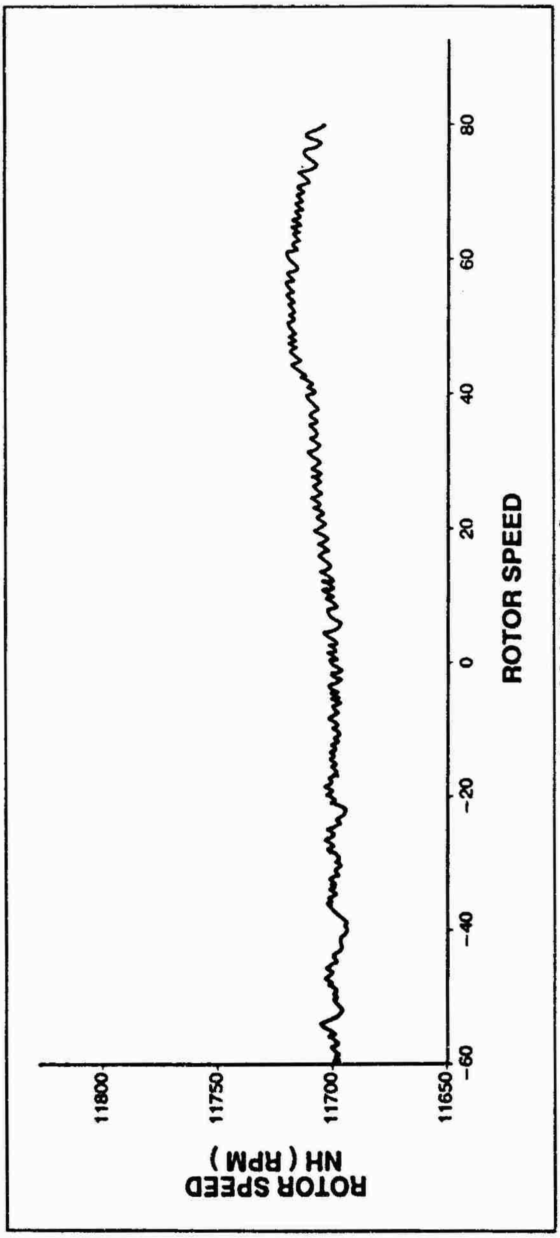


Figure 5.2-6 High Rotor Speed

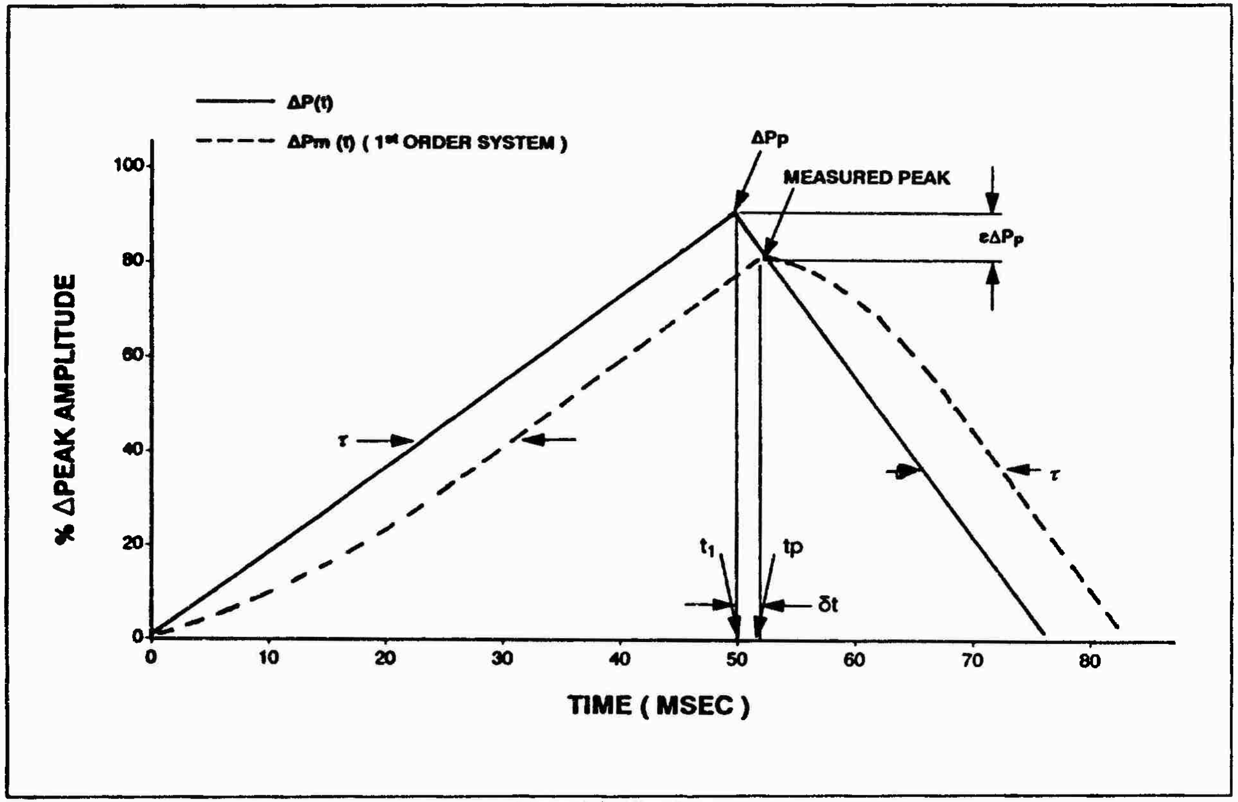


Figure 5.2-7 Saw Tooth

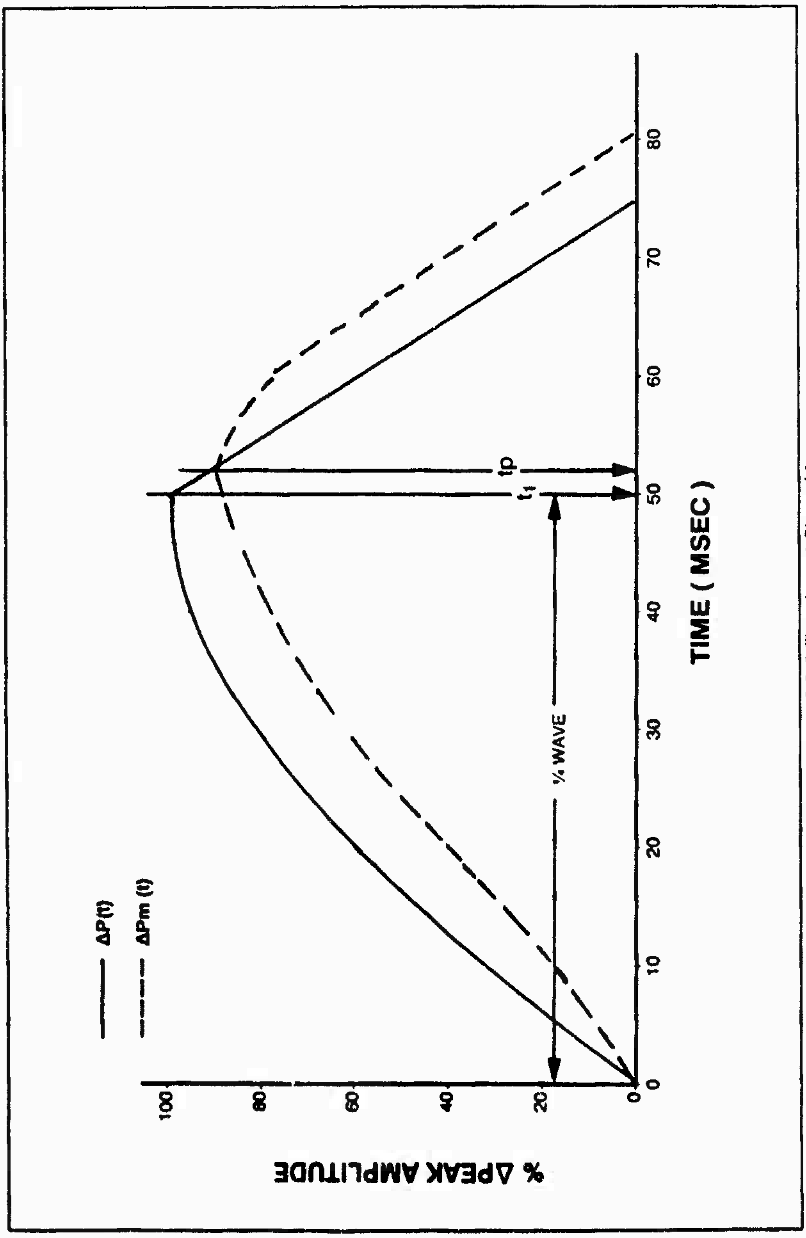


Figure 5.2-8 Terminated Sinusoid

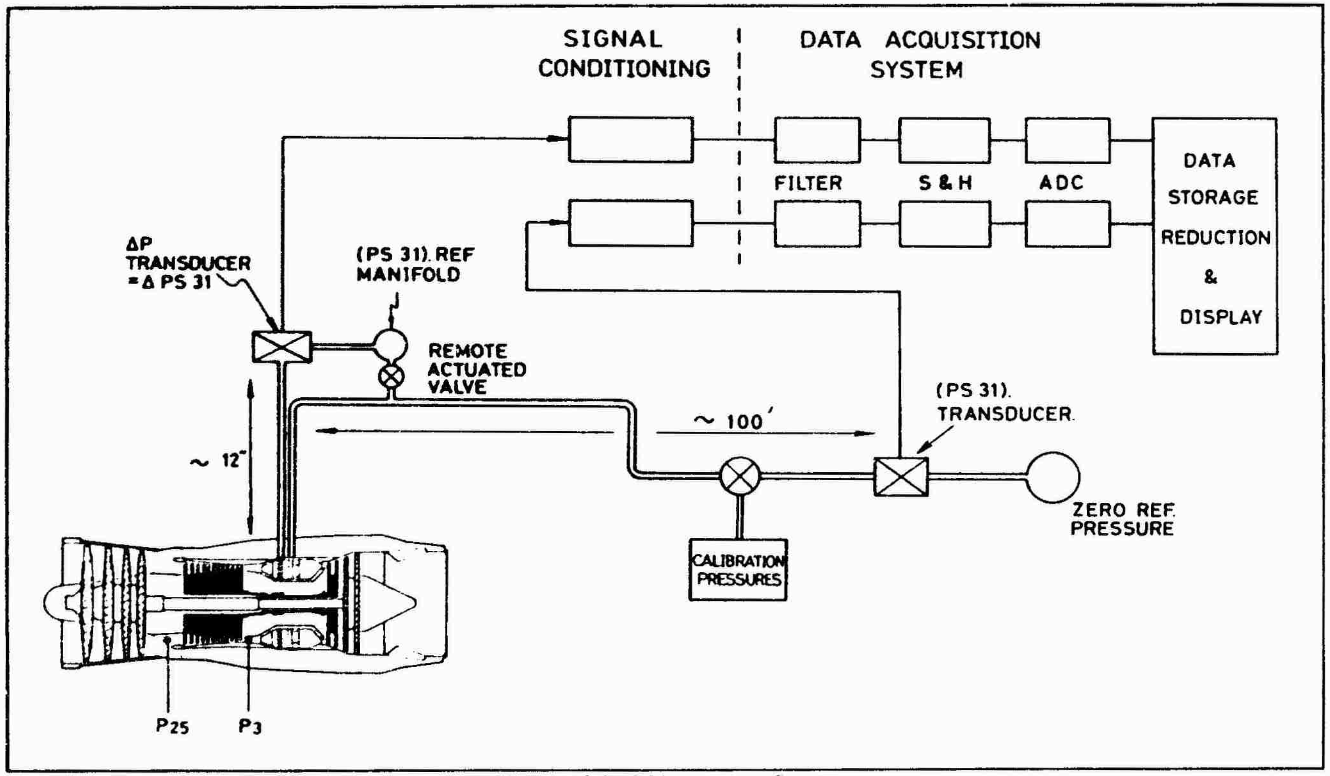


Figure 5.2-9 P3 Measurement System

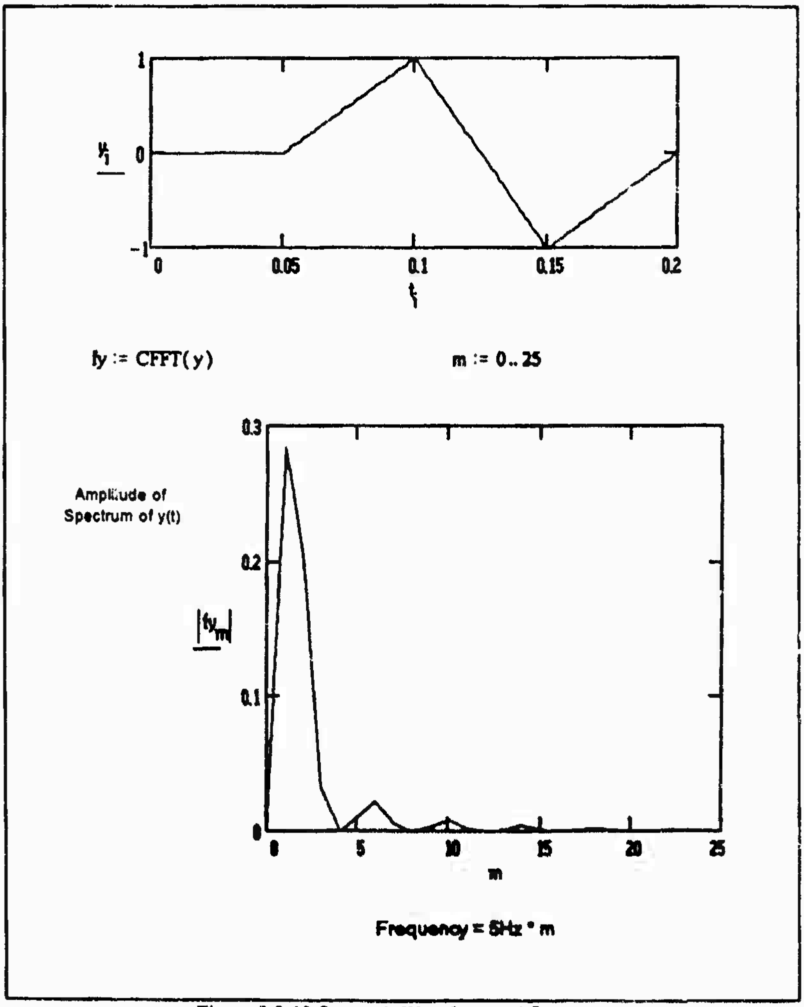


Figure 5.2-10 Sawtooth Waveform and Spectrum

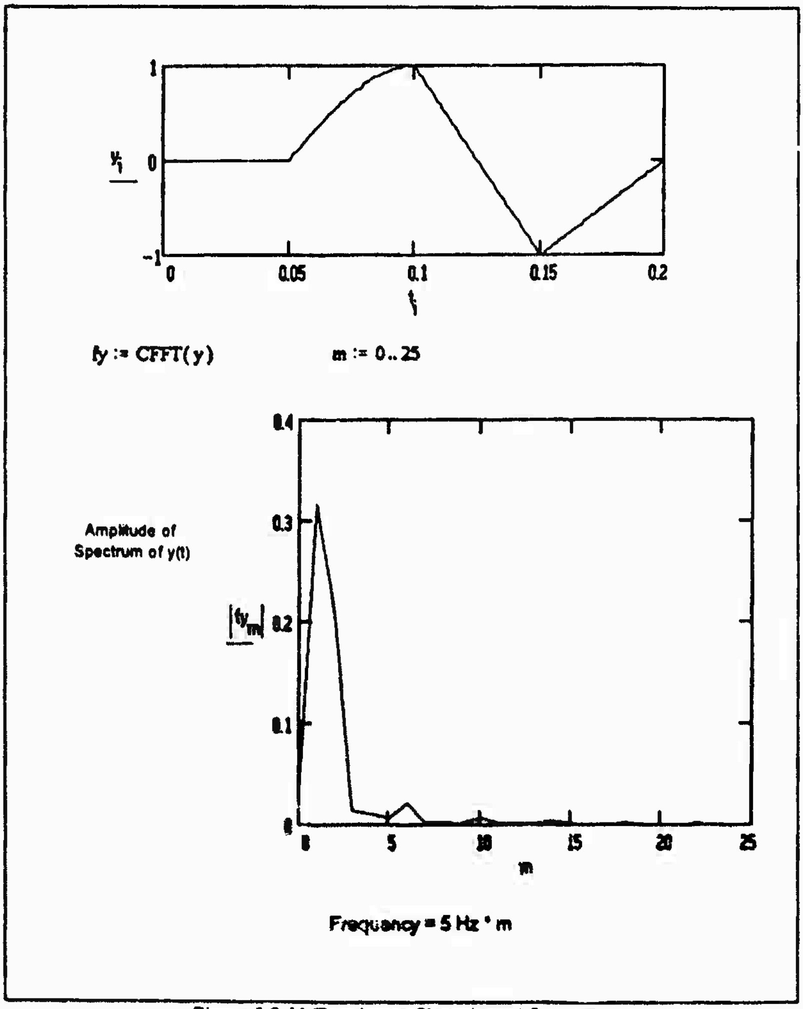


Figure 5.2-11 Terminated Sinusoid and Spectrum

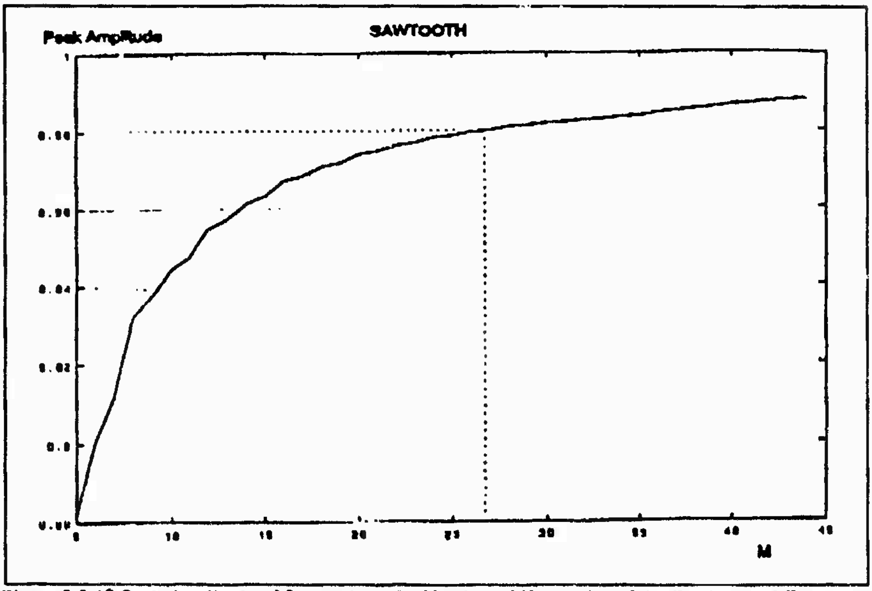


Figure 5.2-12 Peak Amplitude of Sawtooth vs the Number of Harmonics of the Fundamental Frequency

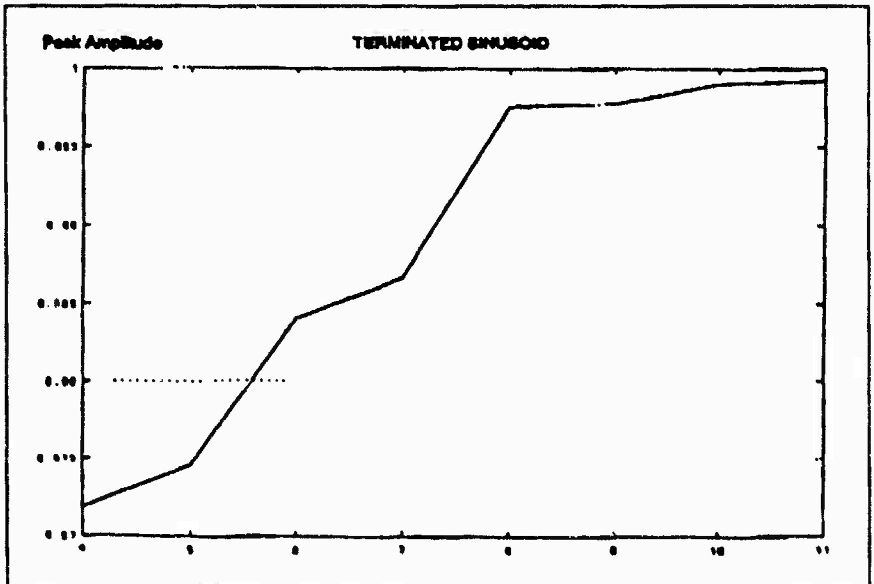


Figure 5.2-13 Peak Amplitude of the Terminated Sinusoid as a Fraction of the Number of Harmonics of the Fundamental Frequency

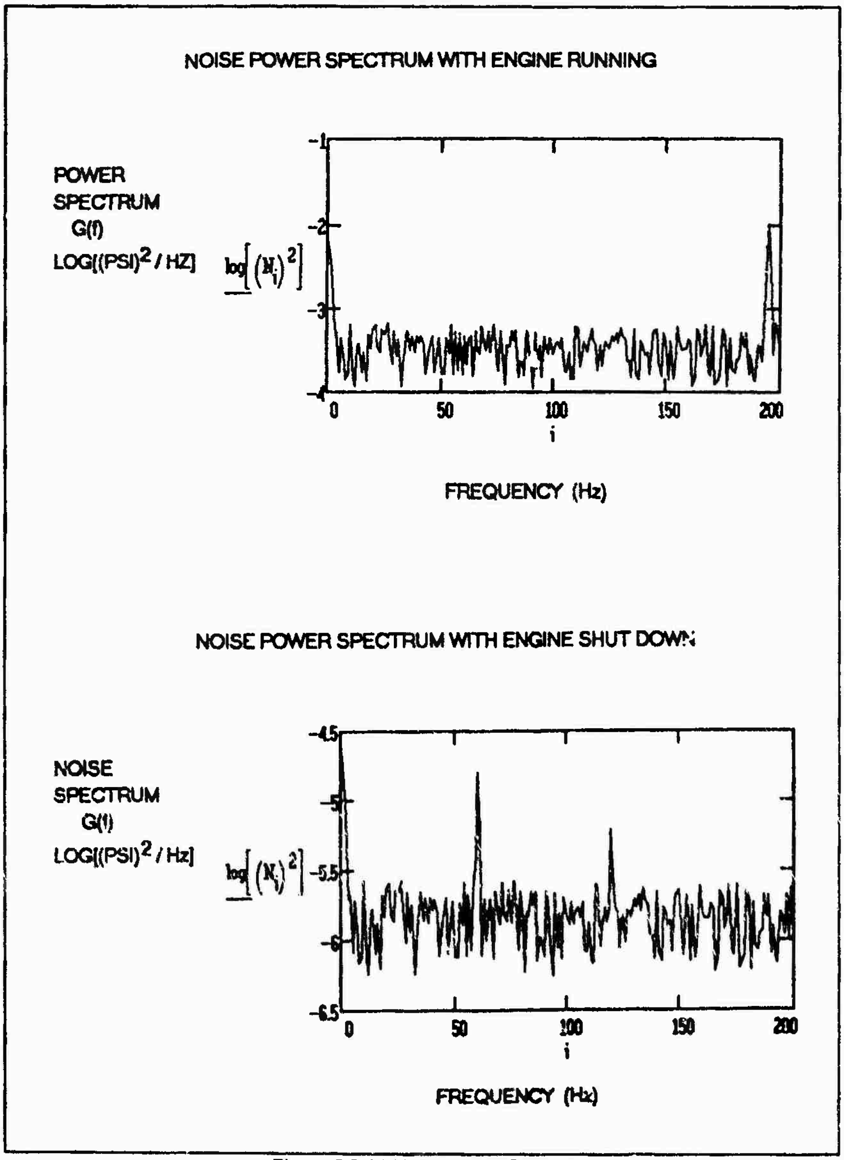


Figure 5.2-14 Noise Power Spectra

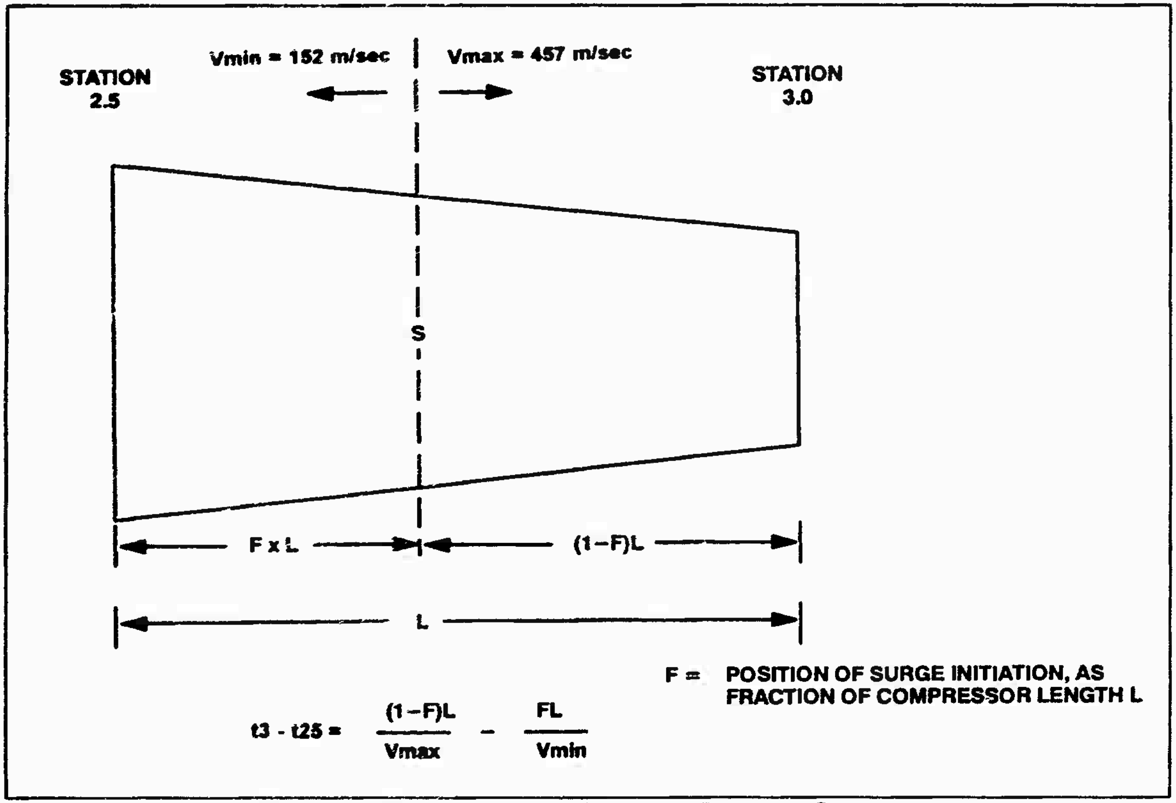


Figure 5.2-15 Propagation Time of Surge Event Through the Compressor

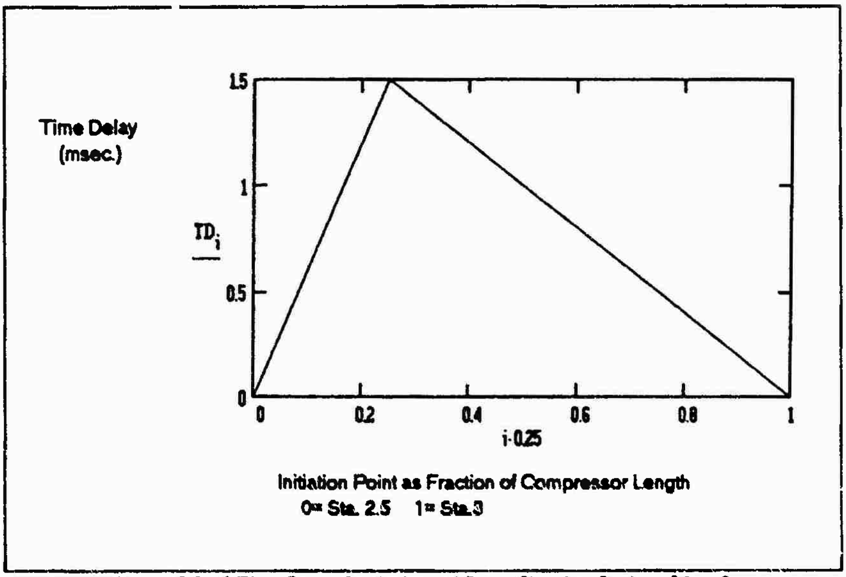
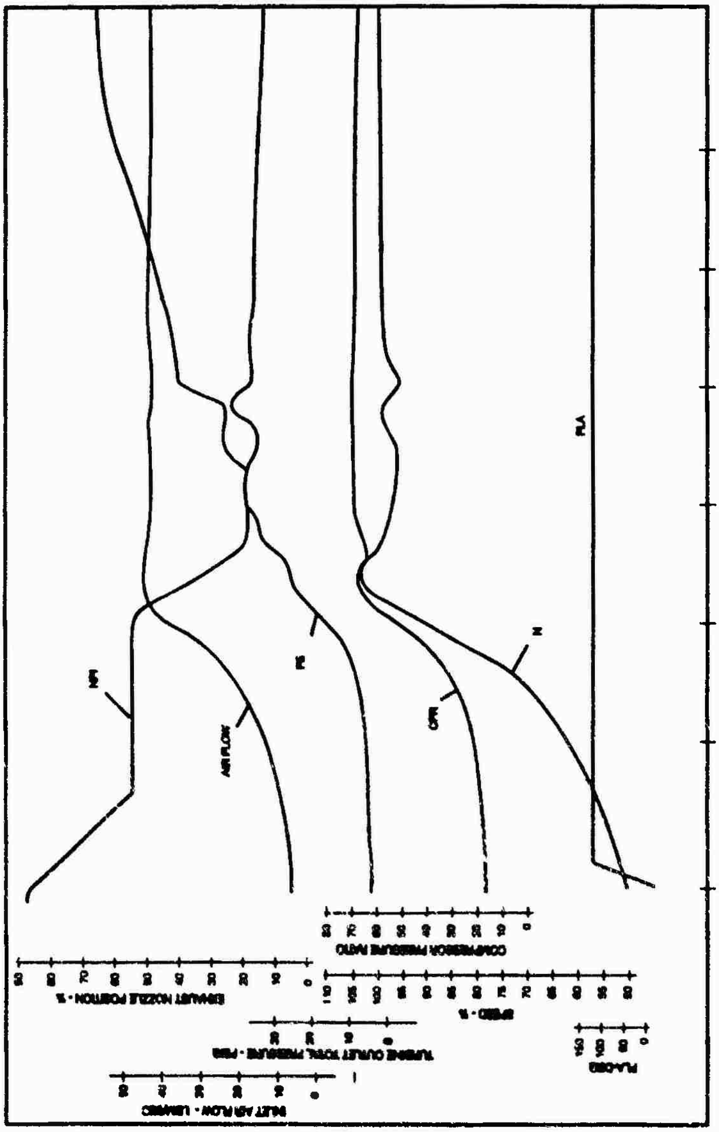


Figure 5.2-16 Time Delay for Arrival of Surge Signal at Stations 25 or 3
(Compressor Length = 1 metre)



Time from Start of Transient (sec)

Figure 5.3-1a Engine Acceleration Test

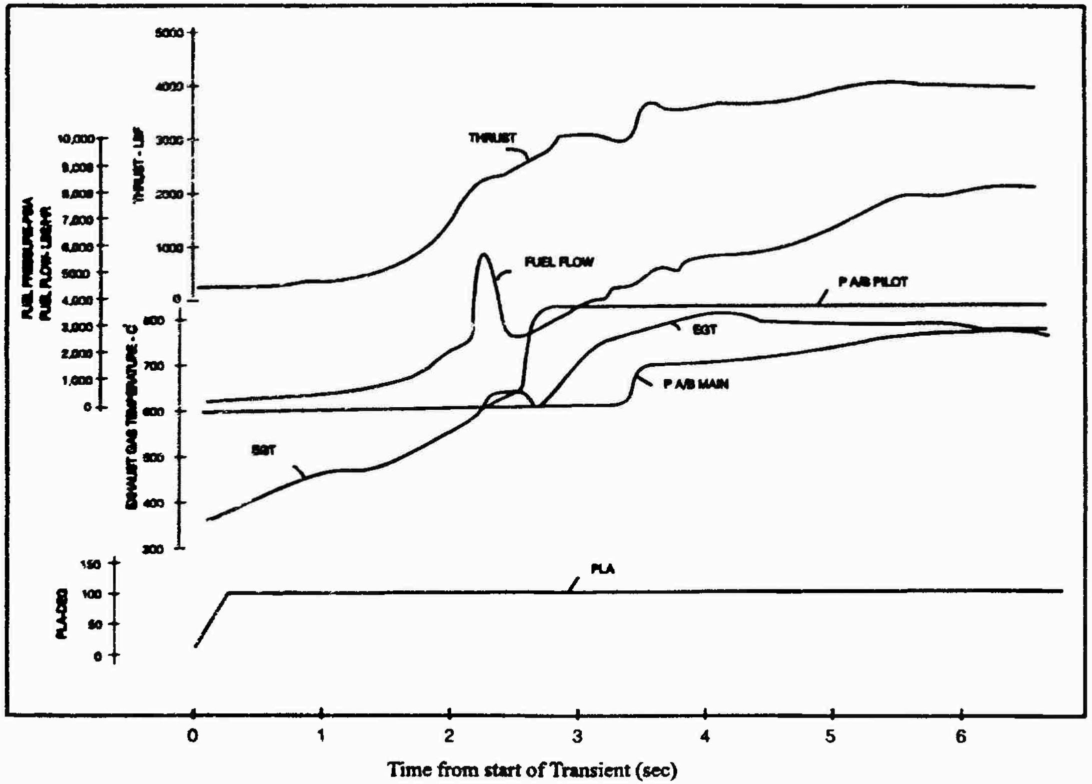


Figure 5.3-1b Engine Acceleration Test

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Aircraft	Examples	Testing
Certifying	Flows	Thrust
Component geometry	Gas turbine engines	Torque
Components	Overhaul facilities	Transient
Control system	Pressures	Transient performance
Data processing	Recommended procedures	Uncertainty estimation

14. Abstract

This report provides a guide for the measurement of *transient* aerothermodynamic performance parameters of aircraft gas turbine engines or components for engine developers, test agencies, certifying authorities and operators of overhaul facilities and aircraft. It may be treated as an extension of AGARD Advisory Reports AR-245 and AR-248. It includes discussion of recommended procedures for the transient measurement of pressures, temperatures, flows, component geometry including rotational speed and clearances, thrust, torque, and the use of the engine control system for transient parameter measures. Typical examples are presented. A section on data acq. isition and processing is included. Higher frequency dynamic measurements are excluded. Two examples, the measurement of compressor ratio and air flow at surge and a measurement of engine acceleration time are discussed in detail.

This Advisory Report was prepared at the request of the Propulsion and Energetics Panel of AGARD.

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