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THESIS

OSCILLATING - FLOW WIND TUNNEL STUDIES FOR A
CIRCULATION CONTROL CIRCULAR CYLINDER

by

George P. Christopoulos

March, 1991

Thesis Advisor: Louis V. Schmidt

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Circulation Control Circular Cylinder

by

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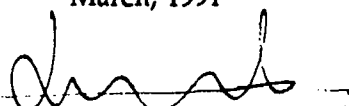of the requirements for the degree of

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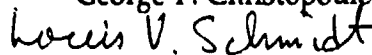
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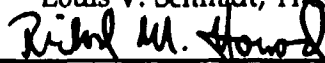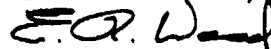March, 1991

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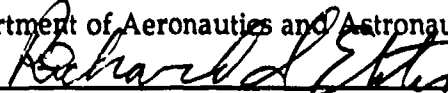Louis V. Schmidt, Thesis Advisor

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ABSTRACT

A two-dimensional circulation control (4.25 inch diameter by 24 inch span) model was designed for installation in the Naval Postgraduate School oscillating flow, low speed wind tunnel. An adjustable, tangential blowing slot was included in the design to provide a circulation control capability using the Coanda flow effect aft of the spanwise slot. Orifice locations were defined for obtaining surface static pressures which could be subsequently processed to yield section lift and drag coefficients.

While the model was being fabricated, pressure system calibrations were made to determine the dynamic transfer function from a simulation of the model's static pressure orifice when connected to the pressure transducer. Similar transfer functions were determined for a static pressure probe. The existing data acquisition system was used to process the sampled digital data sequence.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	Sonic velocity
AoA	Angle of attack
atm	Atmosphere
C	Constant
C_L	Lift coefficient
C_μ	Blowing coefficient
CCA	Circulation control airfoil
ft	Foot
ft/sec	Foot per second
h	Multiplication factor determining the amplitude of the pressure oscillation
Hz	Hertz, cycles/sec
H.O.T.	Higher order terms
ID	Inside diameter
L	Length inside the test section
k	Specific heat ratio
$\dot{m}$	Air mass flow rate (dm/dt)
M	Mach number
MHz	Hz x 10^9
OD	Outside diameter
P	Pressure (see subscripts)

psf	Pounds of force per square foot
psi	Pounds of force per square inch
q	multiplication factor determining the amplitude of the velocity oscillation
Q	Wind tunnel dynamic pressure
rpm	Revolutions per minute
S	Airfoil planform surface area
sec	Second
t	Time, seconds
u	Velocity component in the x-direction
V	Velocity (see subscripts)
ρ	Air density
ϕ	Phase angle
ω	Angular frequency, $2\pi f$, rad/sec
$\Delta(\ )$	Increment or incremental change
$|G(\omega)|$	Dynamic gain magnitude

SUBSCRIPTS

$(\ )_s$	Steady state value
$(\ )_{measured}$	Value measured by Scanivalve®
$(\ )_j$	Coanda jet value

ACKNOWLEDGMENT

I. INTRODUCTION

A.   CIRCULATION CONTROL

The term "Circulation Control" relates to the development of aerodynamic lift over a body immersed in a moving airflow using the technique of tangential blowing of a turbulent jet, located on the upper surface of the body. This turbulent jet can be achieved by discharging fluid from the interior of the body by pressurizing a plenum with the aid of a special blower as illustrated in Figure 1. The location of the tangential injection of fluid varies with configuration; i.e., mid-chord region for a bluff body such as a circular cylinder and near the trailing edge for an airfoil shape.

The term Coanda effect refers to the flow entrainment resulting from the injection of high energy tangential jet flow into the boundary layer with the effect being an alteration of the flow separation point or a shift of the rear stagnation point. The flow remains attached aft of the injection slot due to the pressure of the thin layer of turbulent fluid until a separation occurs at a point downstream of the slot. The location of the Coanda jet separation point depends on factors such as local surface curvature, position of the jet slot, the nature of the boundary layer, and the mass flow rate of the jet.

The tangential jet blowing coefficient, C_μ is defined by:

$$C_\mu = \frac{\dot{m}\, V_j}{Q\, S}$$

where:

$\dot{m}$ = jet mass flow rate,

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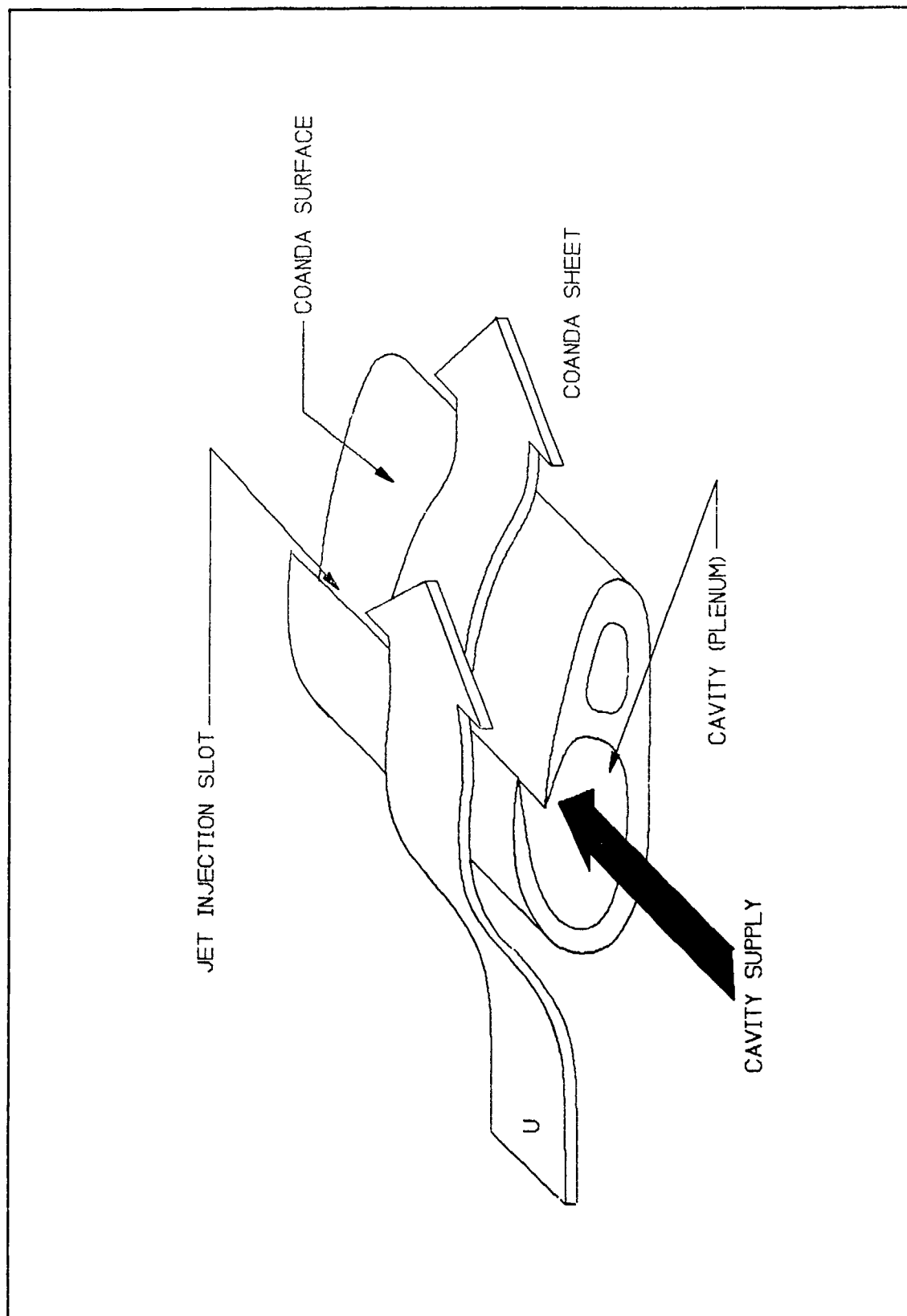
Figure 1 Circulation Control of a Bluff Body

V_j = jet velocity,

Q = dynamic pressure,

S = reference area.

A physical interpretation may be placed upon the dimensionless blowing coefficient C by recognizing that if the jet were pointing vertically downward and perfect flow recovery were achieved, C would translate directly into dimensionless lift coefficient C_L. If the jet were pointing aft, C would translate into an equivalent dimensionless thrust coefficient.

The use of circulation control in an airfoil application becomes attractive when it is realized that the tangential jet velocity, as measured by C , can produce significant lift coefficient changes. Lift amplification, as defined by dC_L/dC , can attain values of up to 50 for well designed airfoil installations. Lift amplification by circulation control on bluff bodies such as circular cylinders may reach values on the order of 10 with the reduction in amplification from that on an airfoil being attributed to the influence of the large separation region on the aft portion of the bluff body.

The ability to control lift force by modulating C will be different for different applications. In a streamlined airfoil scenario, the concept has been investigated for helicopter rotor usage and for fixed-wing aircraft high lift without flaps. C modulation on a bluff body has been actively considered for developing a side force upon a rotorcraft tail boom where the bluff body cross section is immersed in the downwash flow field from the rotor. Thus the time dependent behavior of the circulation control aerodynamics for a range of conditions, including different values of blowing and jet slot location with respect to the free stream, is of particular interest to designers of the NO TAil Rotor (NOTAR™) anti-torque tailboom helicopters, shown in Figure 2.

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As envisioned, a helicopter tailboom equipped with a circulation control form of tangential jet flow coming from a horizontal slot would be able to develop a lateral force (hence an anti-rotor torque yawing moment), providing the tailboom is immersed in the downwash flow field from the rotor. Prototype demonstrations of the concept by McDonnell Douglas Aircraft Company have been quite successful. The benefits to be derived are the removal of a tail rotor with substantial improvement in reliability.

3. PREVIOUS EXPERIMENTAL INVESTIGATIONS

1. Steady Flow Research

The first experimental investigations with circulation control by tangential blowing in steady flow were conducted by Dunham [Ref. 1] and Kind [Ref. 2] in the late sixties on circular cylinders and elliptical Circulation Control Airfoils (CCA). The majority of experimental circulation control work, for the evaluation of the effect of slot height, Reynolds number, trailing euge shape and camber, has been conducted at the David Taylor Research Center (DTRC).

Investigations conducted by Walters [Ref. 3] on a cambered elliptical circulation control airfoil, indicated that additional lift augmentation could be obtained with pulsed blowing. This produced required lift coefficients at reduced injection mass flow.

In 1975 a circulation control helicopter rotor was constructed by Kaman Aerospace Corporation for concept evaluation on the Navy's H-2 helicopter. For the purpose of evaluation of the rotor performance, sinusoidal pressure waves were used for cavity pressurization with amplitude ratios of the order of one, and various combinations of leading and trailing edge blowing. High lift-to-drag ratio surface pressure distributions were reported.

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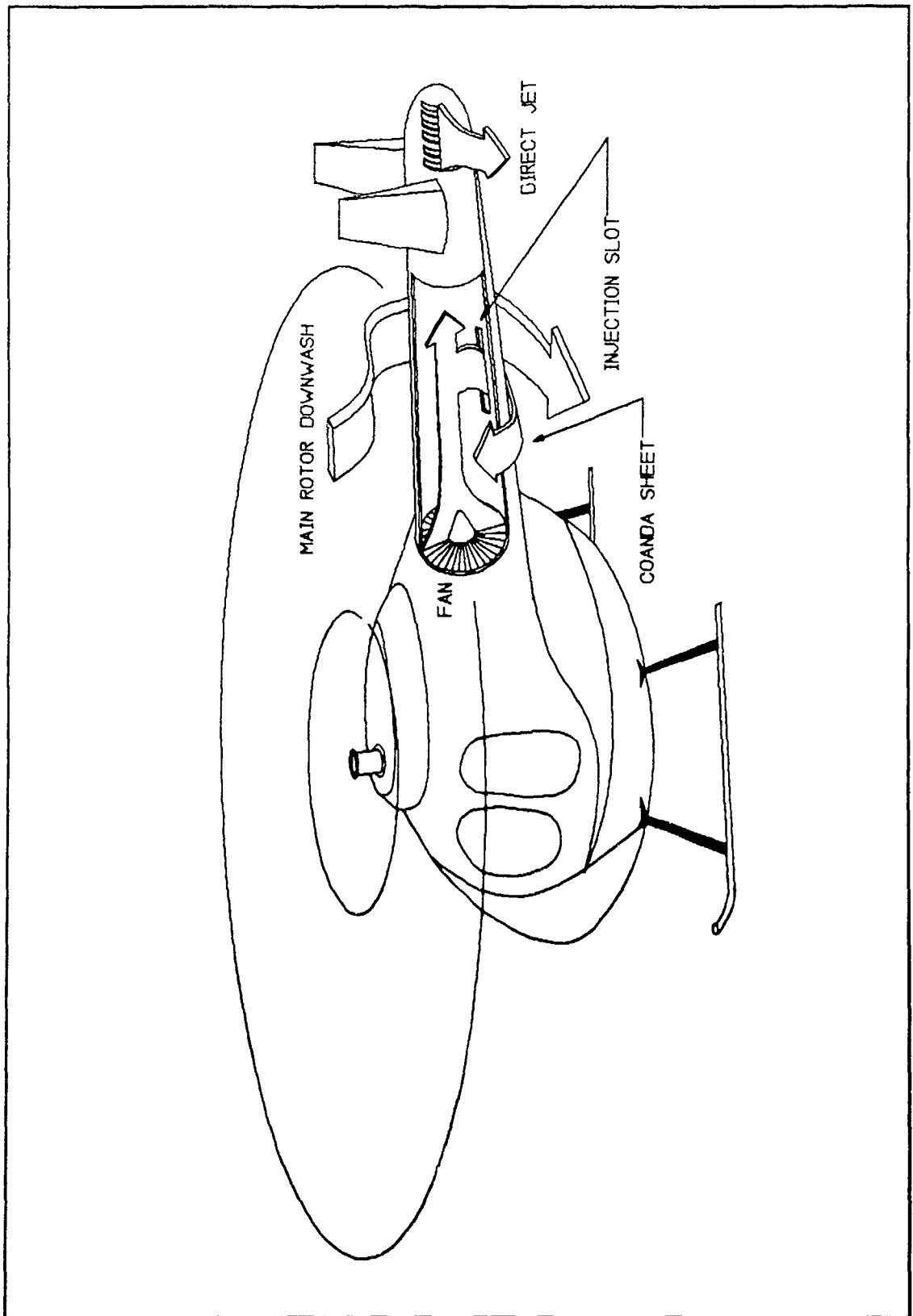
Figure 2 Schematic of a Circulation Control Helicopter Tailboom.

DIRECT JET

INJECTION SLOT

MAIN ROTOR DOWNWASH

COANDA SHEET

FAN

2. Oscillatory Flow Research

Unsteady boundary layer behavior was experimentally investigated by Miller [Ref. 4]. The instantaneous velocity profiles, in oscillatory laminar boundary layers subject to adverse pressure gradients, were measured. Results suggested that the separation point moved upstream from the steady-state point and occurred at the farthest upstream point at which there was reverse flow at some point in the velocity profile throughout the entire cycle of oscillation.

The performance of a circulation control airfoil operating in a steady free stream flow with unsteady blowing was investigated experimentally first by Schmidt [Ref. 5]. An experimental technique was established which allowed the measurement of unsteady static pressures, with the aid of Scanivalves®, and subsequent digital data processing for the express purpose of defining aerodynamic transfer functions of circulation control airfoils. Among the results of this investigation were that the airfoil behaved in a linear manner, the overall airfoil lift transfer function from harmonic circulation control variations had a behavior similar to that of a simple pole in classical control theory, and a frequency dependent damping moment was identified.

C. OUTLINE OF THE INVESTIGATION

In the present investigation a two-dimensional circulation control circular cylinder was designed and constructed for installation in the existing oscillating flow, low speed wind tunnel. A calibration technique was performed in order to obtain the dynamic transfer function for the unsteady pressure data acquisition system. A further objective was to investigate the oscillating flow field produced by a set of rotating shutter vanes aft of the low speed wind-tunnel test section. The method of attack consisted of direct

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measurement of clear tunnel test section aerodynamic characteristics in an oscillating flow field. Comparison was made with analytical predictions of the oscillating flow field.

The detailed investigation   included:

1.   Design and construction of the circulation control model from a circular cylinder for Reynolds numbers below the subcritical point.

2.   Pressure data acquisition system calibrations to determine the dynamic transfer function between the pressure orifices on the surface of the circulation control cylinder and the signal produced by the pressure transducer.

3.   Analytical prediction of the oscillating flow field parameters and propagation characteristics of both static pressure and velocity perturbations due to the reaction of harmonic blockage at the end of the test section.

4.   A static pressure and velocity survey of the wind tunnel test section in steady and oscillating flow, without the model installed.

5.   Correlation between analytical and experimental results for static pressure and velocity oscillation in the test section, and final results for wind tunnel calibration.

II. EXPERIMENTAL EQUIPMENT

A. WIND TUNNEL

The investigation was conducted in the Naval Postgraduate School, Department of Aeronautics and Astronautics laboratories. The experimental information was obtained through the use of the low-speed oscillating flow wind tunnel which is an open-circuit indraft facility.

1. Inlet Section

The tunnel draws ambient air from the outside environment, through high solidity screens, from an eight-foot square inlet into a 16:1 contraction cone. The high solidity turbulence screens and the 16:1 contraction ratio result in a very smooth steady flow through the test section and help maintain freestream turbulence intensities to less than 1 percent for the velocities encountered in the present investigation.

2. Power Section

The power section of the tunnel is comprised of two Joy Axivane Fans, mounted in series aft of the test section. The fan drive consists of two internal, 75 horsepower, 1750 rpm, electric motors direct connected to each fan. The fan blades are internally adjustable through a pitch range of 25 to 55 degrees, providing a wide operating base. Control of the mass flow rate and hence the test section velocity is provided by a set of two externally operated, variable inlet vanes, located immediately upstream of each fan. The multileaf-type inlet preswirls the air in the direction of the fan rotation in order to reduce the power required to operate the wind tunnel. The range of wind-tunnel velocities is from 10 to 250 feet per second.

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3. Test Section

The tunnel test section beginning immediately after the contraction cone, as shown in Figure 3, is 223 inches long and has a 24-inch X 24-inch square cross section. The test section requires extraordinarily stiff construction dictated by the need to minimize deflections due to rapid changes in static pressures when the tunnel operates in the oscillating flow mode. For this reason continuous pieces of two-inch thick aluminum slabs form the upper and lower test section walls. The front side wall consists of three panels, constructed of two-inch thick stress relieved Lucite™, secured by twelve bolts each to the top and bottom slabs. The panels are hinged and may be raised by hydraulic actuators, providing access to the test section. The rear wall is constructed from two-inch thick plywood.

The lower wall provides ports for the purpose of mounting hot-wires probes, pitot-static tubes, and other data acquisition probes, although the plywood construction of the rear wall permits mounting of the model and internal or external instrumentation.

Boundary layer velocity profile measurements at steady flow, have shown that velocity variation is less than 1 percent of the mean to within three inches of any wall.

4. Rotating Shutter Valve

There are in existence several methods which have been developed for the purpose of obtaining an oscillating flow. The method used in this wind tunnel assembly was first used successfully by Karlsson [Ref. 6] and later by Miller [Ref. 7]. The method uses a rotating shutter valve installed at the exit of the test section consisting of several shutter vanes.

The present shutter vanes consist of four one-inch diameter horizontal steel shafts, each of which is slotted to accommodate a flat blade of varying width. The scheme

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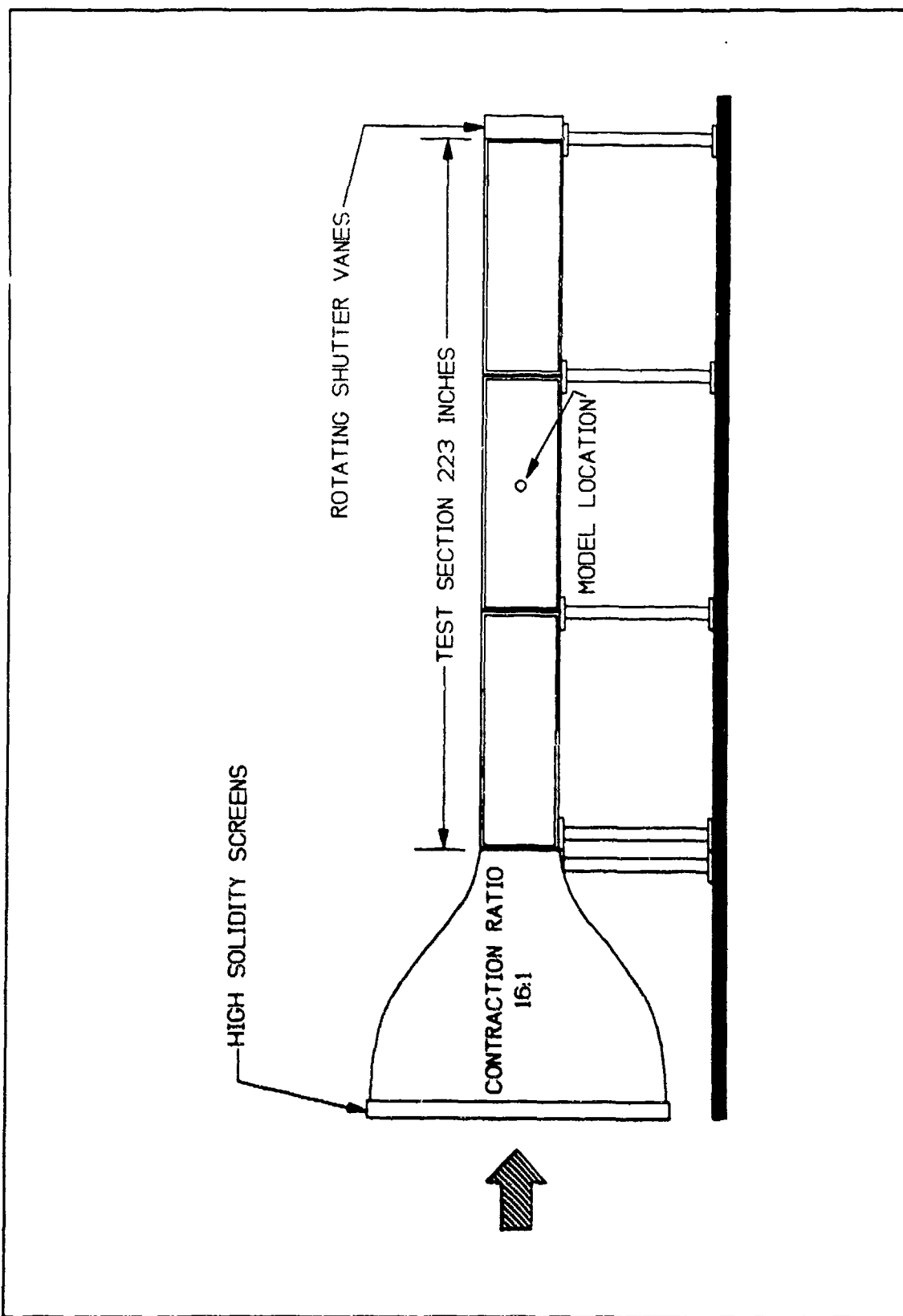
Figure 3 Wind Tunnel Test Section
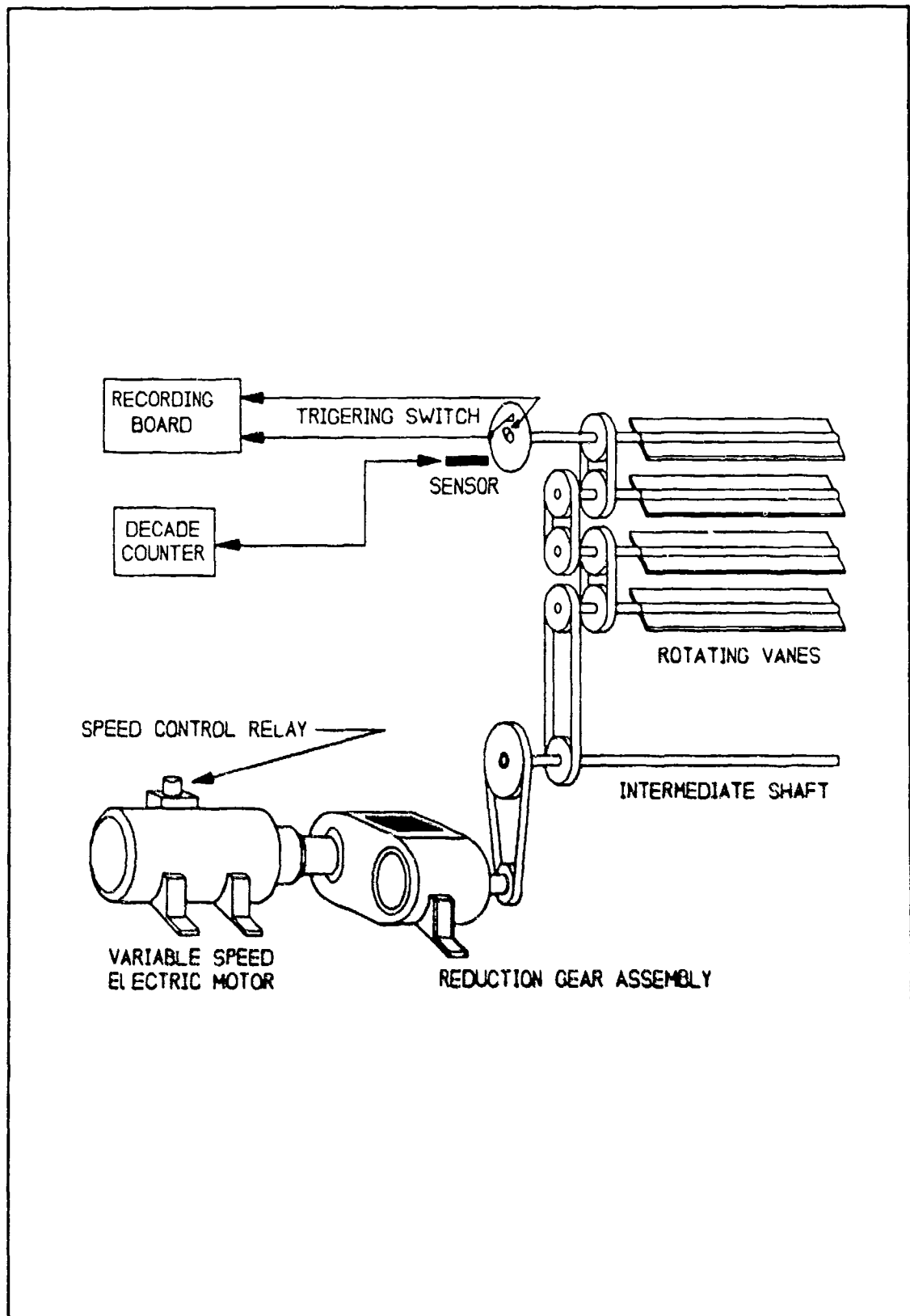
Figure 4 Rotating Shutter Valve Assembly

shown in Figure 5, forms an array of four butterfly valves which span the end of the test section horizontally. A five horsepower, variable-speed electric motor drives an intermediate shaft through a reduction gear assembly. The shaft of the bottom vane is driven by the intermediate shaft and then each vane drives its immediate neighbor by means of timing belts and pulley arrangements in order to keep all four vanes in phase as they rotate.

The intermediate shaft permits a variety of pulley arrangements and a frequency range from two to 240 Hz , while the amplitude of oscillation is controlled by blade width with a test section closure from 25 to 100 percent. There is also a provision to lock the vanes in the horizontal position to allow the tunnel to produce a steady flow.

In this experiment, three inch wide blades were used allowing a blockage or closure ratio from 8.3 to 50 percent. The test section velocity perturbation varied from three to eight percent of the local mean freestream velocity for a frequency range of 10 to 48 Hz.

B.   INSTRUMENTATION

1.   Instrumentation For Pressure Measurement

A Scanivalve® with its own transducer was used to measure the unsteady static pressures from the wind tunnel test section and served as the main element in the design of the instantaneous pressure acquisition system for the ci ulation control model. A solenoid controller and an odd-even decoder controlled the opening of the Scanivaive® ports to the transducer chamber with the capability to send the Scanivalve® port information number to a computer program or to receive port change commands from the computer.

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The analog signal from the Scanivalve® transducer was conditioned by a signal conditioning amplifier and was then connected to a recorder board SRA-1200™ (channel 1). A Tektronix™ type 555 dual-beam oscilloscope was used to monitor the pressure signal in real-time. The Scanivalve® unit was mounted on a free-standing mobile dolly in order to remain isolated from the wind tunnel, thereby minimizing mechanical coupling and signal noise during wind tunnel operation.

2. Instrumentation For Velocity Measurement

A linearized, constant temperature hot-wire anemometer described by Miller [Ref.8] was employed to measure the velocity oscillations of the clean tunnel test section during all experimental runs. The signal from the hot-wire was connected to a second recorder board SRA-1200™ (channel 2), and to the same oscilloscope mentioned above which was used for pressure monitoring. A Singer Ballantine™ RMS volt meter was used to measure the RMS of the velocity analog voltage signal.

The freestream velocity was also measured from a Pitot-Static probe connected to a water manometer with plastic tubing of significant length to damp the pressure fluctuations due to velocity oscillations. This system was used to establish a known steady flow speed in order to calibrate the hot-wire anemometer and for measuring the mean flow velocity during the oscillating flow testing.

3. Data Acquisition Instrumentation

The pressure and velocity signals were output continuously from the Scanivalve® pressure transducer and the hot-wire anemometer, respectively, as analog voltages. The signals during recording were stored on the two recorder boards SRA-1200 (channel 1 and channel 2) with 64K capacity each, installed inside a 80286-based personal

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computer running at a 12 MHz clock speed. The recording boards were of 12-bit resolution, capable of differentiating one part in 4096.

The data acquisition recorder boards were cued by an electric trigger, which was tripped mechanically by a microswitch mounted on the rotating shutter valve system. The frequency of the rotating shutter valve was continuously measured and displayed by a Dynasciences signal counter, while an Analog Devices™ AD 2501 digital thermometer displayed freestream temperature in degrees Fahrenheit, measured by a thermocouple just upstream of the rotating shutter vanes. The set-up of the instrumentation used in the data acquisition is shown in Figure 5.
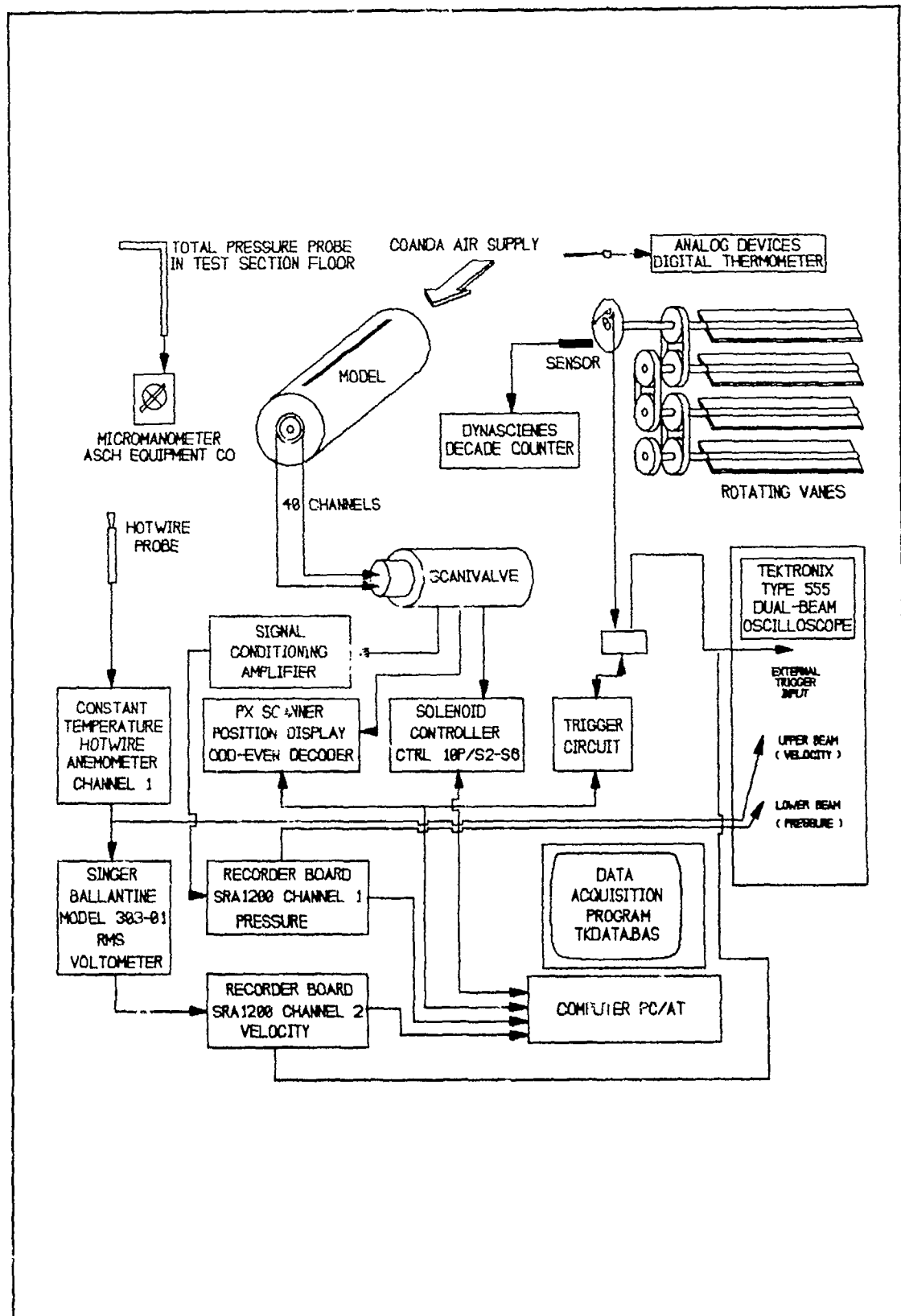
Figure 5 Instrumentation Set-up For Data Acquisition

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III. CIRCULATION CONTROL MODEL

A. GENERAL DESCRIPTION

The model was a prototype circulation control cylinder, designed and constructed in its entirety in the Naval Postgraduate School Department of Aeronautics and Astronautics model shop. An aluminum circular cylinder, with 4.25 inches outside and 4.0 inches inside diameter, was modified to accommodate the injection slot structure.

Special attention was given during the design process to the injection slot configuration. In order to adjust the injection slot width, two separate aluminum pieces were bolted inside the cylinder cavity to help five pairs of "push-pull" screws to vary the distance between the slot lips. The model end sections were capped by two aluminum, flat, circular plates. A one-inch diameter line passed through the rear end plates for external air supply to provide pressurization to the cylinder cavity. The cavity may be considered as a reservoir operating at stagnation conditions and provides the supply air for leakage through the twenty-inch long tailored slot that creates the Coanda sheet which is initially attached to the rounded upper surface of the cylinder. Figure 6 depicts the supply air path, the injection slot location, and the main parts of the model.

B. INSTALLATION IN THE TEST SECTION

The cylinder was designed to span the 24-inch width of the tunnel test section, pivoted at the center of its cross section, for support and injection slot location control. The term "Slot Angle of Attack" (Slot AoA) denotes the angle between the cylinder diameter which is always perpendicular to the tunnel test section center line and the diameter which

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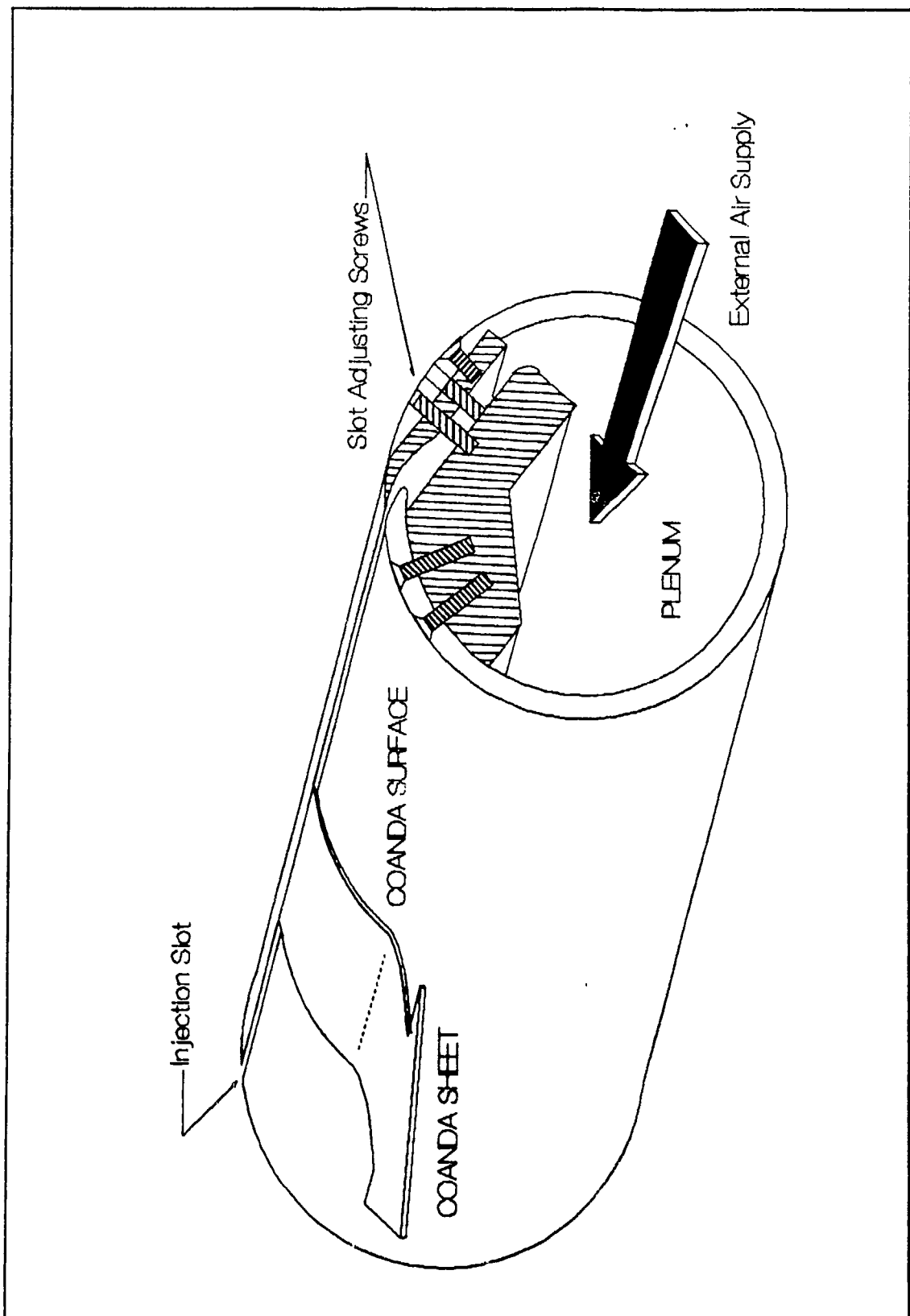
Figure 6 Circulation Control Circular Cylinder

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passes through the injection slot. The slot angle of attack was made adjustable with reference to a vernier mechanism, permitting the operator to set any desired angle from -40 to +40 degrees relative to the upright direction.

C. PRESSURE ORIFICE LOCATIONS

Provisions for twenty-four pressure orifices were made approximately at the model midspan station with an even distribution chordwise every 15 degrees. Four additional pressure taps were distributed chordwise every 90 degrees, left and right of the main 24 pressure taps array and seven inches apart. The purpose of these eight pressure taps was to verify the two-dimei..ional nature of the flow field.

Places for measuring the Coanda jet influence along the model surface, immediately after the injection slot, included a static pressure array of seven orifices spaced chordwise every three degrees. Figure 7 shows a cross-sectional view depicting the location of the 24 midspan pressure orifices with respect to the injection slot location, and Figure 8 an upper surface view of the cylinder depicting the location of the "Coanda" pressure orifices. The decreased angular spacing in the "Coanda" pressure orifices region was for the purpose of defining the attached flow region of the Coanda jet.

D. CONNECTION TO THE PRESSURE MEASUREMENT SYSTEM

The pressure orifices will be connected to the Scanivalve® ports by means of identical lengths of stainless steel tubing 0.065" OD and 0.047" ID. This technique provides the same dynamic transfer function for the connection from each of the surface static pressure orifices to the simple Scanivalve® pressure transducer. It should be noted that in this role, the Scanivalve® acts as a pneumatic multiplexing device since a single transducer is selectively connected to the various static pressure orifices using remote control. A

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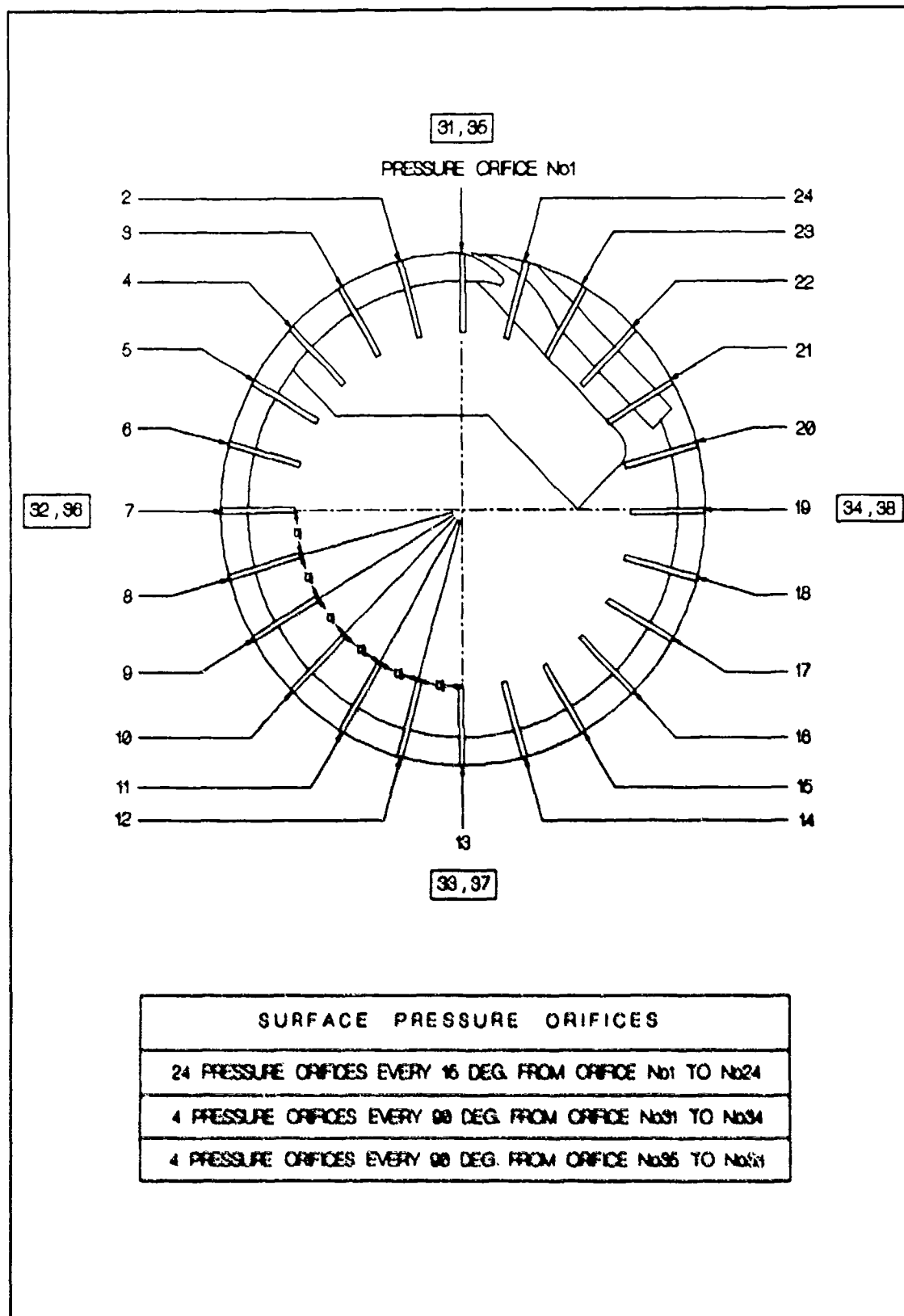
Figure 7 Main Array of Pressure Orifices
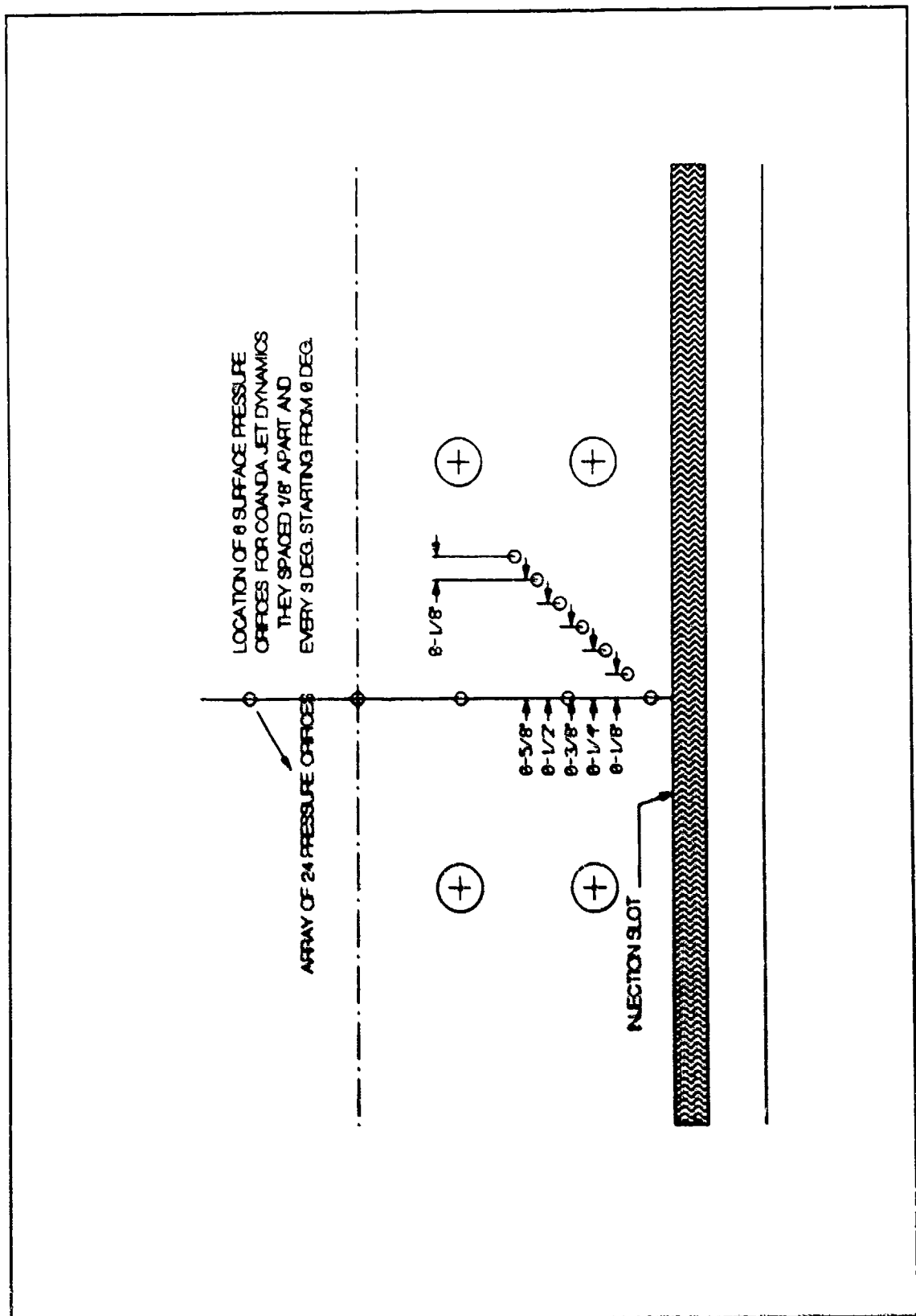
Figure 8 Pressure Orifices For Coanda Flow Region

calibration procedure was applied to the tubing to determine the transfer function necessary to convert the pressure signal received at the Scanivalve® transducer to the proper amplitude and phase representative of the pressure distribution over the circulation control model. The calibration procedure is described in detail in the following chapter.

IV. PRESSURE DATA ACQUISITION SYSTEM CALIBRATION

The transient response of pressure measuring systems is dependent on two factors; the response and sensitivity of the pressure sensor transducer, and the dynamic response of the pressure transmitting fluid and connecting tubing. In the experiment the total and static pressures associated with the oscillating flow were transmitted to the Scanivalve® pressure sensor via a pressure probe and/or stainless steel tubes of specific length. Connecting tubing and unavoidable cavities in the unsteady pressure measurement system introduced losses and phase lags, causing differences between measured and applied pressures.

Because the pressure transducer inside the Scanivalve® provided a large impedance, there was no flow in the tube, and the steady-state average pressure at the end of the tube equals the pressure at the probe or the pressure at the pressure orifice location. On the other hand for time-varying pressures the tubing acts as a transmission line.

A harmonic pressure signal input may be considered as being introduced at a particular model static pressure orifice in the form of:

$$P(t) = P_o (1 + h \cos \omega t) \quad , \quad h < 1$$

The analog signal sensed by the pressure transducer internal to the Scanivalve® following transmission of the information from the model surface through the 0.047" ID stainless steel tubing, or from the static pressure probe in the tunnel, may be viewed as being of the form:

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$$P_{scanivalve}(t) = P_o [1 + |G(\omega)|h \cos(\omega t + \phi)] \quad , \quad h < 1$$

where:

P_o = mean pressure,

h   = multiplication factor determining the amplitude of the pressure oscillation

       input,

$|G(\omega)|$ = dynamic gain magnitude attributed to pressure tubing and internal

       Scanivalve® configuration, and

ϕ = phase lag associated with $|G(\omega)|$.

To determine the phase lag and the dynamic gain as functions of frequency, a calibration

procedure was applied to both the stainless steel tubing and the static pressure probe. The

static pressure probe was used to measure the static pressure dynamics in the clear tunnel

test section.

A.   CALIBRATION INSTRUMENTATION SETUP

A function generator provided a sinusoidal voltage signal which was serially

connected, through an amplifier, to a resonator depicted in Figure 9. A pressure signal of

varying frequency was generated by the 75 Watt acoustic driver of the resonator located

in the center of the cavity. Two pressure ports at the ends of the cavity provided

comparative signals with an estimated accuracy of one degree in phase angle. The pressure

was measured immediately at the first port by a reference transducer and from the other

port the signal was transmitted to the Scanivalve® pressure transducer via the stainless

steel tube or the static pressure probe. The two analog voltage signals, after they passed

through similar signal conditioning amplifiers, were digitized, recorded and stored on the

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two SRA 1200™ recorder boards. A data acquisition / data reduction program, listed in Appendix C , written in Quick Basic™, calculated the phase difference and the amplitude ratio between the two signals using a simple discrete data cross-correlation algorithm. The Tektronix™ Type 555 Dual Beam Oscilloscope was used to monitor the same pressure signals in real-time, and a digital voltmeter measured the analog output of the pressure transducers to a sensitivity of +/-0.001 volts DC with a range of +/-10.000 volts.

B. CALIBRATION RESULTS

1. Static Transducer Calibration

Before the dynamic calibration of the stainless steel tubing and the static pressure probe was conducted, a static transducer calibration was performed to determine the sensitivity of both the reference transducer and the Scanivalve® transducer. A water manometer was used to establish static pressure in inches of water and a digital voltmeter to measure the transducer's output in millivolts with an accuracy of +/-0.01 millivolt. Both transducers displayed linear static calibration curves, shown in Figure 10, with the Scanivalve® transducer having a sensitivity of 0.0346 Volts/psf and the reference transducer 0.1063 Volts/psf (three times more sensitive than the Scanivalve®).

2. Calibration Results For Circulation Control Model Tubing

Four different tube lengths, 28, 26, 24, and 22 inches, were tested in order to form a transfer function data-bank necessary to convert the pressure signals received at the Scanivalve® back to the proper amplitude and phase representation of the static pressures on the surface of the circulation control circular cylinder. For the calibration tests the tubes were connected to the Scanivalve® leads with one-inch length plastic tubing, which configuration must be preserved in the final model pressure orifices connection to the

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Scanivalve® leads. Calibration curves showing the phase lag and dynamic gain as a function of applied frequency are shown on Figures 11 and 12 respectively. The 28-inch length of tubing offers more flexibility for Scanivalve® attachment to the model's pressure measurement system.

3. Calibration Results For Static Pressure Probe

The probe used in the clear-tunnel test section static pressure measurements was also tested with the same instrumentation setup. A special fitting was made to allow positioning of the probe in the resonator cavity. The output lead of the probe was connected to the same Scanivalve® used above, by means of a 3 inch plastic tubing, a configuration that was preserved during the actual test section static pressure measurements. The calibration curve for phase lag displayed a linear behavior, as shown in Figure 13, while the calibration curve for the dynamic gain showed a gain increase of 16 percent of the static value at an applied pressure perturbation frequency of 39 Hz followed by a smooth decrease in gain as frequency increased to 100 Hz, as shown in Figure 14.

Figure 9 Instrumentation Set-up For Dynamic Calibration

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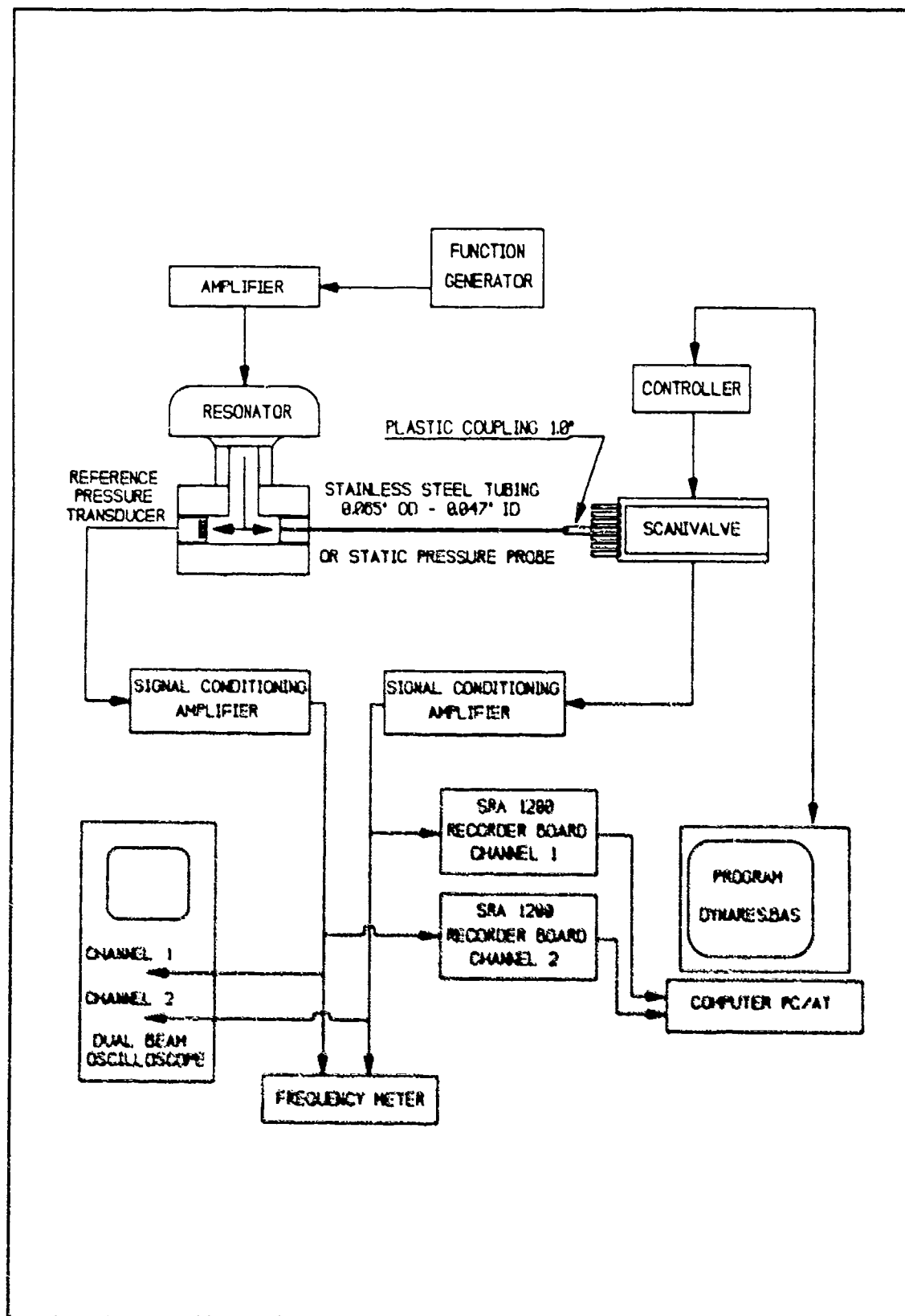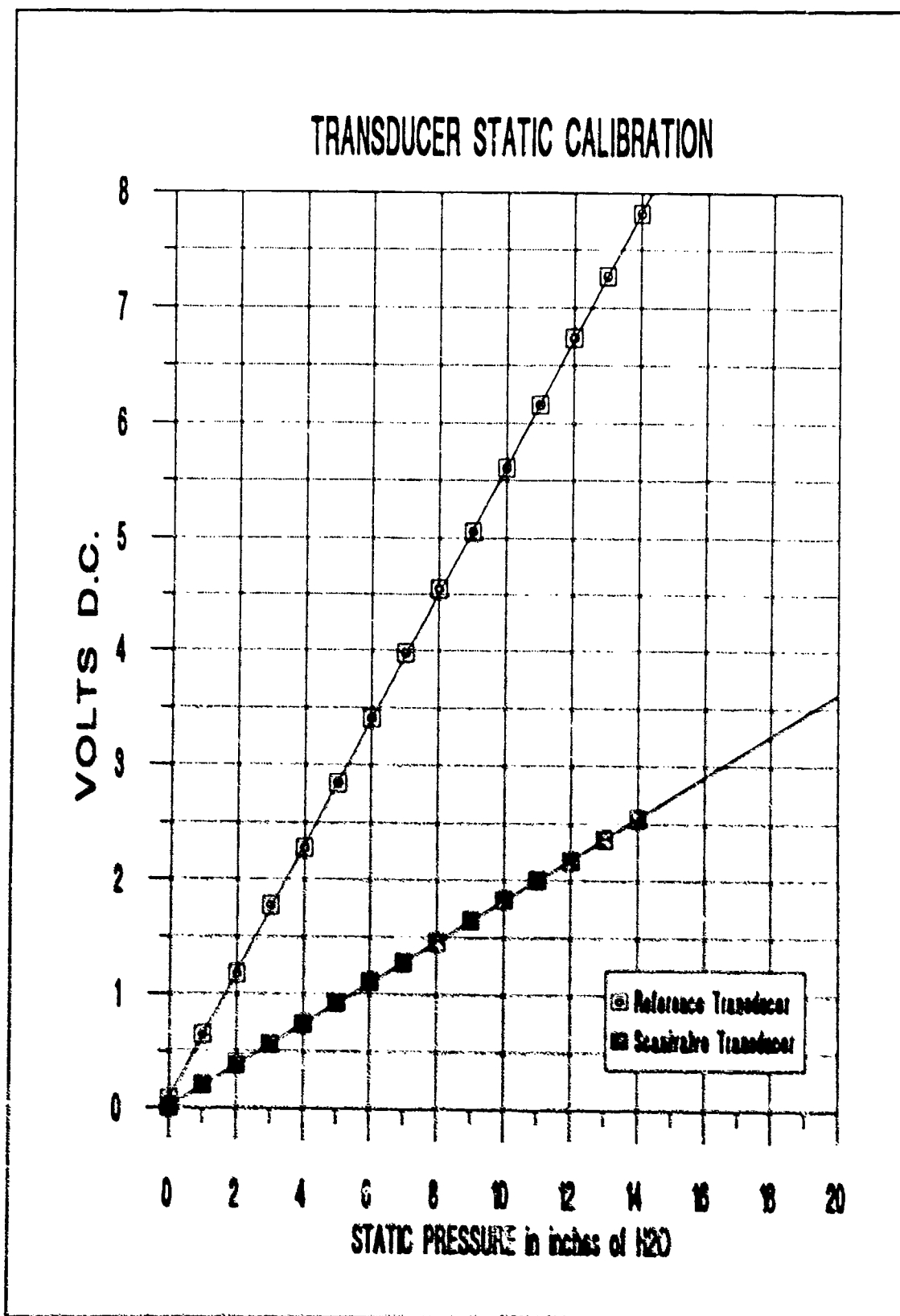
Figure 10 Static Calibration For Pressure Transducers

Figure 11 Tubing Calibration Curve For Phase Lag

CONFIGURATION : Stainless Steel Tubing 0.065" OD , 0.047" ID and 1.0" Plastic Tube Connection to the Scanivalve Leads.
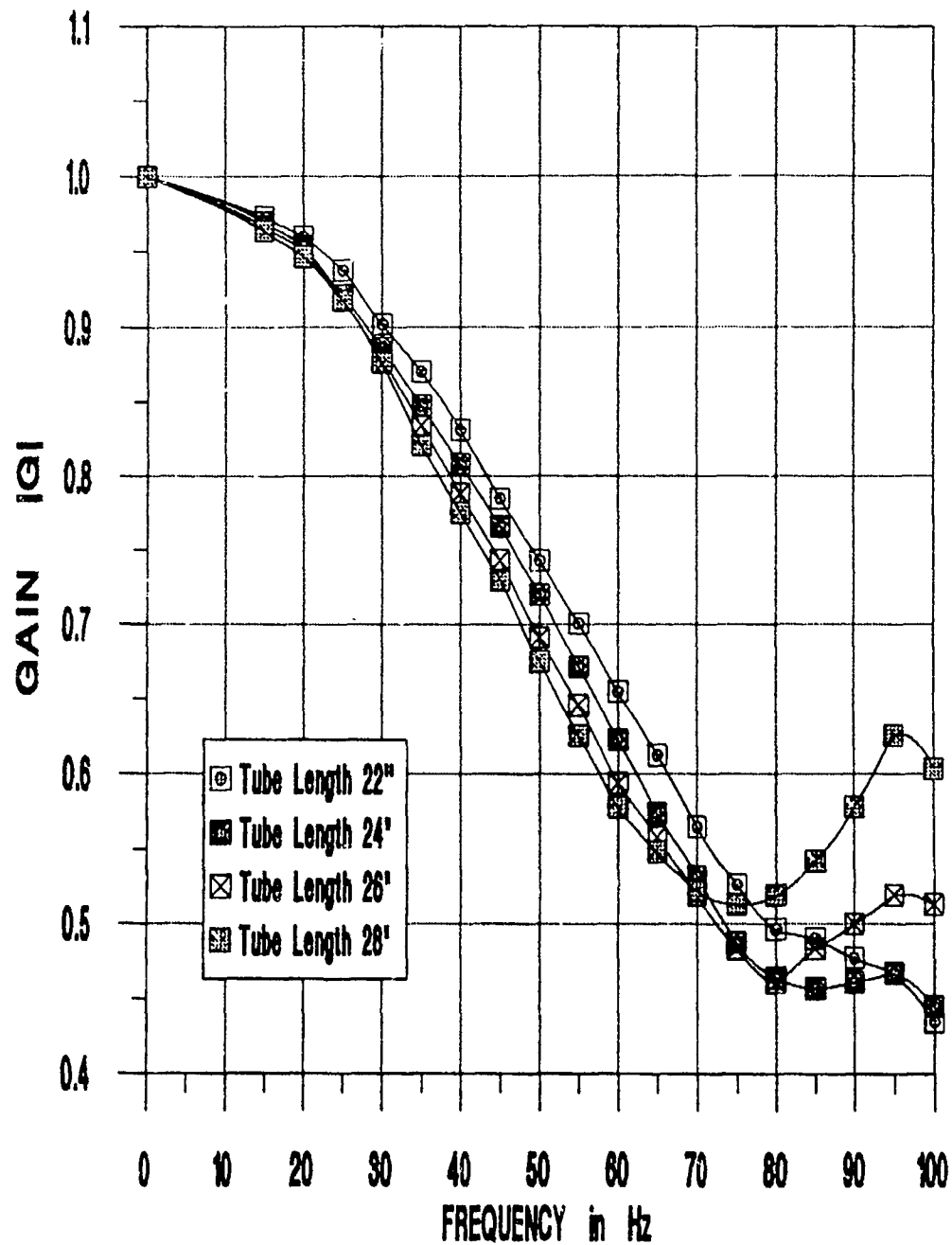
Figure 12 Tubing Calibration Curve For Dynamic Gain

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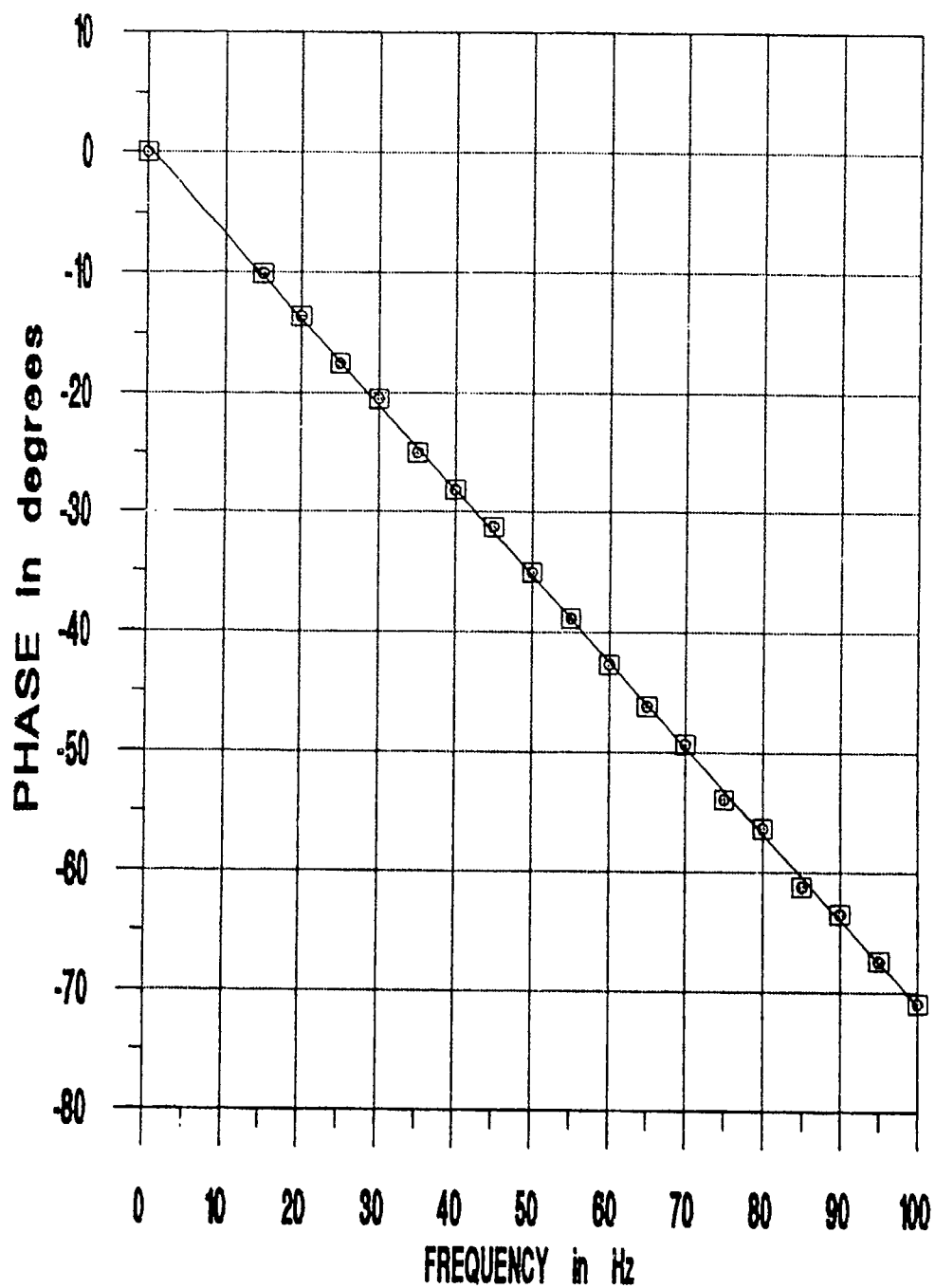
Figure 13 Pressure Probe Calibration Curve For Phase Lag

30
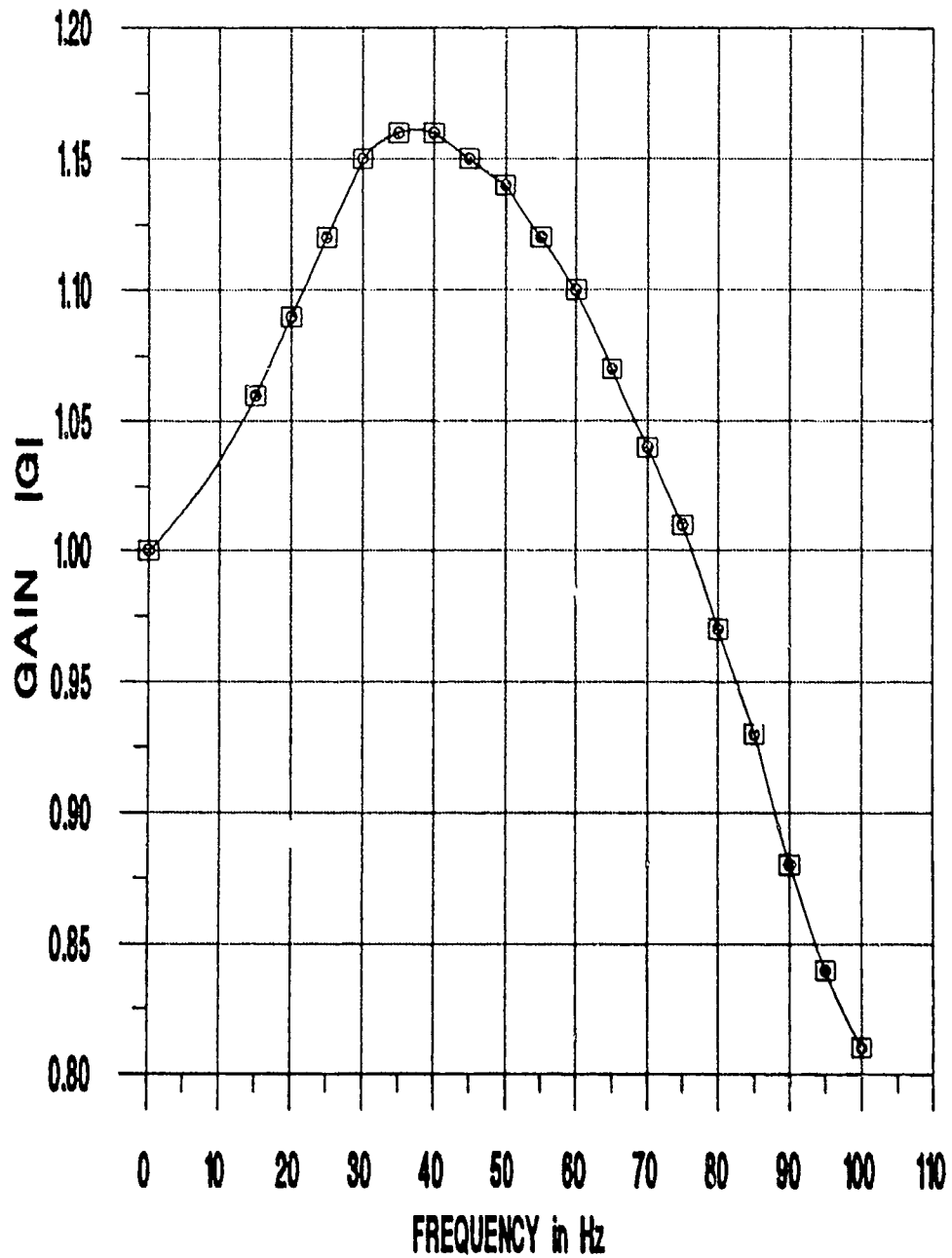
Figure 14 Pressure Probe Calibration Curve For Dynamic Gain

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IV. CALCULATION OF STATIC PRESSURE AND VELOCITY OSCILLATIONS IN THE TUNNEL TEST SECTION

Consider the inviscid, unsteady flow through the test section of the tunnel. The air is generally moving at the speed u (on the order of 100 ft/sec) with properties P (static pressure) ρ (density) and a (local sonic velocity), while the presence of the rotating shutter valve superimposes a periodic variation of velocity on the mean flow. The purpose of the analysis that follows was to obtain general expressions for the static pressure and the velocity at any instant of time and at any point in the test section, downstream of the rotating shutter valve, as a function of the rotation frequency. In order to avoid mathematical difficulties, it was necessary to make a number of simplifying assumptions. First of all the viscosity and thermal conductivity of the gas were neglected. This means that all properties of the gas were related through isentropic relations. Then it was assumed that the flow was geometrically one-dimensional, implying that all fluid properties were uniform over each cross section of the passage, that no changes in the cross section took place in the test section, and that the length of the oscillating pressure wave was much greater than the tunnel's characteristic cross-sectional dimension.

A. EQUATIONS OF MOTION

The one-dimensional momentum equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial P}{\partial x}.$$

combined with the following expression for the speed of sound (energy equation):

$$a^2 = \frac{\partial P}{\partial \rho} \Big| \; @ \; constant \; entropy$$

becomes:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{a^2}{\rho} \frac{\partial \rho}{\partial x} = 0 \qquad (1)$$

while the one-dimensional continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} = 0$$

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} = 0 \qquad (2)$$

Now using small perturbation assumptions, the local density and local velocity have the following forms:

$$\rho = \rho_0 + \Delta \rho$$

$$u = U_0 + \Delta u$$

Substitution into equations (1) and (2) of the above expressions for local density and velocity, yields:

$$\frac{\partial \Delta u}{\partial t} + (U_0 + \Delta u) \frac{\partial \Delta u}{\partial x} + \frac{a^2}{\rho_0 + \Delta \rho} \frac{\partial \Delta \rho}{\partial x} = 0 \qquad (3)$$

$$\frac{\partial \Delta \rho}{\partial t} + (U_0 + \Delta u)\frac{\partial \Delta \rho}{\partial x} + (\rho_0 + \Delta \rho)\frac{\partial \Delta u}{\partial x} = 0 \qquad (4)$$

The Taylor series expansion of sonic velocity squared a^2, about point ρ_o, gives:

$$a^2 = a_0^2 + (\frac{\partial a^2}{\partial \rho})(\rho - \rho_0) + H.O.T.$$

$$a^2 \approx a_0^2 + (\frac{\partial a^2}{\partial \rho}) + \Delta \rho$$

Substitution into equation (3) yields:

$$\frac{\partial \Delta u}{\partial t} + (U_0 + \Delta u)\frac{\partial \Delta u}{\partial x} + \frac{1}{\rho + \Delta \rho}[a_0^2 + (\frac{\partial a^2}{\partial \rho})\Delta \rho]\frac{\partial \Delta \rho}{\partial x} = 0 \qquad (5)$$

Performing an order-of-magnitude analysis because:

$$\Delta \rho \ll \rho_0 \qquad \wedge \qquad \Delta u \ll a_0$$

the following terms:

$$\Delta u \frac{\partial \Delta u}{\partial x} \approx 0 \; , \; \Delta \rho \frac{\partial \Delta \rho}{\partial x} \approx 0 \; , \; \rho_0 - \Delta \rho \approx \rho_0 \; , \; \Delta u \frac{\partial \Delta \rho}{\partial x} \approx 0 \; , \; \Delta \rho \frac{\partial \Delta u}{\partial x} \approx 0$$

can be neglected and the equations (5) and (4) finally become:

$$\frac{\partial \Delta u}{\partial t} + U_0 \frac{\partial \Delta u}{\partial x} + \frac{a_0^2}{\rho_0}\frac{\partial \Delta \rho}{\partial x} = 0 \qquad (6)$$

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$$\frac{\partial \Delta \rho}{\partial t} + U_0 \frac{\partial \Delta \rho}{\partial x} + \rho_0 \frac{\partial \Delta u}{\partial x} = 0 \qquad (7)$$

Now the perturbations of density and velocity can be written as functions of position x and time t:

$$\Delta \rho = \rho_0 s(x,t)$$

$$\Delta u = U_0 r(x,t)$$

thus the local density and local velocity become:

$$\rho = \rho_0[1 + s(x,t)]$$

$$u = U_0[1 + r(x,t)]$$

Using the above expressions for the perturbed quantities, equations (6) and (7) become:

$$U_0 \frac{\partial r(x,t)}{\partial t} + U_0^2 \frac{\partial r(x,t)}{\partial x} + a_0^2 \frac{\partial s(x,t)}{\partial x} = 0$$

$$\frac{\partial s(x,t)}{\partial t} + U_0 \frac{\partial s(x,t)}{\partial x} + U_0 \frac{\partial r(x,t)}{\partial x} = 0$$

and because:

$$M_0 = \frac{U_0}{a_0}$$

the above equations take the form:

$$\frac{M_0}{a_0}\frac{\partial r(x,t)}{\partial t} + M_0^2\frac{\partial r(x,t)}{\partial x} + \frac{\partial s(x,t)}{\partial x} = 0$$

$$\frac{1}{a_0}\frac{\partial s(x,t)}{\partial t} + M_0\frac{\partial s(x,t)}{\partial x} + M_0\frac{\partial r(x,t)}{\partial x} = 0$$

or:

$$M_0\frac{\partial r(x,t)}{\partial(a_0 t)} + M_0^2\frac{\partial r(x,t)}{\partial x} + \frac{\partial s(x,t)}{\partial x} = 0$$

$$\frac{\partial s(x,t)}{\partial(a_0 t)} + M_0\frac{\partial s(x,t)}{\partial x} + M_0\frac{\partial r(x,t)}{\partial x} = 0$$

and finally:

$$M_0[\frac{\partial r(x,t)}{\partial(a_0 t)} + M_0\frac{\partial r(x,t)}{\partial x}] + \frac{\partial s(x,t)}{\partial x} = 0 \qquad (8)$$

$$[\frac{\partial s(x,t)}{\partial(a_0 t)} + M_0\frac{\partial s(x,t)}{\partial x}] + M_0\frac{\partial r(x,t)}{\partial x} = 0 \qquad (9)$$

Now the following transformation:

$$z = \frac{x}{M_0} + a_0 t$$

applied to the equations (8) and (9) yields:

$$M_0 \frac{\partial r}{\partial z} + \frac{\partial s}{\partial x} = 0 \qquad (10)$$

$$\frac{\partial s}{\partial z} + M_0 \frac{\partial r}{\partial x} = 0 \qquad (11)$$

Taking the first derivative with respect to x of equation (10), and then the first derivative with respect to z of equation (11), yields:

$$M_0 \frac{\partial}{\partial x} (\frac{\partial r}{\partial z}) + \frac{\partial^2 s}{\partial x^2} = 0 \qquad (12)$$

$$\frac{\partial^2 s}{\partial z^2} + M_0 \frac{\partial}{\partial z} (\frac{\partial r}{\partial x}) = 0 \qquad (13)$$

The result of the subtraction between equations (12) and (13) is a form of the wave equation:

$$\frac{\partial^2 s}{\partial x^2} = \frac{\partial^2 s}{\partial z^2}$$

with the well known solution [Ref. 8] :

$$s(x,z) = F(x+z) + G(x-z)$$

or:

$$s(x,t) = F[x(1+\frac{1}{M_0}) + a_0 t] + G[x(1-\frac{1}{M_0}) - a_0 t] \qquad (14)$$

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Now taking the first derivative with respect to z of equation (10), and then the first derivative with respect to x of equation (11), yields:

$$M_0 \frac{\partial^2 r}{\partial z^2} + \frac{\partial}{\partial z}(\frac{\partial s}{\partial x}) = 0 \qquad (15)$$

$$\frac{\partial}{\partial x}(\frac{\partial s}{\partial z}) + M_0 \frac{\partial^2 r}{\partial x^2} = 0 \qquad (16)$$

The result of the subtraction between equations (15) and (16) is again the wave equation:

$$\frac{\partial^2 r}{\partial x^2} = \frac{\partial^2 r}{\partial z^2}$$

with solution:

$$r(x,z) = f(x+z) + g(x-z)$$

or:

$$r(x,t) = f[x(1 + \frac{1}{M_0}) + a_0 t] + g[x(1 - \frac{1}{M_0}) - a_0 t] \qquad (17)$$

B. DEVELOPMENT OF STATIC PRESSURE WAVEFORM

Assuming an isentropic process, the relation between local pressure and local density is:

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$$\frac{P}{\rho^k} = constant \quad \rightarrow \quad \frac{P}{\rho^k} = \frac{P_0}{\rho_0^k} \quad \rightarrow \quad P = P_0 \left(\frac{\rho}{\rho_0}\right)^k$$

Using the previous expression for the local density:

$$\rho = \rho_0[1 + s(x,t)]$$

the local pressure can be written:

$$P = P_0[1 + s(x,t)]^k \quad \rightarrow \quad P = P_0[1 + ks(x,t)]$$

or:

$$P = P_0[1 + p(x,t)]$$

where:

$$p(x,t) = F[x(1 + \frac{1}{M_0}) + a_0 t] + G[x(1 - \frac{1}{M_0}) - a_0 t]$$

which can be modified to include an harmonic form as:

$$p(x,t) = F(\frac{\omega L}{a_0}[\frac{x}{L}(1 + \frac{1}{M_0})] + \frac{a_0 t}{L}) + G(\frac{\omega L}{a_0}[\frac{x}{L}(1 - \frac{1}{M_0}) - \frac{a_0 t}{L}) \quad (18)$$

Next, we shall assume that the rotating shutter vanes superimpose a harmonic pressure perturbation upon the free stream of the form:

$$P = P_0[1 + h \cos\omega t]$$

where h<1 , at x=0 , so:

$$p(0,t) = F(\omega t) + G(\omega t) = h \cos\omega t$$

The static pressure harmonic perturbations at an upstream distance (x=-L) from the source remain consistent with the form of equation (18) and become:

$$p(-L,t) = \frac{h}{2}\{\cos[\frac{\omega L}{a_0}[-(1+\frac{1}{M_0})+\frac{a_0'}{L}]] + \cos[\frac{\omega L}{a_0}[-(1-\frac{1}{M_0})-\frac{a_0'}{L}]]\}$$

or:

$$p(-L,t) = h[\cos(\frac{\omega L}{a_0})\cos(\frac{\omega L}{a_0 M_0})\cos\omega t + \cos(\frac{\omega L}{a_0})\sin(\frac{\omega L}{a_0 M_0})\sin\omega t]$$

or:

$$p(-L,t) = h \cos(\frac{\omega L}{a_0})[\cos(\frac{\omega L}{a_0 M_0})\cos\omega t + \sin(\frac{\omega L}{a_0 M_0})\sin\omega t]$$

or:

$$p(-L,t) = h \cos(\frac{\omega L}{a_0})\cos(\frac{\omega L}{a_0 M_0} - \omega t)$$

with the final expression for the static pressure at a distance L upstream due to the pressure oscillation introduced by the rotating shutter vanes:

$$P = P_0 [1 + h \cos(\frac{\omega L}{a_0}) \cos(\frac{\omega L}{a_0 M_0} - \omega t)]$$

or:

$$P = P_0 [1 + h \cos\frac{\omega L}{a_0} \cos(\frac{\omega L}{U_0} - \omega t)]$$

and the general expression for the static pressure at any distance x and at a given time t, due to a harmonic perturbation source at x=0, becomes:

$$P(x,t) = P_0[1 + h \cos\frac{\omega x}{a_0}\cos(\frac{\omega x}{U_0} - \omega t)] \qquad (19)$$

C. DEVELOPMENT OF VELOCITY WAVEFORM

The above general expression for the static pressure yields:

$$p(x,t) = h \cos\frac{\omega x}{a_0}\cos(\frac{\omega x}{U_0} - \omega t)$$

and since:

$$P = P_0 [1 + h s(x,t)]$$

s(x,t) has the following form:

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$$s(x,t) = \frac{h}{k} \cos\frac{\omega x}{a_0}\cos(\frac{\omega x}{U_0}-\omega t) \qquad (20)$$

Differentiation of equation (20) with respect to t, yields:

$$\frac{\partial s(x,t)}{\partial t} = \frac{h\omega}{k} \cos\frac{\omega x}{a_0}\sin(\frac{\omega x}{U_0}-\omega t)] \qquad (21)$$

while differentiation, again of equation (20) now with respect to x, yields:

$$\frac{\partial s(x,t)}{\partial x} = -\frac{h\omega}{ka_0}\sin\frac{\omega x}{a_0}\cos(\frac{\omega x}{U_0}-\omega t)-\frac{h\omega}{kU_0}\cos\frac{\omega x}{a_0}\sin(\frac{\omega x}{U_0}-\omega t) \quad (22)$$

Substitution of equations (21) and (22) into equation (9), yields:

$$\frac{\partial r(x,t)}{\partial x} = \frac{h\omega}{ka_0}\sin\frac{\omega x}{a_0}\cos(\frac{\omega x}{U_0}-\omega t)$$

Integrating the above expression of r(x,t), with respect to x:

$$r(x,t) = \frac{h\omega}{ka_0}\int(\sin\frac{\omega x}{a_0}\cos(\frac{\omega x}{U_0}-\omega t))dx + C(t)$$

or:

$$r(x,t) = \frac{h\omega}{2ka_0}\int(\sin(\frac{\omega x}{a_0}+\frac{\omega x}{U_0}-\omega t)-\sin(\frac{\omega x}{a_0}-\frac{\omega x}{U_0}+\omega t))dx + C(t)$$

or:

$$r(x,t)=\frac{h\omega}{2ka_0}\int\{\sin[\frac{\omega x}{U_0}(M_0+1)-\omega t]+\sin[\frac{\omega x}{U_0}(M_0-1)+\omega t]\}dx \; + \; C(t)$$

and finally:

$$r(x,t) = \frac{-h}{2k} \{ \; \frac{M_0}{M_0+1} \; \cos[\frac{\omega x}{U_0}(M_0+1)-\omega t] \; +$$

$$+ \; \frac{M_0}{M_0-1} \; \cos[\frac{\omega x}{U_0}(M_0-1)+\omega t] \; \} \; + \; C(t) \qquad (23)$$

Now the rotating shutter vanes superimpose on the free stream a harmonic pressure perturbation of the form:

$$U = U_0[1 + q \; \cos(\omega t)]$$

where q<1 , at x=0 , so:

$$r(0,t) = q \; \cos(\omega t)$$

and:

$$r(0,t) = \frac{-h}{2k} [\; \frac{M_0}{M_0+1}\cos(-\omega t) \; + \; \frac{M_0}{M_0-1}\cos(\omega t) \;] \; + \; C(t)$$

thus:

$$C(t) = (q + \frac{h}{k} \frac{M_0^2}{M_0^2 - 1}) \cos(\omega t)$$

Substitution of the above expression for C(t) into equation (23), yields the final expression for r(x,t):

$$r(x,t) = \frac{-h}{2k} \frac{M_0}{M_0^2 - 1} \{ (M_0 - 1)\cos[\frac{\omega x}{U_0}(M_0 + 1) - \omega t] +$$

$$+ (M_0 + 1)\cos[\frac{\omega x}{U_0}(M_0 - 1) + \omega t] + 2[\frac{qk(M_0^2 - 1)}{hM_0} + M_0]\cos(\omega t) \} \qquad (24)$$

and the final expression for the velocity in the test section at any distance x from the rotating shutter valve and at any time t, becomes:

$$u = U_0 - U_0 \frac{h}{2k} \frac{M_0}{M_0^2 - 1} \{ (M_0 - 1)\cos[\frac{\omega x}{U_0}(M_0 + 1) - \omega t] +$$

$$+ (M_0 + 1)\cos[\frac{\omega x}{U_0}(M_0 - 1) + \omega t] + 2[\frac{qk(M_0^2 - 1)}{hM_0} + M_0]\cos\omega t \} \qquad (25)$$

Now for free stream Mach numbers below 0.1:

$$M_0 \leq 0.1 \quad \rightarrow \quad M_0^2 \leq 0.01 \quad \rightarrow \quad M_0^2 - 1 \approx -1$$

equation (25) can be written:

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$$u = U_0 + U_0 \frac{hM_0}{2k} \{ (M_0-1)\cos[\frac{\omega x}{U_0}(M_0+1)-\omega t] +$$

$$+ (M_0+1)\cos[\frac{\omega x}{U_0}(M_0-1)+\omega t] + 2[\frac{qk}{hM_0}+M_0]\cos\omega t \} \qquad (26)$$

VI. EXPERIMENTAL PROCEDURES IN THE INVESTIGATION OF THE OSCILLATING FLOW FIELD IN THE CLEAR-TUNNEL TEST SECTION

In order to measure the static pressure oscillations at the same time as the velocity oscillation in the clear tunnel test section, a static pressure probe and a hot wire probe were used. Both probes were installed at the same distance of 10.2 feet from the rotating shutter vanes and two inches apart, almost in the middle of the test section, just in front of the circulation control model future location.

Exactly the same instrumentation setup designed for the circulation control circular cylinder was used to obtain the experimental data. Thus the static pressure probe was connected to port number one of the Scanivalve® with the same tubing configuration used for its dynamic calibration.

A. CALIBRATION PROCEDURES

1. Pressure Measurement System Calibration

In addition to the test section static pressure the Scanivalve® received atmospheric pressure for calibration purposes. With the zero port of the Scanivalve® unit open to the atmosphere, the output of the transducer was adjusted to be equal to zero Volts. Then with application of an external static pressure input of 10 inches of water (52 psf) above atmospheric pressure, the pressure transducer voltage gain was adjusted to read 1.5 Volts. Thus the voltage output of the Scanivalve® would represent:

$$P_{scanivalve} = P_{testsection} - P_{atm}$$

The maximum voltage span of the Scanivalve® was set at plus or minus 5 Volt thus pressures equal to P_{atm} plus or minus 173.33 psf (1.2 psi) were able to be measured without over-voltage of the pressure acquisition system. The SRA 1200™ recorder board (Channel 1) was also calibrated for a true zero reading at zero Volts input, and set to accept plus or minus 2046 digital counts at plus or minus 5 Volts.

2. Velocity Measurement System Calibration

The hot-wire anemometer was adjusted at zero velocity, by placing a cover over the hot-wire probe, and at maximum gain to obtain an output of zero Volts. Then with the wind tunnel running at 100 ft/sec (the flow was adjusted to generate a water column corresponding to 100 ft/sec in the water micromanometer, based on local barometric pressure and temperature) and after selecting the 5 Volts scale, the hot-wire output was adjusted to obtain a reading of 0.8 full-scale Volts using the gain control knob, corresponding to an actual output of 4.0 Volts.

The SRA 1200™ (Channel 2) recorder board once again was calibrated for a true zero reading at zero volts input and set to accept plus or minus 2046 digital counts at plus or minus 5 volts. Thus to avoid over-voltage of the data acquisition system, a maximum of 5 Volts, corresponding to 125 feet per second, was used for velocity measurements.

B. DATA ACQUISITION

The pressure and velocity signals were output continuously from the Scanivalve® pressure transducer and the hot-wire anemometer, respectively, as analog voltages corresponding to a percent deflection of full scale, where full scale refered to a full scale deflection of the recorder boards. The time-dependent experimental data were recorded

and stored in order of occurrence on the 64-K capacity recorder boards. A data acquisition program, written in Quick Basic™, was cued by the electric signal which was tripped mechanically by the rotating shutter vanes, and armed the two recorder boards. When the boards were triggered, 2048 samples of pressure and velocity were recorded simultaneously over a period of 1024 milliseconds. This sample rate was programmed to match oscillation frequencies in a range between 10 and 50 Hz.

By calibrating the pressure signal recording board response for a maximum signal of plus or minus 173.33 psf (1.2 psi), a capability to resolve 0.085 psf (0.0006 psi) was achieved. The velocity recording board was calibrated for a maximum velocity of plus or minus 125 ft/sec; therefore its resolution was 0.061 ft/sec.

The signals were averaged to permit a separation of the time dependent portion of each signal from its respective mean value. This resulted in a discrete representation of both the oscillating pressure and. the corresponding velocity over a few cycles of flow oscillations. A complete program listing appears in Appendix B.

The operator supplied information to the program regarding tunnel operating conditions and ambient conditions for inclusion in the output data file header. The tunnel velocity, pressure and velocity signals were monitored continuously to ensure proper operation throughout the run. For steady flow operation, after the rotating shutter vanes were secured fully open in the horizontal position, a flow speed of 100 ft/sec was established as measured by the Pitot-Static tube and the water micromanometer. Oscillating flow fields were investigated at a range of oscillation frequencies of 14 to 40 Hz at increments of two Hz.

VII. DATA ANALYSIS

A.   DATA REDUCTION

In this investigation the rotating shutter vanes included three-inch wide blades, producing 50 percent closure. After conducting preliminary tests, it became evident that the mean value of the free stream velocity and the mean value of the static pressure measured from the Scanivalve® did not change with the flow oscillating frequency. The objective of these tests was accordingly expanded to include correlation of the experimental data with flow parameter variation. The value of 80 ft/sec was measured for the mean velocity at a frequency range of 15 to 40 Hz, and the value of 9.9 psf for the mean static pressure was measured by the Scanivalve® for the same frequency range.

After the time dependent portions of the signals were separated from the mean values, unsteady hot-wire velocity signals showed the presence of high frequency noise attributable to various sources such as the blower fan. A digital low-pass filter was included in the digital processing of the velocity signal with an equivalent low-pass filter time constant of five times the sampling frequency, with the algorithm set for a sampling rate of about 2000 samples per second. The pressure signal was filtered by the Scanivalve® signal conditioning amplifier and for this reason a clean signal was obtained.

The pressure data were corrected for phase lag and amplitude attenuation to account for the static pressure probe configuration, using the calibration curves for the probe from Chapter V. The unsteady pressure and velocity data were compared together versus time, using the same time and amplitude scales for each data set, for both phase angle and amplitude.

B. CORRELATION BETWEEN ANALYTICAL AND EXPERIMENTAL RESULTS

Velocity and static pressure waveforms showed sinusoidal behavior except around 25 Hz where a resonance occurred, deforming the velocity wave. It was estimated that the resonance appeared due to wave reflection on the constant pressure boundary at the tunnel inlet (organ pipe effect).

After the waveforms for velocity oscillations were plotted, it was apparent that the amplitude of oscillation did not changed significantly with the oscillation frequency. With some small variations the velocity amplitude maintained the same value of 4 ft/sec throughout the whole frequency spectrum that was tested. This value corresponds to 5 percent of the mean velocity, which was measured to be 80 ft/sec. But when the corrected waveforms for static pressure oscillations were plotted, the amplitude of oscillation displayed periodic dependence upon the oscillation frequency. The maximum value for the static pressure amplitude of 7.9 psf was observed at the oscillation frequency of 34 Hz corresponding to approximately 80 percent of the mean static pressure measured by the Scanivalve® (9.9 psf), while the minimum value of 2.0 psf was observed at 18 Hz.

The above experimental results were used to estimate the amplitude multiplication coefficients q and h in the analytical expressions for velocity and pressure harmonic perturbations, superimposed on the free stream from the rotating shutter vanes:

$$U = U_o (1 + q \cos\omega t) \quad , \quad q < 1$$

and:

$$P = P_o (1 + h \cos\omega t) \quad , \quad h < 1$$

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Thus the maximum percentage variation of static pressure amplitude was used to approximate the amplitude multiplication coefficient h , and the constant percentage variation of the velocity amplitude was used to approximate the amplitude multiplication coefficient q. Changes to the above coefficients were observed when the flow blockage, introduced by the rotating shutter vanes, was increased by increasing the width of the blades.

The analytical expressions developed in Chapter V for the velocity and static pressure as functions of the oscillation frequency ω , of the distance from the rotating shutter vanes x , and time , were evaluated using the waveforms obtained from the corrected experimental data. Because the hot-wire and the static pressure probes were installed at the same distance, L=10.2 ft, from the rotating shutter vanes, it was not possible to verify the distance dependance of velocity and static pressure oscillations in the test section. The terms "local velocity" and "local static pressure" oscillations were more appropriate to be used for the experimentally obtained waveforms, denoting only velocity and pressure variations in the vicinity of the future model location, approximately 9 ft from the perturbation generator, the rotating shutter valve.

The analytical results for local velocity and local pressure were plotted versus time using the same plot format and at exactly the same frequencies (14 Hz to 40 Hz with increments of two Hz) for which the experimental investigation was conducted. The analytically obtained waveforms were then superimposed on the existing experimental data for direct comparison. Figures 15, 16, 17, 18, 19, and 20 illustrate typical waveforms observed for the frequencies 14, 20, 24, 30, 34, and 40 Hz respectively.

Analytical and experimental data appear to have the same phase angle and the same amplitude for all six different frequencies. The local velocity amplitude remained almost

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constant with increasing oscillation frequency at 4 ft/sec while the local pressure amplitude started to decrease at 14 Hz, reaching its minimum value around 20 Hz; it then started to increase, reaching its maximum value (8 psf) around 34 Hz; and then it started to decrease again. Direct comparison between analytical and experimental results was also made for the intermediate frequencies verifying once more the above observations. The relevant graphs are listed in Appendix A.

In order to obtain a more detailed picture of amplitude variations with increasing oscillation frequency, the amplitude of local velocity and the amplitude of local static pressure were analytically calculated for frequencies between 10 Hz and 100 Hz, and then plotted as functions of the oscillating frequency. The behavior of both amplitudes is illustrated in Figure 21.

The significant information appears to lie in the periodic nature of these functions. The local static pressure amplitude changes continuously with increasing frequency, jumping up between 4 and 80 percent of the value almost every 35 Hz. The local velocity amplitude demonstrated a behavior like a sinusoidally amplitude-modulated wave with a maximum value 9 percent and a minimum value 1 percent of the mean value. But from a macroscopic point of view, local velocity amplitude appears to remain constant at 4 percent of the mean value. In Figure 21 a comparison was attempted between analytic results of local static pressure and velocity amplitudes as a function of frequency.

Local velocity amplitude changes with frequency are very small compared to local static pressure amplitude changes and for this reason local velocity amplitude may be considered as a constant for a wide range of oscillation frequencies. Figures 22 and 23 provide a direct comparison between analytical and experimental results for amplitude variations. It is apparent that analytical results correlated well with the experimental

52
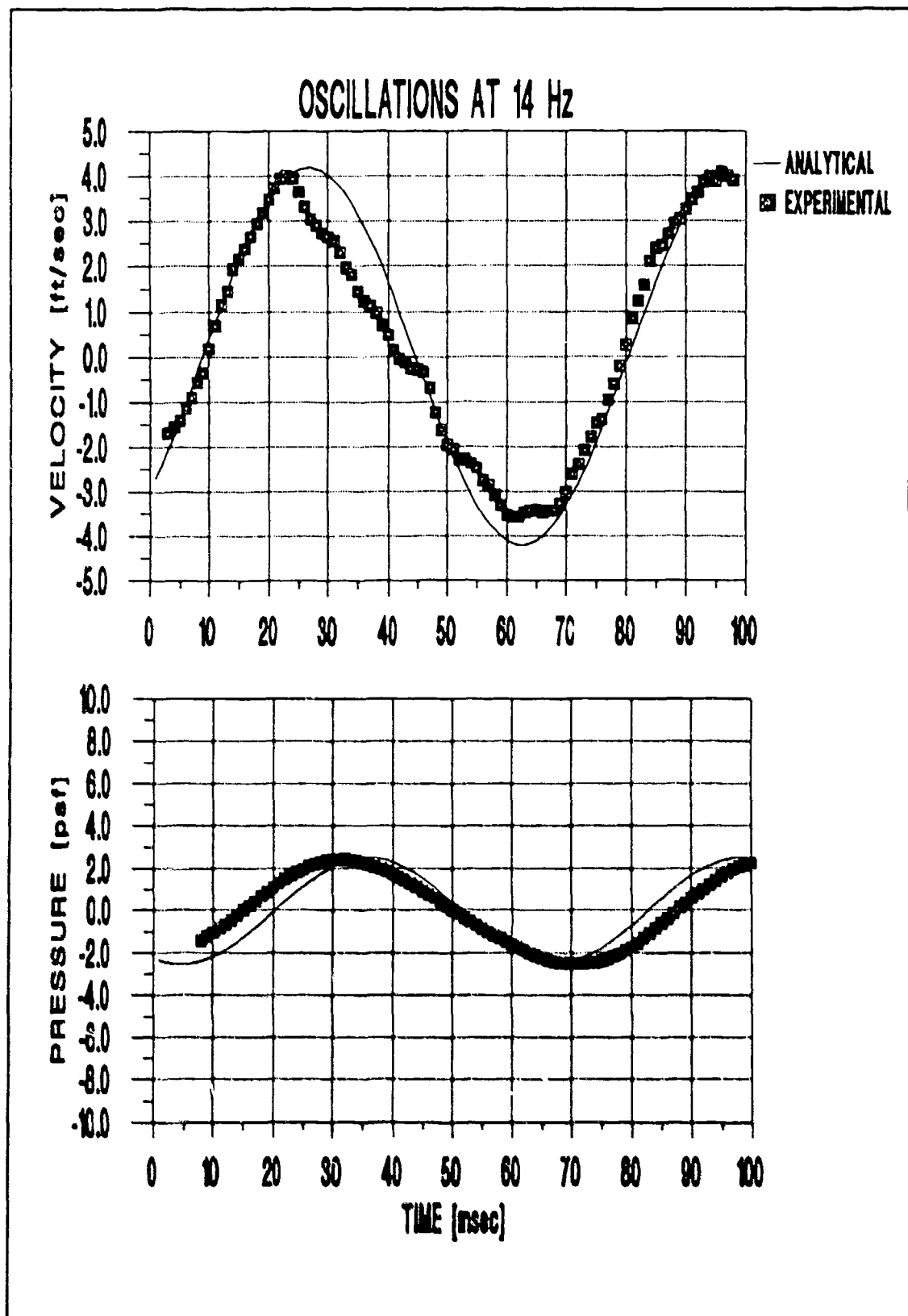
Figure 15 Velocity And Static Pressure Waveforms At 14 Hz
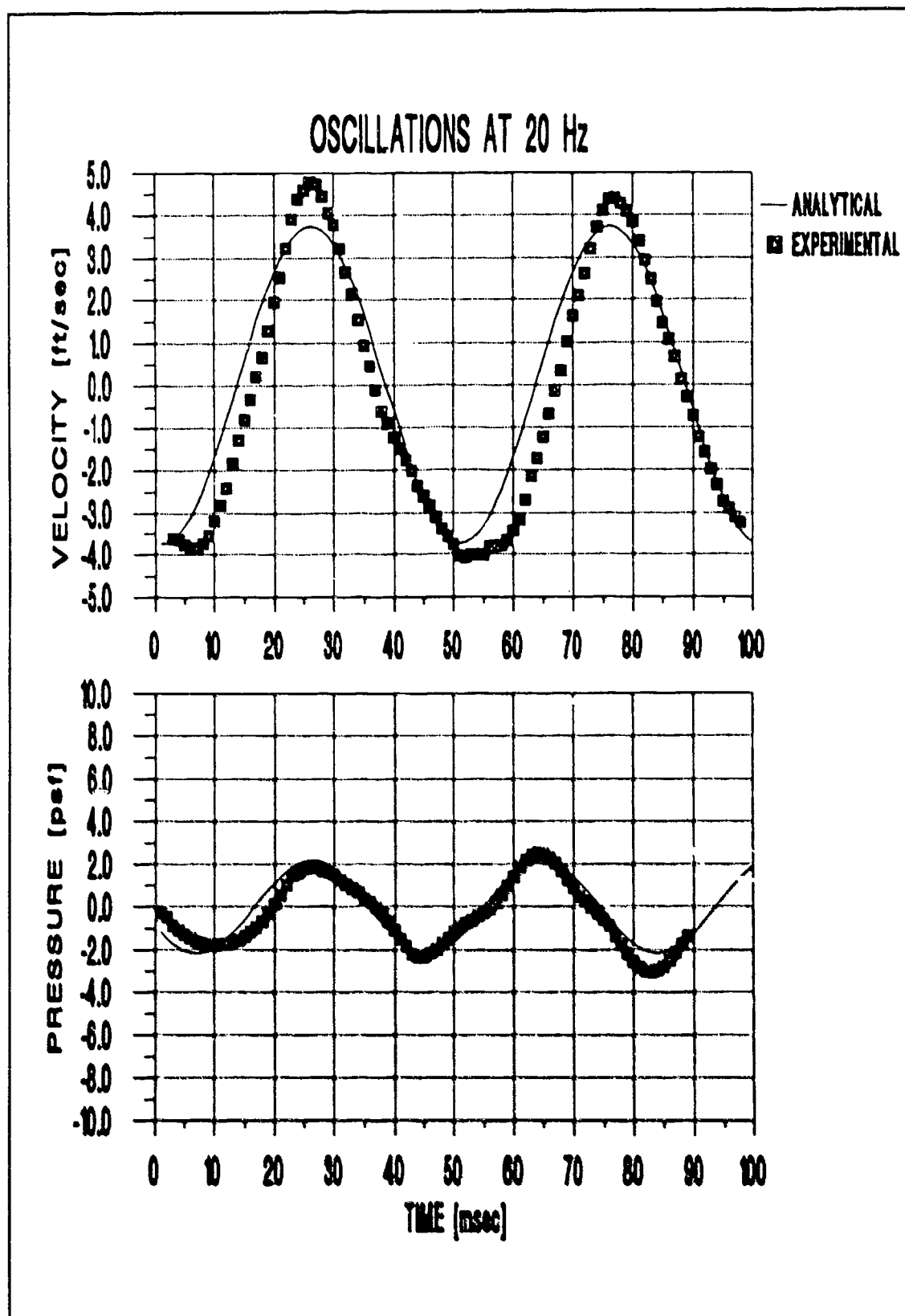
Figure 16 Velocity And Static Pressure Waveforms At 20 Hz
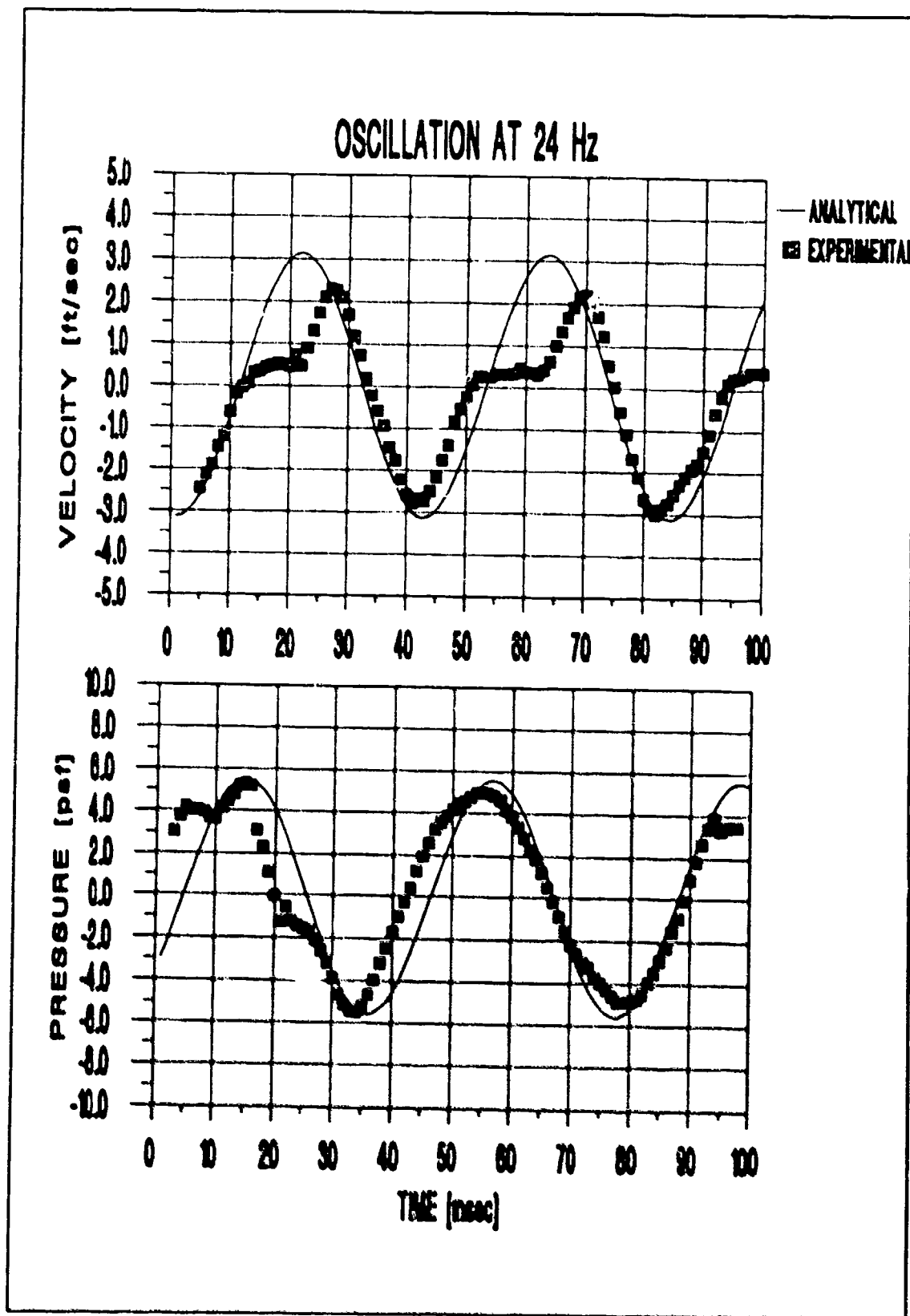
Figure 17 Velocity And Static Pressure Waveforms At 24 Hz

55
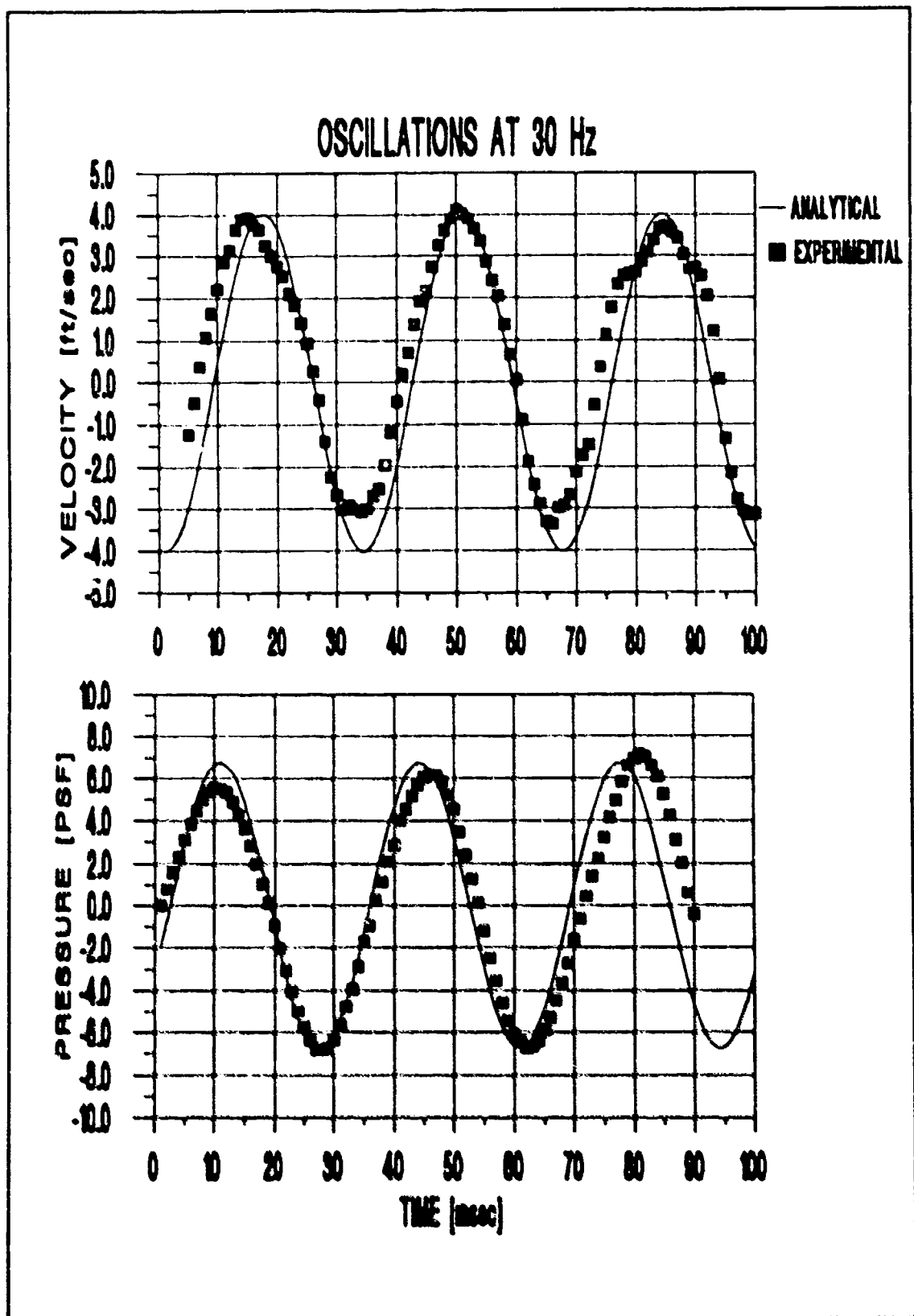
Figure 18 Velocity And Static Pressure Waveforms At 30 Hz

56
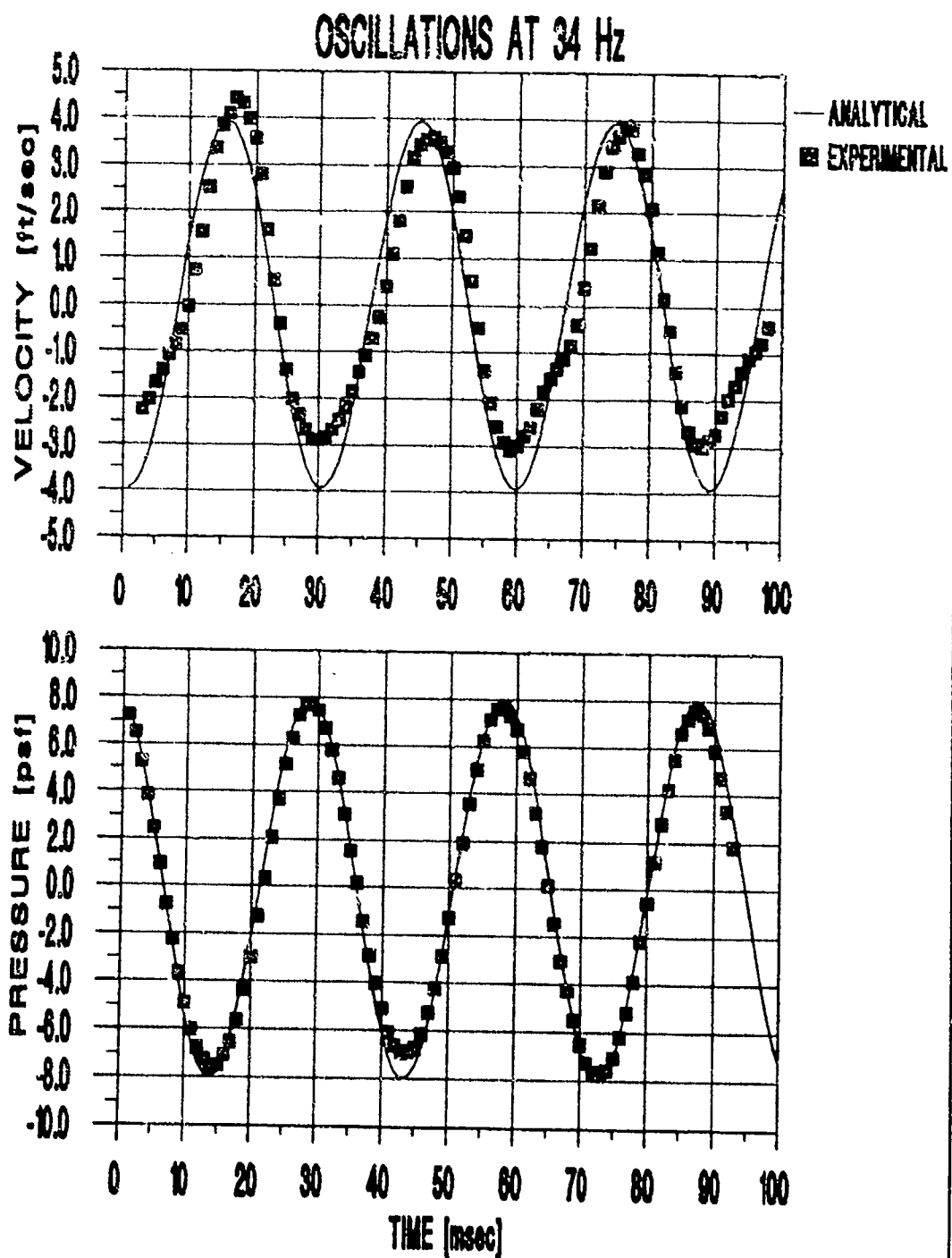
Figure 19 Velocity And Static Pressure Waveforms At 34 Hz
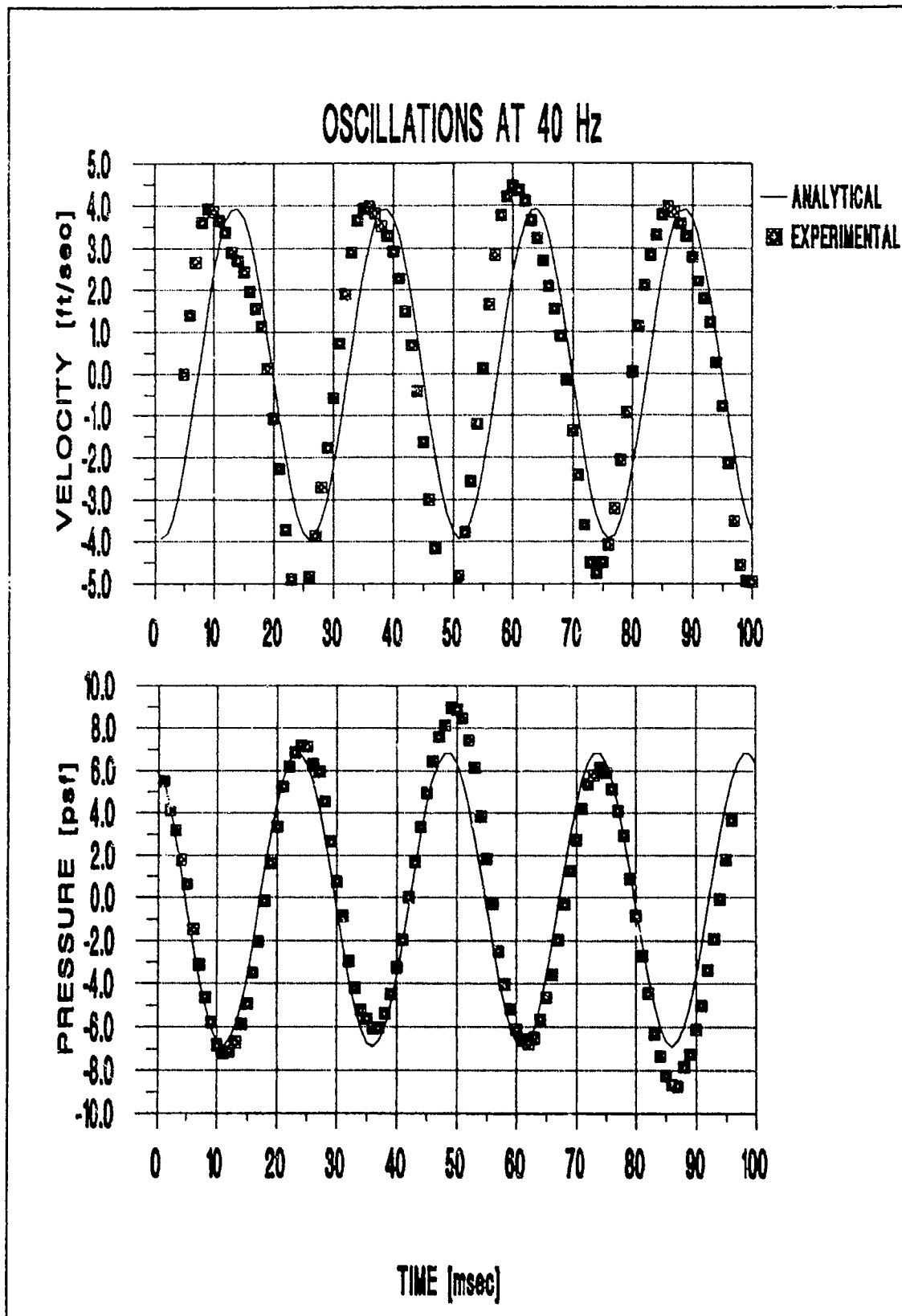
Figure 20 Velocity And Static Pressure Waveforms At 40 Hz

58
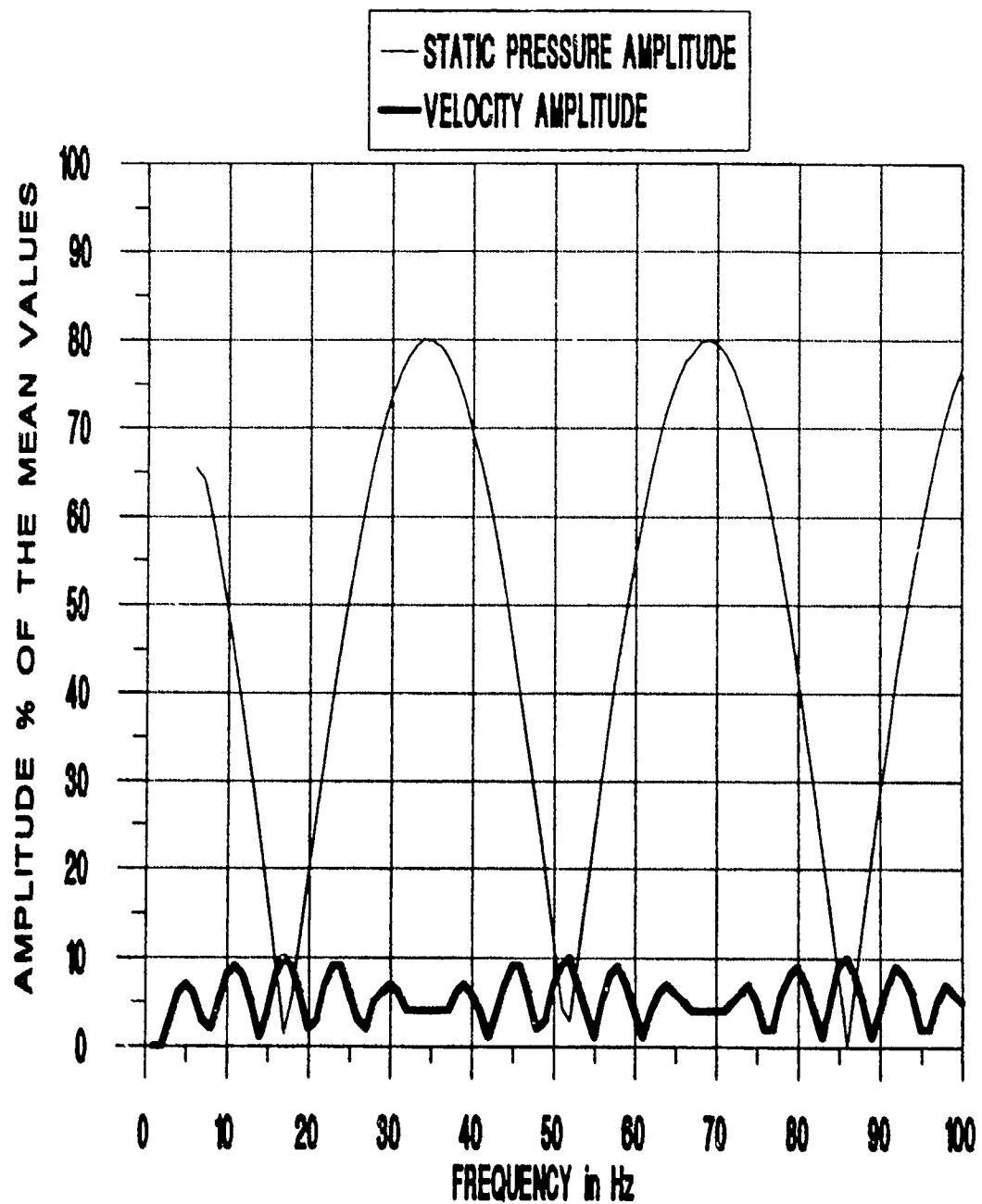
Figure 21 Static Pressure And Velocity Amplitude Variations

59
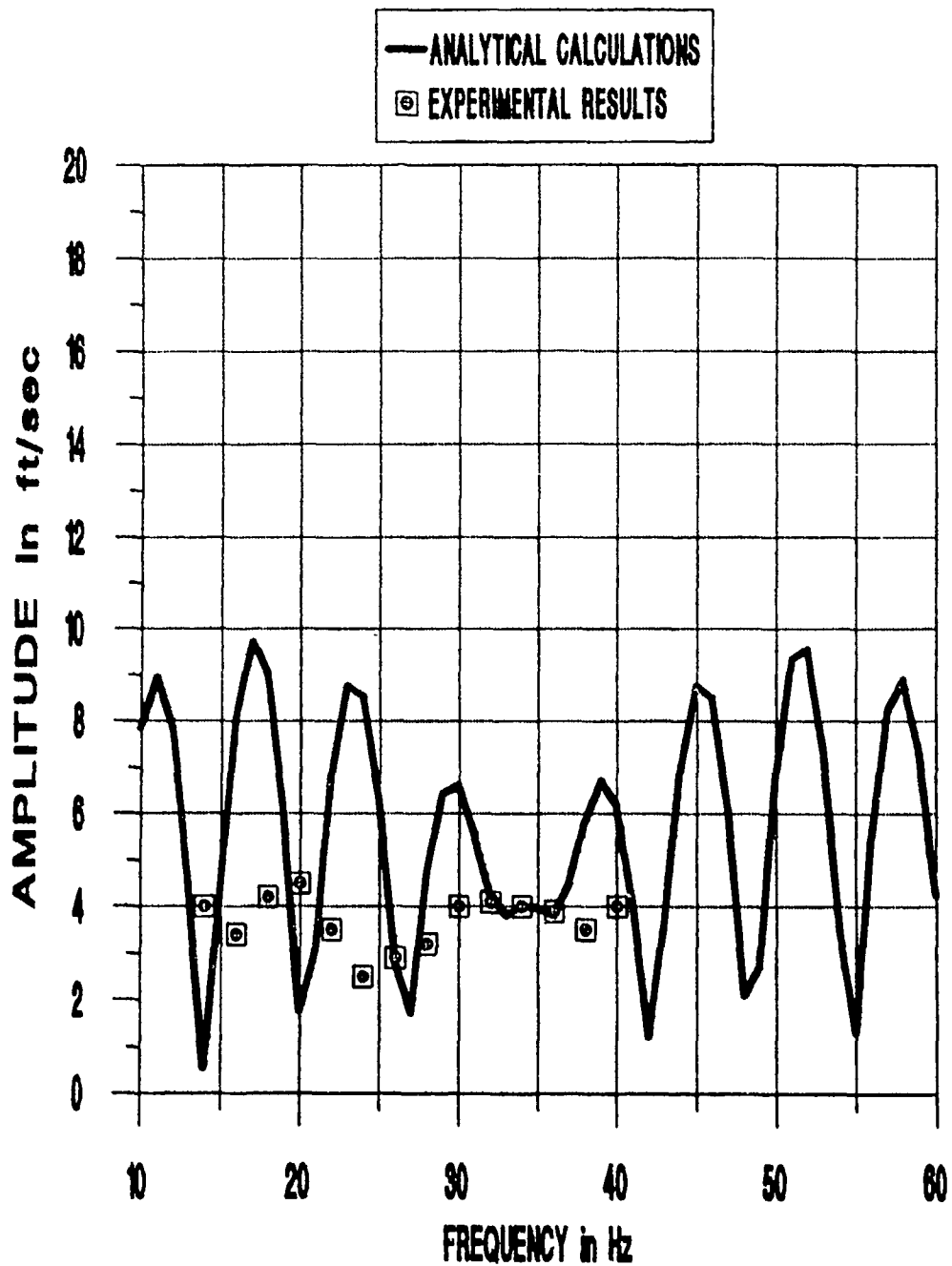
Figure 22 Experimental Results For Velocity Amplitude

60
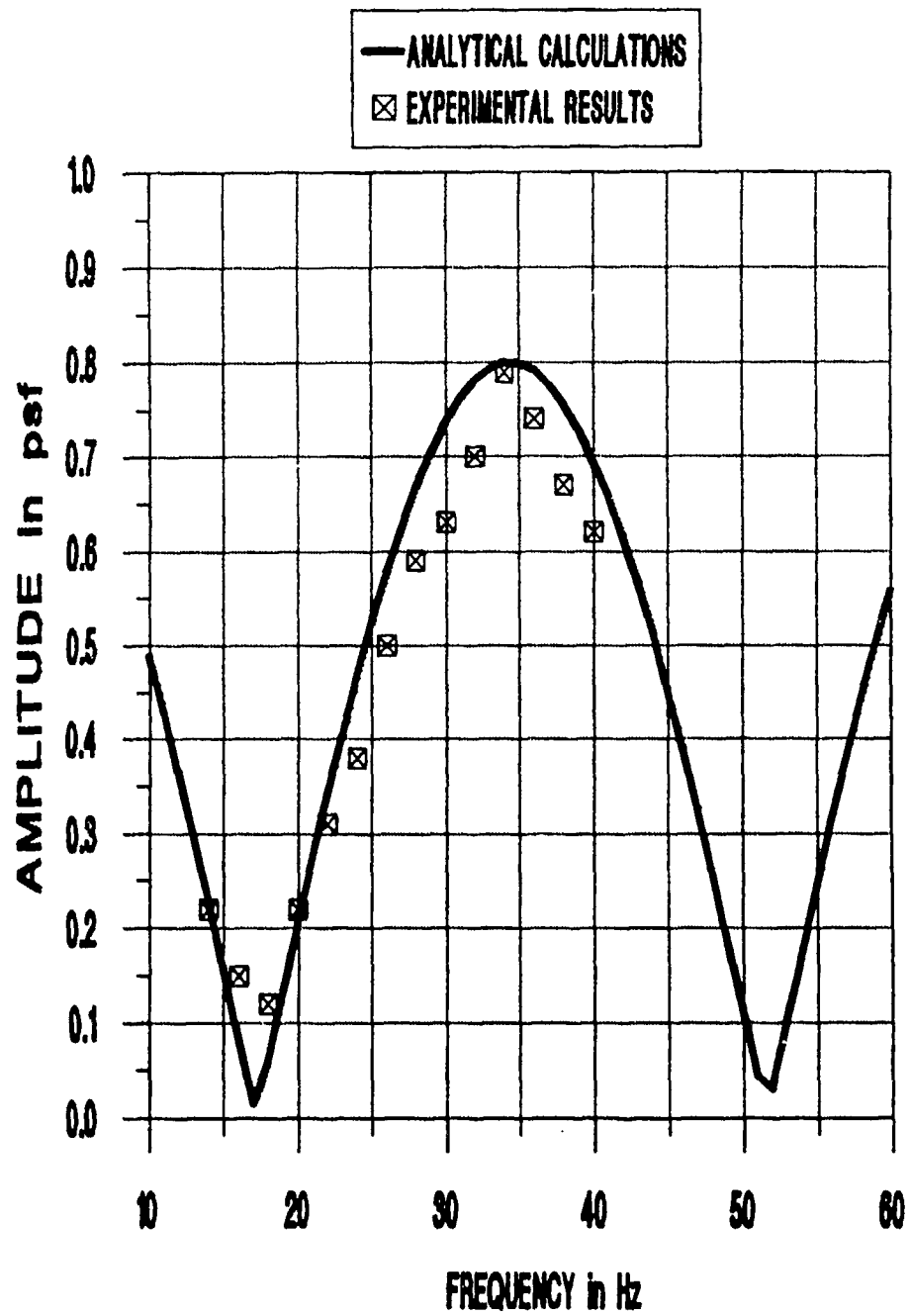
Figure 23 Experimental Results For Static Pressure Amplitude

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measurements. From this one might conclude that the pressure amplitude at the source

(the rotating shutter vanes), h , was itself not strongly dependent on frequency.

VIII. CONCLUSIONS

A Circulation Control model representing a generic, two-dimensional form of a tailboom configuration for a no tail rotor (NOTAR™) helicopter was designed and fabricated for subsequent testing in the low-speed oscillating flow wind tunnel. A frequency response calibration was performed of the unsteady pressure data acquisition system to determine the phase lag and amplitude reduction introduced from the transmission line connecting the pressure orifices on the model surface to the remote pressure transducer inside a Scanivalve®, for a variety of configurations. The calibration procedure was also performed on a static pressure probe used to obtain the static pressure inside the clear-tunnel test section. An existing real-time data acquisition system was used during both the instrumentation and wind tunnel calibrations. Modifications to existing software were made as needed.

Analytical expressions were developed for static pressure and velocity oscillations in the tunnel test section, introduced by the harmonic perturbations superimposed upon the free stream by the rotating shutter vanes. Comparisons were made between the analytic predictions and experimental data obtained during the clear tunnel test section calibrations. Data included measurements of local velocity using a constant temperature hot-wire and local static pressure using the dynamically calibrated static pressure probe.

From the direct comparison between experimental and analytical results the following conclusions may be drawn:

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1.   Analytical predictions for the oscillating flow field inside the tunnel test section strongly agreed with the experimentally obtained waveforms for local velocity and local static pressure.

2.   Changing oscillation frequency produced no significant amplitude variations of the local velocity perturbations. The local velocity amplitude remained almost constant at 5percent of the mean value as applied frequency was varied.

3.   Oscillation frequency induced significant periodic amplitude variations of local static pressure oscillations with a maximum value 80 percent of the mean value appearing first at the oscillation frequency of 18 Hz and followed by peak amplitudes thereafter at frequency intervals of 35 Hz.

The presentation of these results is the first indication of velocity and static pressure details in the oscillating flow wind tunnel. Follow on research is suggested to investigate the tunnel dynamic behavior at a second tunnel station located at a different axial position. Correlation of the static pressure and velocity perturbations between two axial locations will provide added credibility to the $\cos(\omega x/a_s)$ amplitude modulation factor shown on equation (19). Furthermore, it is suggested that confirmation of the dynamic behavior also be made at a second value of harmonic blockage.

The understanding of the flow phenomena in the oscillation frequency low-speed wind tunnel will improve the quality of the follow on tests on the circulation control circular cylinder model.

APPENDIX A: Velocity and Static Pressure Waveforms for Oscillation Frequencies

16, 18, 22, 26, 28, 32, 36, and 38 Hz

Local velocity and static pressure waveforms are presented for direct comparison with analytical predictions for the above intermediate frequencies, frequencies that were not listed in Chapter VI.

OSCILLATIONS AT 16 Hz

66
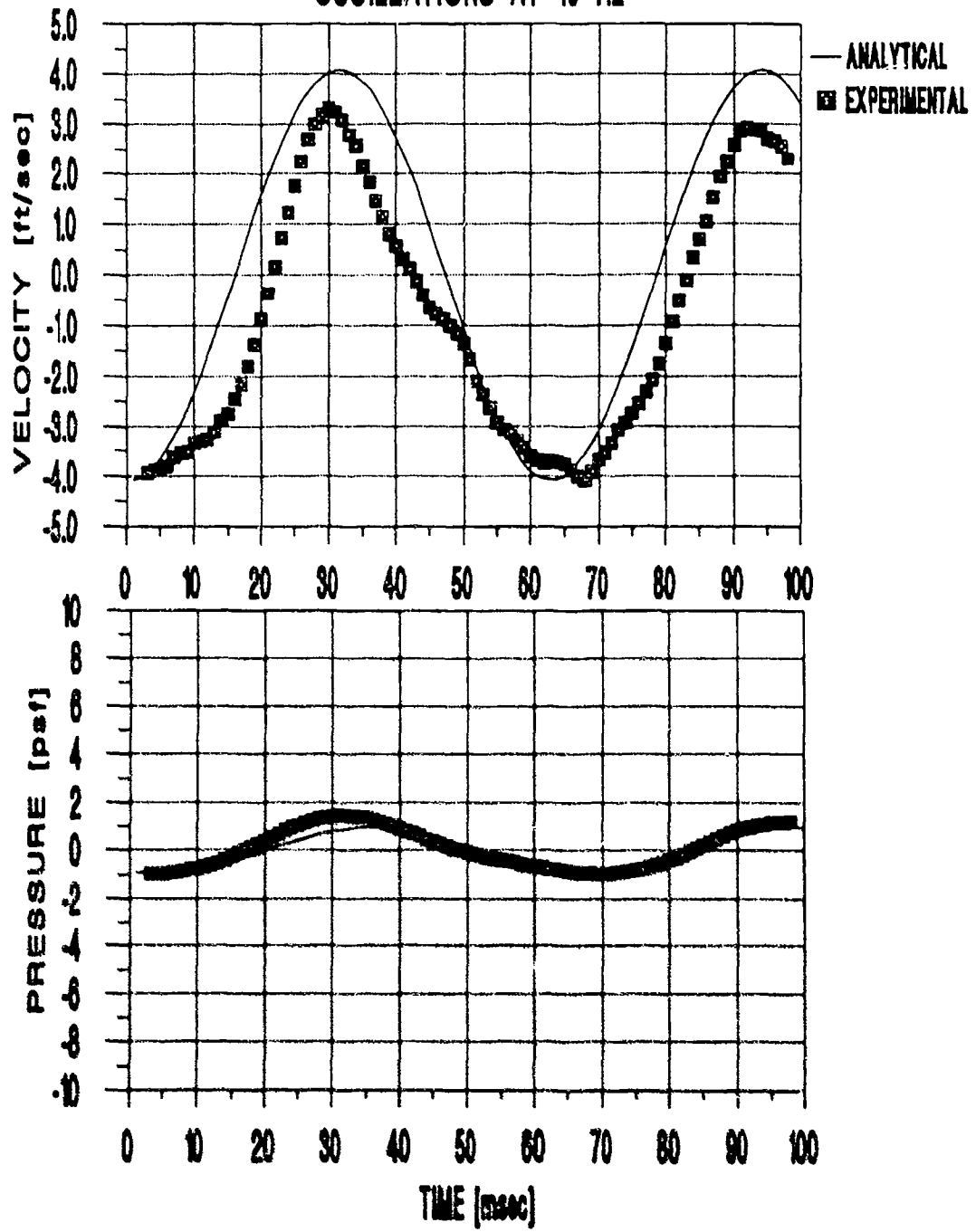
OSCILLATIONS AT 18 Hz

67
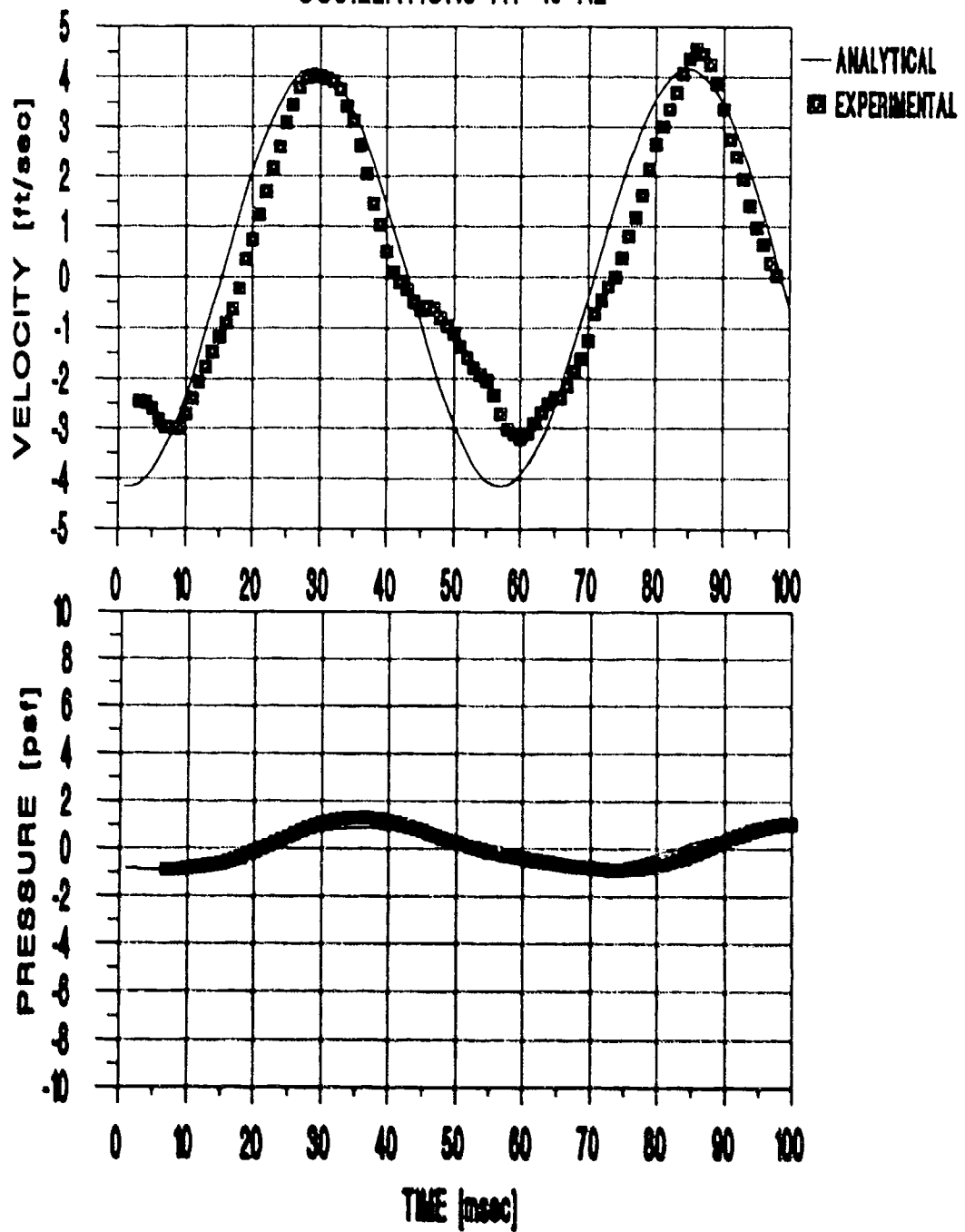
OSCILLATIONS AT 22 Hz

68
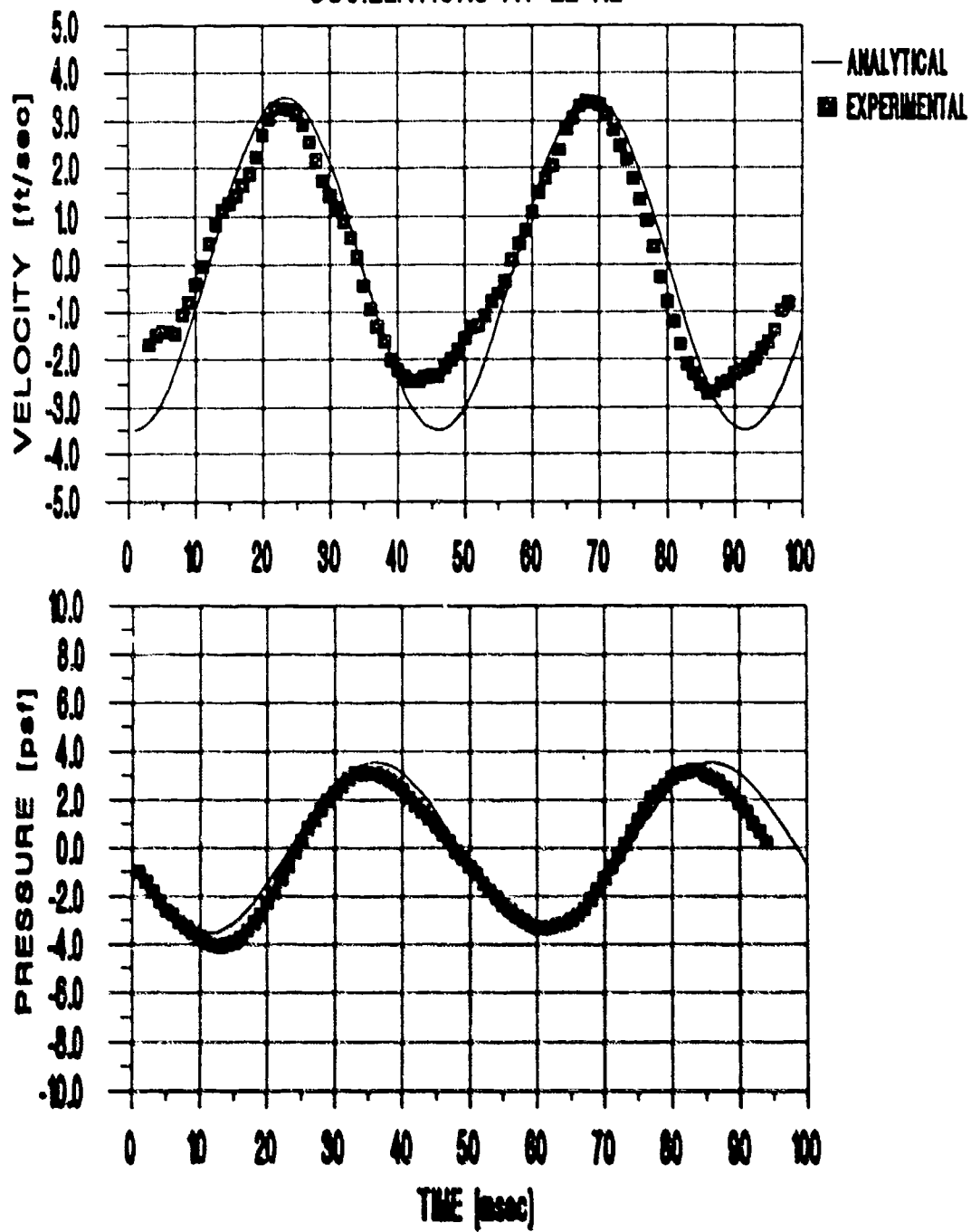
OSCILLATIONS AT 26 Hz
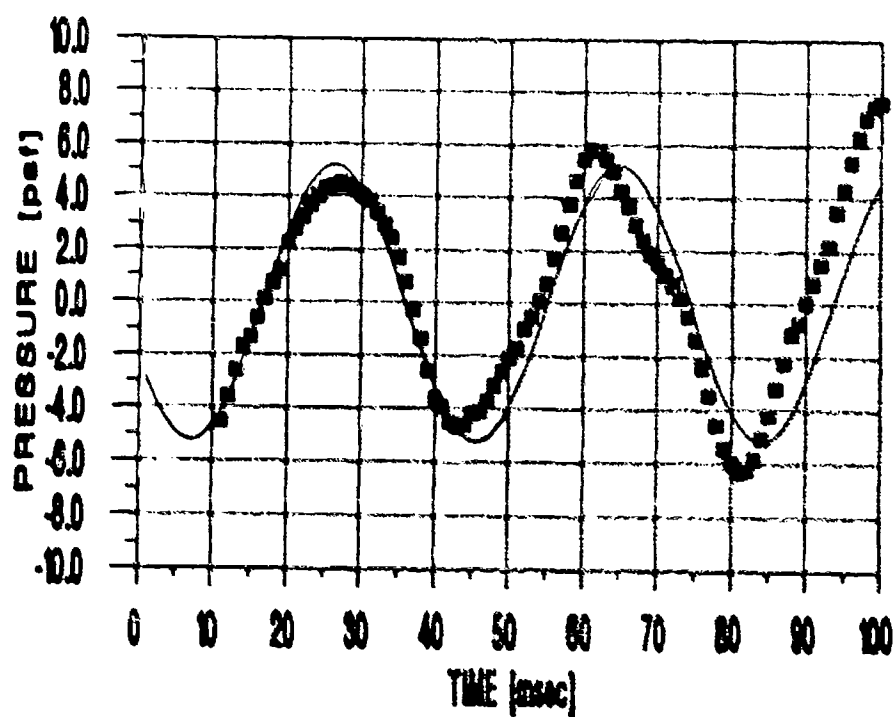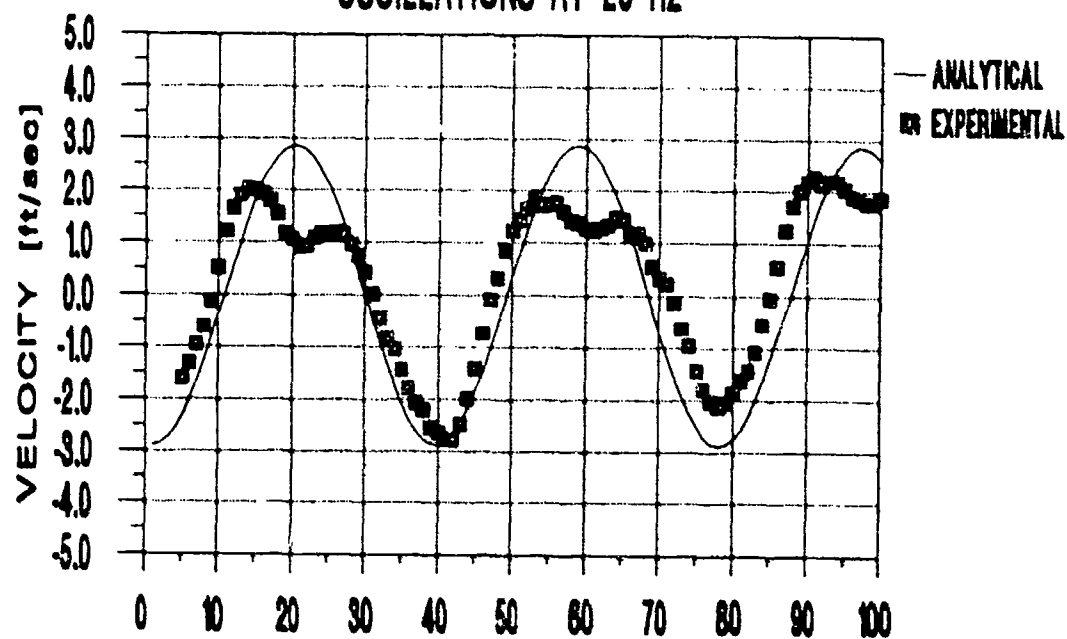
OSCILLATIONS AT 28 Hz
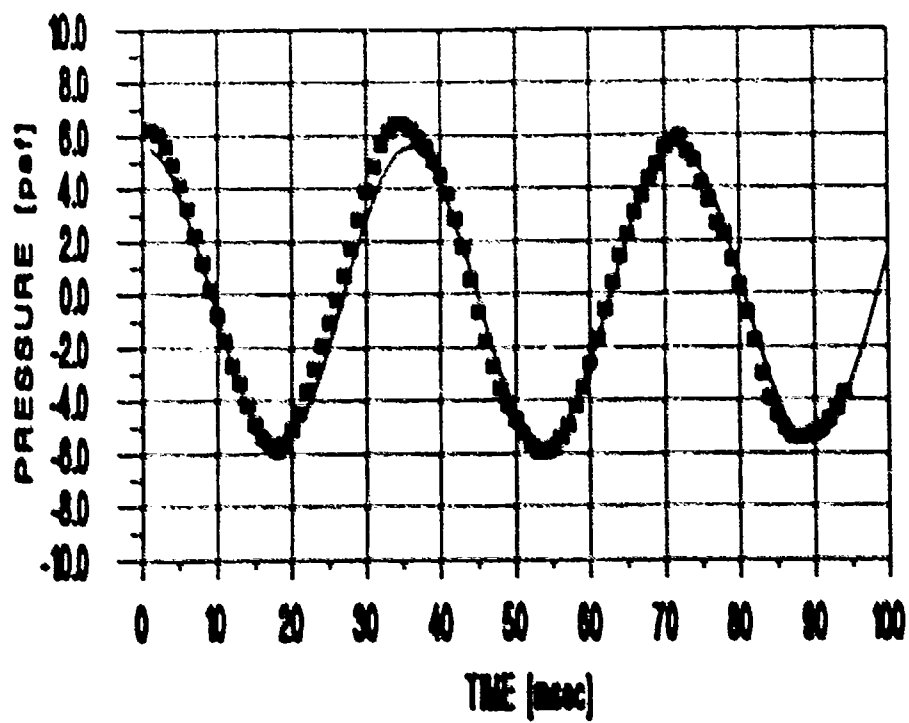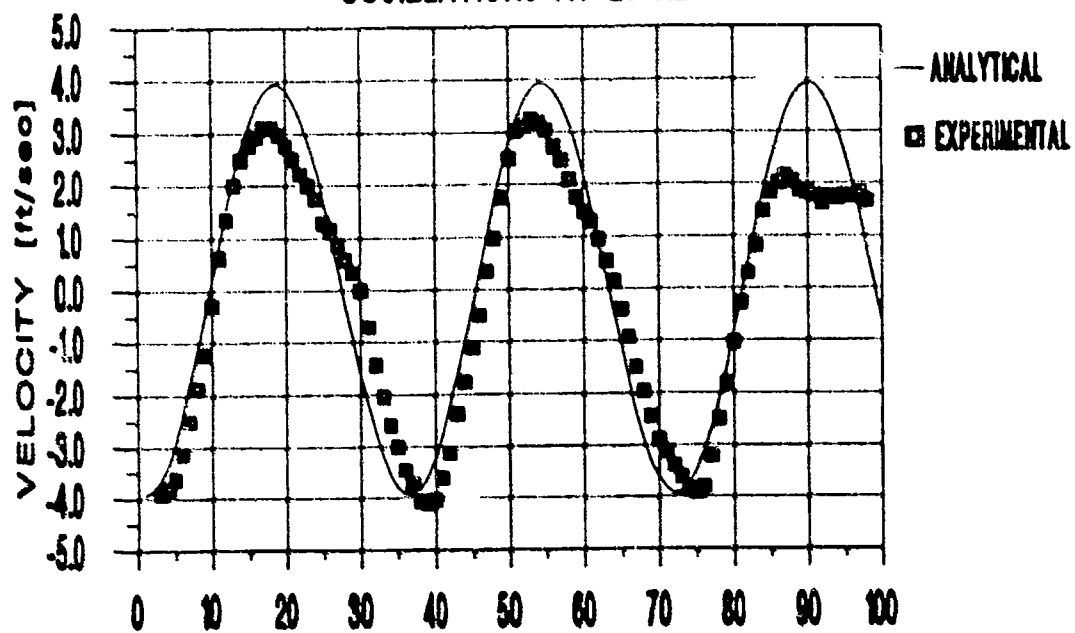
OSCILLATIONS AT 32 Hz

OSCILLATIONS AT 36 Hz

— ANALYTICAL
▨ EXPERIMENTAL

72
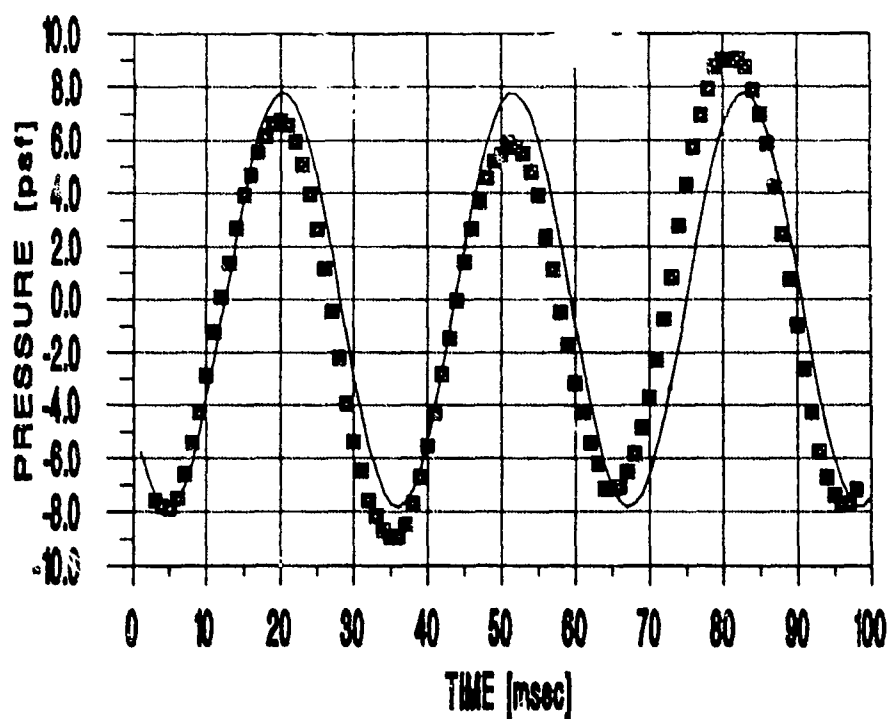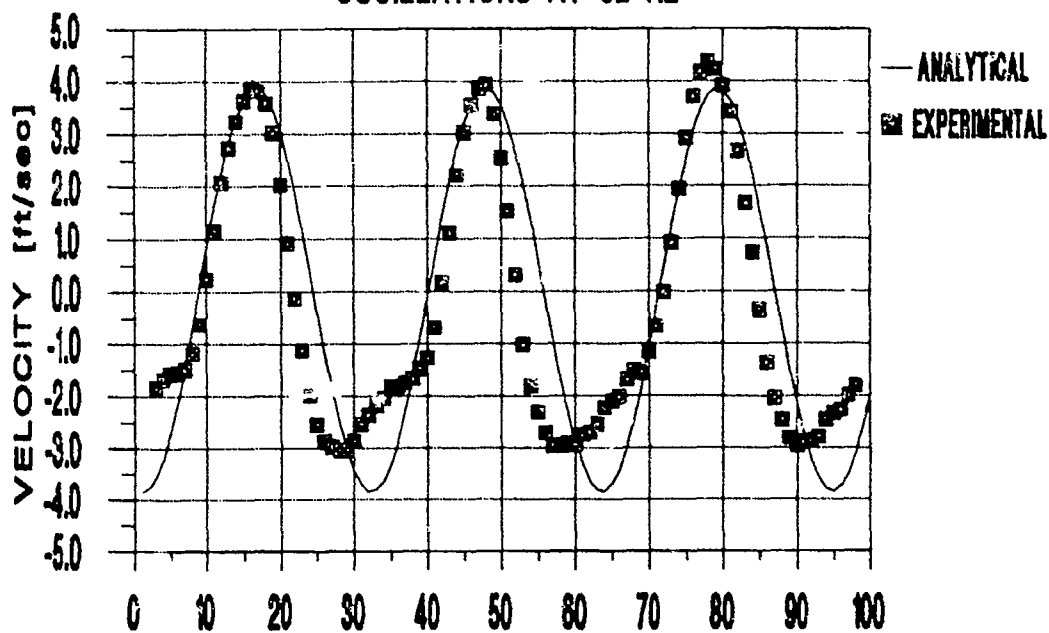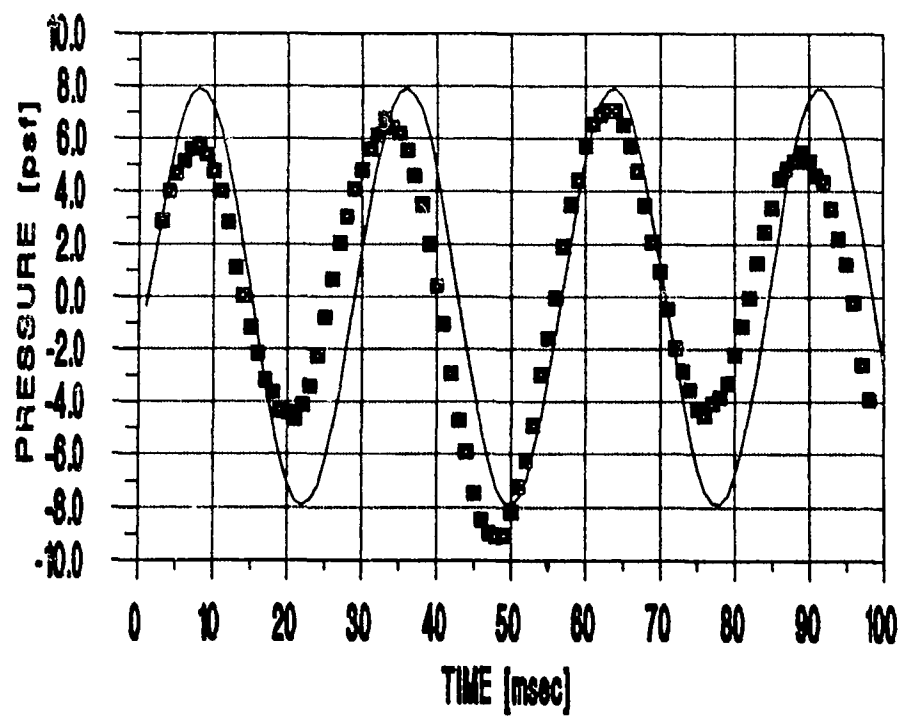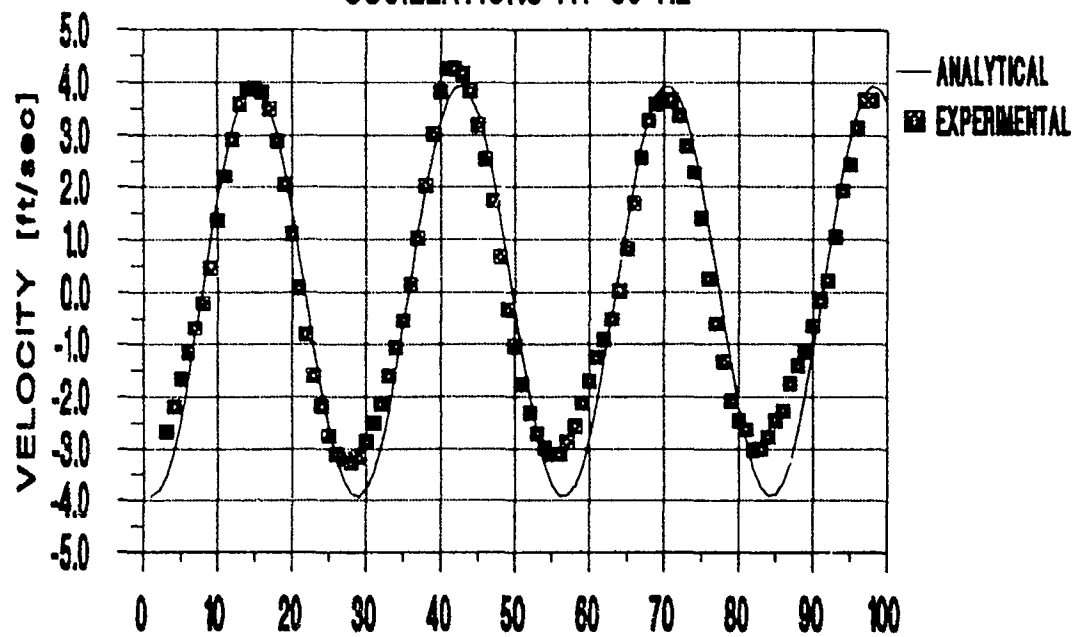
OSCILLATIONS AT 38Hz

73
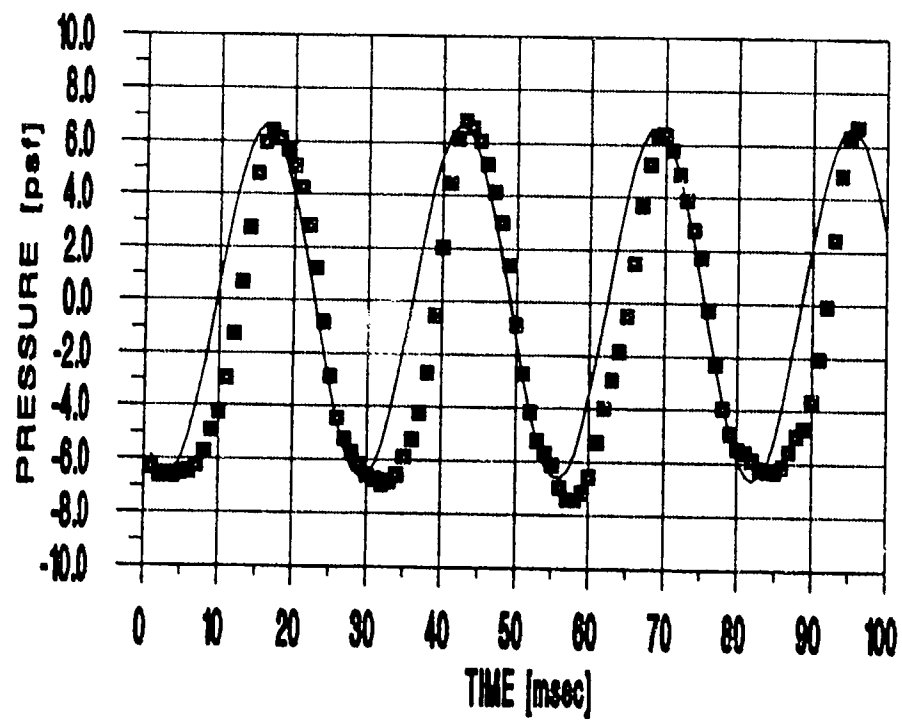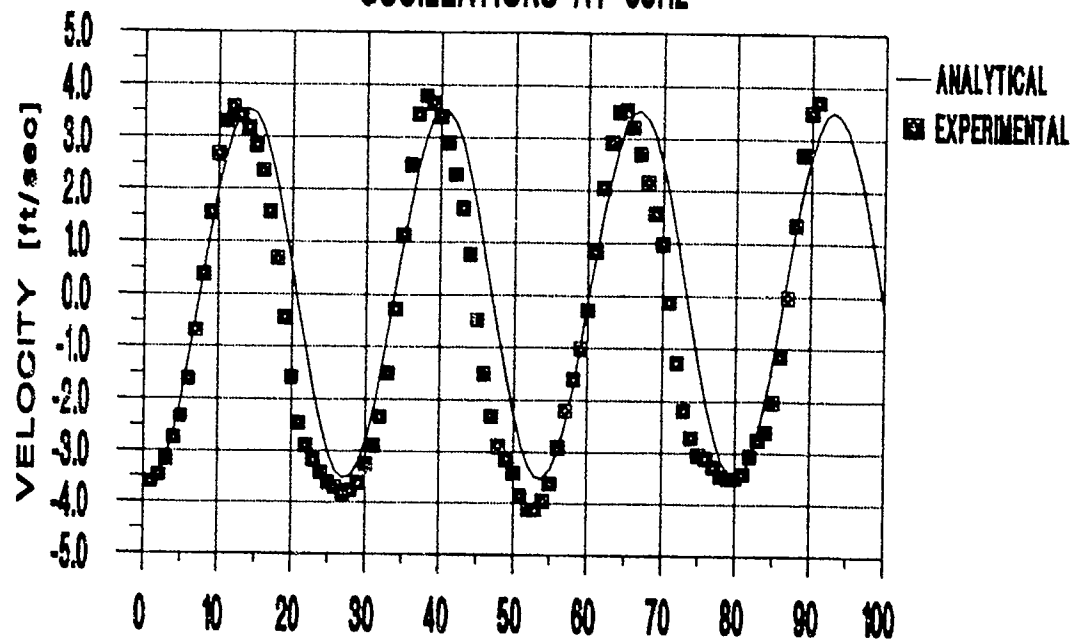
APPENDIX B: Data Acquisition / Data Reduction Program for Clear Tunnel Test

Section Survey

'PROGRAM TKDATA This program contains SUBROUTINES to control the SCANIVALVE,
　　　　'setup the SRA 1200 RECORDER boards, take dat, download that
　　　　'data into arrays VRAW, representing the raw velocity data,
　　　　'PRAW, representing the raw pressure data, process that data,
　　　　'and write the output to file and/or plot it on the screen.
　　　　'These SUBROUTINES and their respective functions are:

　　　　　　'HOME - Returns SCANIVALVE to HOME
　　　　　　'HEADER - Inputs data for a file header
　　　　　　'PORTNUM - Returns SCANIVALVE number (PORTNO)
　　　　　　'INIT - Initializes recorder boards
　　　　　　'RECORD - Records data
　　　　　　'getstartadd - Returns starting address of record
　　　　　　'getdat - Returns data samples
　　　　　　'PLOT - Plots data on screen
　　　　　　'LOAD - Loads two arrays, VRAW and PRAW, (in pseudo-
　　　　　　　　　'complex format)
　　　　　　'MEAN - Computes the mean of the arrays PRAW and VRAW,
　　　　　　　　　'subtracts the means and scales the values
　　　　　　'PORT - Advances the SCANIVALVE port
　　　　　　'ARRAY - Loads mean values of pressure and velocity
　　　　　　　　　'into vectors PMEAN and VMEAN and pressure
　　　　　　　　　'and velocity data into arrays P and V
　　　　　　'DISK - Outputs pressure, velocity and header data
　　　　　　　　　'to a file called DATA.XXX where XXX is the
　　　　　　　　　'Run Number.

```
VSCALE = 125!
PSCALE = 144!
OPTION BASE 1              'Sets lower bound of subscripts = 1
DIM physicaladdress(2)     'Physical adresses of the recorders
DIM inputscale(2)          'Full scale input voltage for each
                           'channel. May be 1, 2, 5, or 10 volts
DIM starts(2)              'Array containing starting addresses
DIM VRAW(4096)             'Array containing raw velocity data
DIM PRAW(4096)             'Array containing raw pressure data
DIM P(100)                 'Array containing pressure data
DIM V(100)                 'Array containing velocity data
GOSUB HEADER               'Calls for header information
GOSUB HOME                 'Sets SCANIVALVE to PORT 0
GOSUB PORT                 'Advances SCANIVALVE to PORT 1
GOSUB INIT                 'Use once before using recorders
```

'RECORDER CONTROL PARAMETERS
'These parameters are:
'   rate, the sample rate in mico-seconds, from 1 to 32767
'   samples, the number of samples per record, from 1 to memmax
'   psamples, the number of samples that preceed the trigger from
'   1 to memmax, but less than samples.

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```
'     mode$, trigger slope control, either "PLUS" or "MINUS"
'     setpoint, for trigger threashold, range is -100 to 100 %
'     optional:
'     inputscale(n) controls programmable gain for channel n.
'     Valid with values of 1, 2, 5 and 10; n may be either 1 or 2.

         SAMPLES = 2048            'Number of samples per record, (must
                                   'be of the form 2**n for processing)
         psamples = 1000           'Number of pretrigger samples
         setpoint = 10             'Trigger setpoint in % of full scale
         mode$ = "PLUS"            'Trigger mode$, (either "PLUS"
                                   'or "MINUS")
         rate = 1000              'Sample rate in u-seconds per point


         inputscale(1) = 5         'full scale for channel 1 is 5 volts
         inputscale(2) = 5         'full scale for channel 2 is 5 volts



FOR J = 1 TO 20000                'Delays data acquisition to allow
NEXT J                            'SCANIVALVE to settle
GOSUB PORTNUM                     'Reads current port number
GOSUB RECORD                      'Records data for one port
GOSUB PLOT                        'Plots recorded data for debugging
GOSUB LOAD                        'Loads data into arrays VRAW & PRAW
GOSUB PORT                        'Advances SCANIVALVE to next port
GOSUB MEAN                        'Computes the mean of each array,
                                 'subtracts the means (PBAR and VBAR),
                                 'and scales all values with PSCALE
                                 'and VSCALE so that output is in psf
                                 'and ft/sec. Arrays remain named PRAW
                                 'and VRAW
GOSUB ARRAY                       'Loads PBAR and VBAR into vectors
                                 'and PRAW and VRAW into arrays
GOSUB DISK:                       'Writes all header data, the vectors
                                 'PMEAN and VMEAN and the arrays P and
                                 'V to disk in a file RUNXXX.DAT
END                               'End of application code......
'=========================================================================================


'    SUBROUTINES FOR PROGRAM TKDATA


'_____

INIT:  'Use this routine once at startup for variable and hardware initialization

         k = 1024                 'k is 2 ** 10
         SAMPLES = 2000           'init # of samples per record
         psamples = INT(SAMPLES / 4)   'init presamples at .25 total record
         setpoint = 50            'trigger setpoint in % of full scale
         mode$ = "PLUS"           'trigger mode$ is either "PLUS" or "MINUS" or -
         rate = 4                 'default sample rate in us.
         memmax = (64 * k) - 1    'recorder memory size
         tbc = &H205              'time base control register address
         cwr = &H21E              '8253 control write register
         ctr0 = &H206             '8253 counter #1
         ctr1 = &H20E             '8263 counter #2
         ctr2 = &H216             '8253 counter #3
         clkie = 1                'for hardware hook not being used
```

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```
FOR J = 1 TO 2

'set up list for physical address starting at &h200
physicaladdress(J) = &H200 + (J * 32) - 32

'Read board jumpers and set inputscale(j)
'Absent boards get inputscale = 0
'Others will return 1, 2, 5 or 10

x = INP(physicaladdress(J) + 5) 'read jumpers w4, w5, w6, w7
x = x AND &H70

SELECT CASE x

    CASE 96
    inputscale(J) = 1

    CASE 80
    inputscale(J) = 2

    CASE 64
    inputscale(J) = 5!

    CASE 48
    inputscale(J) = 10!

    CASE ELSE
    inputscale(J) = 0

END SELECT

NEXT J

'Initialize timebase and run through one cycle:
rate = 1000

'Toggle reset line
OUT tbc, &HEF
OUT tbc, &HE3

'Set counter 0 to mode 3
OUT cwr, &H36

'Set sample rate
A = rate * 2
ha = INT(A / 256)
la = A - (ha * 256)
OUT ctr0, la
OUT ctr0, ha

'Set counter 1 to mode 3
'And divide by 4

OUT cwr, &H76
OUT ctr1, 4
OUT ctr1, 0
```

```
'Set counter 2 to mode 5
OUT cwr, &HBA

'Set number of samples
B = (SAMPLES - psamples) / 4
hb = INT(B / 256)
lb = INT(B - (hb * 256))

OUT ctr2, lb
OUT ctr2, hb

'Set trigger level
A = INT(setpoint * 1.28 * -1) + 127 - 7
OUT &H203, A

'Arm timebase in chosen mode

'First create timebase control word
 tbctw = &HF7

'clkie always equals 1
IF clkie = 1 THEN tbctw = tbctw AND &HFB

'Test mode$( PLUS or MINUS )
IF mode$ = "MINUS" THEN tbctw = tbctw AND &H7F
OUT tbc, tbctw AND &HED

'Wait loop to get pretrigger data
ptdelay = psamples * rate * .000001
A = TIMER + ptdelay + 1

'This loop generates and error when timing through midnight
WHILE (TIMER < A AND INKEY$ = ""): WEND

OUT tbc, tbctw AND &HFE
OUT tbc, tbctw

'Force a trigger

OUT tbc, tbctw OR 8
FOR J = 1 TO 500: NEXT J
OUT tbc, tbctw

'This ends the time base first cycle and initialization..

RETURN
'_____


RECORD: 'recording sequence control

    CLS

    'VIEW
    'WINDOW (0, 2048)-(511, -2048)
    'LINE (50, 2000)-(461, -1850), lincol, B

    LOCATE 3, 27
```

```
PRINT "RECORDING SEQUENCE CONTROL "

LOCATE 8, 25
PRINT "1. ) Initialize Recorder Hardware "

'First set the gain on boards 1 and 2.

FOR J = 1 TO 2

SELECT CASE inputscale(J)

        CASE 1
        mask = &H9F

        CASE 2
        mask = &HDF

        CASE 5
        mask = &HBF

        CASE 10
        mask = &HFF

        CASE ELSE
        mask = &HFF

END SELECT

IF J = 1 THEN mask1 = mask
OUT physicaladdress(J) + 5, mask

NEXT J

'Toggle reset line
OUT tbc, &HEF AND mask1
OUT tbc, &HE3 AND mask1

'Set counter 0 to mode 3
OUT cwr, &H36

'Set sample rate
A = rate * 2

ha = INT(A / 256)
la = A - (ha * 256)
OUT ctr0, la
OUT ctr0, ha

'Set counter 1 to mode 3
'And divide by 4

OUT cwr, &H76
OUT ctr1, 4
OUT ctr1, 0

'Set counter 2 to mode 5
OUT cwr, &HBA
```

```basic
'Set number of samples
B = (SAMPLES - psamples) / 4
hb = INT(B / 256)
lb = INT(B - (hb * 256))

OUT ctr2, lb
OUT ctr2, hb

'Set trigger level
A = INT(setpoint * 1.28 * -1) + 127 - 7
OUT &H203, A

'Arm timebase in chosen mode

'First create timebase control word
 tbctw = &HF7 AND mask1

'clkie always equals 1
IF clkie = 1 THEN tbctw = tbctw AND &HFB

'Test mode$( PLUS or MINUS )
IF mode$ = "MINUS" THEN tbctw = tbctw AND &H7F

LOCATE 10, 25
PRINT "2. ) Pretrigger Delay "

OUT tbc, tbctw AND &HED
REM out tbc,tbctw

'Wait loop to get pretrigger data
ptdelay = psamples * rate * .000001
A = TIMER + ptdelay + 1

'This loop generates and error when timing through midnight
WHILE (TIMER < A AND INKEY$ = ""): WEND

LOCATE 12, 25
PRINT "3. ) Arm Recorder...wait for trigger"

OUT tbc, tbctw AND &HFE
OUT tbc, tbctw

B$ = ""
A = 1

WHILE (A <> 0 AND INKEY$ = "")
A = INP(&H205) AND 3

    IF INKEY$ <> "" THEN
    OUT tbc, tbctw OR 8
    FOR J = 1 TO 500: NEXT J
    OUT tbc, tbctw
    END IF
WEND

LOCATE 14, 25
PRINT "4. ) Triggered ...wait until recording complete"
```

```
WHILE (A = 1 AND INKEY$ = "")
A = INP(&H205) AND 1
WEND

LOCATE 16, 25
        PRINT "6. ) Recording port number..."; PORTNO
PRINT "6. ) Hit any Key to Exit"

A$ = ""
WHILE A$ = ""
A$ = INKEY$
WEND

CLS
```

RETURN
'_____

```
getstartadd:  'read 18 bit stop address from 3 ports and convert to number
              'only 16 bit stop address from 2 ports for 64 k sample memory

        stopadd = 0

        'bits 16 and 17
        REM sadd1 = INP(physicaladdress(i) + 2) AND &H3
        REM sadd1 = sadd1 * 64 * 1024
        REM stopadd = sadd1

        'bits 8 thru 15
        sadd1 = INP(physicaladdress(I) + 1)
        sadd1 = sadd1 * 256
        stopadd = stopadd + sadd1

        'bits 0 thru 7
        stopadd = INP(physicaladdress(I)) + stopadd

        'Calculate starting address by subtracting samples
        starts(I) = stopadd - SAMPLES - 4

        'Starting address is never negative, so fix it if needed.
        IF starts(I) < 0 THEN starts(I) = starts(I) + 65536
```

RETURN
'_____

```
        'GETDAT and gd1 both get a single value from the recorder memory,
        'this value is returned in the variable DAT. DAT is a
        'number that ranges from -2048 to +2047.

        'GETDAT will initialize the memory pointer with the value in BRDST.
        'However, this me... wory pointer need only be initialized one time per
        'record transfer.  Then the calling routine can continuously call gd1
        'and the recorder memory pointer will auto increment after each call
```

'_____

```
getdat:
```

```basic
        IF brdst > memmax THEN brdst = brdst - memmax
        IF brdst < 0 THEN brdst = brdst + memmax

        REM str = INT(brdst / 65536)
        REM brdst = brdst - (str * 64 * 1024)
        strhi = INT(brdst / 256)
        strlo = brdst - (strhi * 256)

        OUT physicaladdress(I), strlo
        OUT physicaladdress(I) + 1, strhi
        REM OUT physicaladdress(i) + 2, str


gd1:
        A = INP(physicaladdress(I) + 3)
        B = INP(physicaladdress(I) + 4)
        B = (B AND &HF) * 256
        DAT = (A + B - 2048) * -1


RETURN
```
'———————————————————————————————

PLOT: This routine will plot the arrays to the screen.

```basic
        SCREEN 2                    '2 for cga, 3 for hercules and
                                    '9 for ega. (Only required for
                                    'plotting)

        WINDOW (0, 2048)-(SAMPLES, -2048)

        'plot data on screen
        FOR I = 1 TO 2

                GOSUB getstartadd       'Determines the starting point of
                                        'the record in memory
                brdst = starts(I)       'Initializes memory pointer and gets
                GOSUB getdat            'first data point
        PSET (0, DAT)

                FOR J = 1 TO SAMPLES
                        GOSUB gd1       'gets sample in dat and auto inc. ptr

                        LINE -(J, DAT)
                NEXT J
        NEXT I
```

RETURN
'———————————————————————————————

LOAD: 'Load data into an array
```basic
        FOR I = 1 TO 2

                GOSUB getstartadd       'Initializes boards for data
                brdst = starts(I)       'downloading and gets first
                GOSUB getdat            'sample
```

```
FOR J = 1 TO (2 * SAMPLES) STEP 2

        GOSUB gd1      'Gets sample and increments pointer
        IF I = 1 THEN
            VRAW(J) = DAT
            VRAW(J + 1) = 0!
        END IF
        IF I = 2 THEN
            PRAW(J) = DAT
            PRAW(J + 1) = 0!
        END IF

    NEXT J
    NEXT I


RETURN
'_____


HEADER:
    'This subroutine collects run information for a file header and
    'data processing
        CLS                         'Clear screen
        LOCATE 2, 10                     'Locates text
        PRINT "RUN DATA INPUT"
        LOCATE 4, 20
        PRINT "1. Input a Run Number consisting of the Model"
        LOCATE 5, 25
        PRINT "Number and the Angle of Attack in the form XYY."
        INPUT RUNNO$
        LOCATE 6, 25
        PRINT "RUN NUMBER - "; RUNNO$
        LOCATE 8, 20
        PRINT "2. Input Date"
        INPUT DAIT$
        LOCATE 9, 25
        PRINT "DATE-"; DAIT$
        LOCATE 11, 20
        PRINT "3. Input Time"
        INPUT TYME$
        LOCATE 12, 25
        PRINT "TIME-"; TYME$
        LOCATE 14, 20
        PRINT "4. Input Model Description"
        INPUT MODEL$
        LOCATE 15, 25
        PRINT "MODEL-"; MODEL$
        LOCATE 17, 20
        PRINT "5. Input Angle of Attack (+/-) in Degrees"
        INPUT AOA
        LOCATE 18, 25
        PRINT "ANGLE OF ATTACK-"; AOA; "DEGREES"
        LOCATE 20, 20
        PRINT "6. Input Mean Dynamic Pressure in CM of Water"
        INPUT PDYN
        LOCATE 21, 25
        PRINT "MEAN DYNAMIC PRESSURE-"; PDYN; "CM-WATER"
        LOCATE 23, 20
```

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```
            PRINT "7. Input Indicated Oscillation Frequency (Hz)"
            INPUT OMEGA
            LOCATE 24, 25
            CLS
            LOCATE 3, 20
            PRINT "OSCILLATION FREQUENCY-"; OMEGA; "Hz"
            LOCATE 5, 20
            PRINT "8. Input Barometric Pressure (In Hg)"
            INPUT PREF
            LOCATE 7, 25
            PRINT "BAROMETRIC (REF) PRESSURE-"; PREF; "IN HG"
            LOCATE 9, 20
            PRINT "9. INPUT Freestream Temperature (F)"
            INPUT TEMP
            LOCATE 10, 25
            PRINT "FREESTREAM TEMPERATURE-"; TEMP; "F"
```

RETURN
'_____

HOME:

   This subroutine advances the SCANIVALVE to HOME

```
                FOR I = 1 TO 50000
                OUT &H2A8, 2
                NEXT I
                OUT &H2A8, 0
```

RETURN
'_____

PORTNUM:
This file contains the text of the subprogram PORTNUM in TKDATA

     This subprogram reads the BCD output of the SCANIVALVE.
   '(PORTNO)

```
                PORTNO = 255 - INP(&H2A9)
```
RETURN

'_____

PORT:

This file contains the text of the subprogram PORT in TKDATA
    This subprogram advances the SCANIVALVE one port

```
                FOR I = 1 TO 1000
                OUT &H2A8, 1
                NEXT I
                OUT &H2A8, 0
```
RETURN

'_____

MEAN: 'Determines the mean values of the two arrays PRAW and VRAW, PBAR

'and VBAR, and replaces the arrays with the mean values subtracted

```
VBAR = 0!
PBAR = 0!

FOR I = 1 TO (2 * SAMPLES) STEP 2
     VBAR = CDBL(VRAW(I) * (VSCALE / 2048) + VBAR)
     PBAR = CDBL(PRAW(I) * (PSCALE / 2048) + PBAR)
NEXT I

VBAR = VBAR / SAMPLES
PBAR = PBAR / SAMPLES

FOR I = 1 TO (2 * SAMPLES) STEP 2
     VRAW(I) = VRAW(I) * (VSCALE / 2048) - VBAR
     PRAW(I) = PRAW(I) * (PSCALE / 2048) - PBAR
NEXT I

RETURN
```

ARRAY: This subroutine loads PBAR and VBAR into vectors PMEAN and VMEAN,
'and PRAW and VRAW into arrays P and V. (It truncates the 1024
'records in PRAW and VRAW into 1000 records, performs an ensemble
'average over the 10 ensembles and loads a 100 sample array.)

```
PMEAN(PORTNO) = PBAR
VMEAN(PORTNO) = VBAR

FOR k = 1 TO 100
     PEA = 0!
     VEA = 0!
          FOR J = 0 TO 9
               PEA = PRAW((2 * k) - 1 + (J * 100))
               VEA = VRAW((2 * k) - 1 + (J * 100))
          NEXT J


     P(PORTNO, k) = PEA
     V(PORTNO, k) = VEA
NEXT k

RETURN
```

DISK: This subroutine creates a file A:RUNXXX.DAT, (where XXX is the
'RUN NUMBER), and writes all HEADER DATA, PMEAN and VMEAN
'and the pressure and velocity arrays, P and V to that file.

```
CLS
LOCATE 10, 15
PRINT "INSERT A FORMATTED DISK IN DRIVE A:"

LOCATE 15, 15
PRINT "PRESS ANY KEY TO WRITE RUN DATA TO FILE"

A$ = ""
```

```
WHILE A$ = ""
A$ = INKEY$
WEND

CLS
LOCATE 10, 10
PRINT "Run data is being written to file A:RUN" + RUNNO$ + ".DAT"

'Open the file:

OPEN "A:RUN" + RUNNO$ + ".DAT" FOR OUTPUT AS #2

'Write header data:

        WRITE #2, RUNNO$, DAITE$, TYME$, MODEL$: 'Strings!
        WRITE #2, AOA: 'degrees
        WRITE #2, PDYN * 2.048: 'psf
        WRITE #2, OMEGA: 'hertz
        WRITE #2, PREF * 70.73: 'psf
        WRITE #2, TEMP + 459.7: 'deg Rankine

'Next write pressure and velocity data:
   WRITE #2, PMEAN
   WRITE #2, VMEAN
        FOR J = 1 TO 100
               WRITE #2, P(J): 'Pressure array
        NEXT J
        FOR J = 1 TO 100
               WRITE #2, V(J): 'Velocity array
        NEXT J
CLS
BEEP
LOCATE 10, 10
PRINT "    RUN COMPLETE AND DATA WRITTEN TO FILE"

RETURN
```

APPENDIX C: Data Acquisition / Data Reduction Program for Unsteady Pressure Measurement System Calibrations

```
'PROGRAM DYNARES.BAS (DYNAmic RESponse)

'The program records the pressure signals from the scanivalve transducer
'( Channel 2 ) and the reference pressure transducer ( Channel 1 ).
'The pressure signals are output continuously from the transducers as DC
'voltages corresponding to a percent deflection of full scale of the recorder
'board. In both channels, full scale deflection is limited to +/- 5 Volts.
'The program arms the boards and when is triggered ( manually from the
'rotating shutter vanes switch ), 1024 samples of pressure are recorded
'simultaneously from each channel over a period of 1.024 seconds ( sample
'rate 1000 samples/sec ) which spans 10 cycles of pressure oscillation.
'The program uses the following subroutines:

'HEADER - Inputs data for a file header

'INIT - Initializes recorder boards

'RECORD - Records data

'getstartadd - Returns starting address of record

'getdat - Returns data samples

'PLOT - Plots data on screen

'LOAD - Loads two arrays, P1RAW and P2RAW

'DISK - Outputs P1RAW, P2RAW and header data
'        to a file called SCAN.XXX where XXX is the scanivalve port number


        P1SCALE = 144!
        P2SCALE = 144!
        OPTION BASE 1            'Sets lower bound of subscripts = 1
        DIM physicaladdress(2)      'Physical adresses of the recorders
        DIM inputscale(2)           'Full scale input voltage for each
                                 'channel. May be 1, 2, 5, or 10 volts
        DIM starts(2)              'Array containing starting addresses
        DIM P1RAW(2048)             'Array containing raw pressure1 data
        DIM P2RAW(2048)             'Array containing raw pressure2 data


        GOSUB HEADER              'Calls for header information
        GOSUB INIT               'Use once before using recorders
'_____

'RECORDER BOARDS CONTROL PARAMETERS

        SAMPLES = 1024            'Number of samples per record, (must
                                 'be of the form 2**n for processing)
```

```
        psamples = 1000            'Number of pretrigger samples
        setpoint = 10             'Trigger setpoint in % of full scale
        mode$ = "PLUS"              'Trigger mode$, (either "PLUS"
                                'or "MINUS")
        rate = 1000               'Sample rate in u-seconds per point

        inputscale(1) = 10         'full scale for channel 1 is 10 volts
        inputscale(2) = 10         'full scale for channel 2 is 10 volts

'_____

        FOR J = 1 TO 20000         'Delays data acquisition to allow
        NEXT J                     'scanivalve to settle

        GOSUB RECORD                'Records data for one port

        GOSUB PLOT                  'Plots recorded data for debugging

        GOSUB LOAD                  'Loads data into arrays P1RAW & P2RAW
                                'of length 2048

        GOSUB PHASE                 'Calculates the phase lag between
                                'arrays P2RAW and P2RAW

        'GOSUB DISK:                 'Writes all header data, P1RAW and
                                'P2RAW to disk in a file SCNXXX.DAT

        END                        'End of application code......


'==============================================================================

'    SUBROUTINES WHICH CALLED BY PROGRAM DYNARES


INIT:   'Use this routine once at startup for variable and hardware init.

        k = 1024                'k is 2 ** 10
        SAMPLES = 2000              'init # of samples per record
        psamples = INT(SAMPLES / 4)  'init presamples at .25 total record
        setpoint = 50             'trigger setpoint in % of full scale
        mode$ = "PLUS"             'trigger mode$ is either "PLUS" or "MINUS" or -
        rate = 4                'default sample rate in us.
        memmax = (64 * k) - 1       'recorder memory size

        tbc = &H205                'time base control register address
        cwr = &H21E                 '8253 control write register
        ctr0 = &H206               '8253 counter #1
        ctr1 = &H20E               '8263 counter #2
        ctr2 = &H216               '8253 counter #3

        clkie = 1                'for hardware hook not being used


        FOR J = 1 TO 2

        'set up list for physical address starting at &h200
```

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physicaladdress(J) = &H200 + (J * 32) - 32

'Read board jumpers and set inputscale(j)
'Absent boards get inputscale = 0
'Others will return 1, 2, 5 or 10

x = INP(physicaladdress(J) + 5) 'read jumpers w4, w5, w6, w7
x = x AND &H70

SELECT CASE x

    CASE 96
    inputscale(J) = 1

    CASE 80
    inputscale(J) = 2

    CASE 64
    inputscale(J) = 5!

    CASE 48
    inputscale(J) = 10!

    CASE ELSE
    inputscale(J) = 0

END SELECT

NEXT J

'Initialize timebase and run through one cycle:

rate = 1000

'Toggle reset line

OUT tbc, &HEF
OUT tbc, &HE3

'Set counter 0 to mode 3
OUT cwr, &H36

'Set sample rate
A = rate * 2
ha = INT(A / 256)
la = A - (ha * 256)
OUT ctr0, la
OUT ctr0, ha

'Set counter 1 to mode 3
'And divide by 4

OUT cwr, &H76

```
OUT ctrl, 4
OUT ctrl, 0

'Set counter 2 to mode 5
OUT cwr, &HBA

'Set number of samples
B = (SAMPLES - psamples) / 4
hb = INT(B / 256)
lb = INT(B - (hb * 256))

OUT ctr2, lb
OUT ctr2, hb

'Set trigger level
A = INT(setpoint * 1.28 * -1) + 127 - 7
OUT &H203, A

'Arm timebase in chosen mode

'First create timebase control word
 tbctw = &HF7

'clkie always equals 1
IF clkie = 1 THEN tbctw = tbctw AND &HFB

'Test mode$( PLUS or MINUS )
IF mode$ = "MINUS" THEN tbctw = tbctw AND &H7F
OUT tbc, tbctw AND &HED

'Wait loop to get pretrigger data
ptdelay = psamples * rate * .000001
A = TIMER + ptdelay + 1

'This loop generates and error when timing through midnight
WHILE (TIMER < A AND INKEY$ = ""): WEND

OUT tbc, tbctw AND &HFE
OUT tbc, tbctw

'Force a trigger

OUT tbc, tbctw OR 8
FOR J = 1 TO 500: NEXT J
OUT tbc, tbctw

'This ends the time base first cycle and initialization..

RETURN

'_____

RECORD: 'recording sequence control

    CLS

    'VIEW
```

```
'WINDOW (0, 2048)-(511, -2048)
'LINE (50, 2000)-(461, -1850), lincol, B

LOCATE 3, 27
PRINT "RECORDING SEQUENCE CONTROL "

LOCATE 8, 25
PRINT "1. ) Initialize Recorder Hardware "

'First set the gain on boards 1 and 2.

FOR J = 1 TO 2

SELECT CASE inputscale(J)

        CASE 1
        mask = &H9F

        CASE 2
        mask = &HDF

        CASE 5
        mask = &HBF

        CASE 10
        mask = &HFF

        CASE ELSE
        mask = &HFF

END SELECT

IF J = 1 THEN mask1 = mask
OUT physicaladdress(J) + 5, mask

NEXT J


'Toggle reset line
OUT tbc, &HEF AND mask1
OUT tbc, &HE3 AND mask1

'Set counter 0 to mode 3
OUT cwr, &H36

'Set sample rate
A = rate * 2

ha = INT(A / 256)
la = A - (ha * 256)
OUT ctr0, la
OUT ctr0, ha


'Set counter 1 to mode 3
'And divide by 4
```

```
OUT cwr, &H76
OUT ctrl, 4
OUT ctrl, 0


'Set counter 2 to mode 5
OUT cwr, &HBA

'Set number of samples
B = (SAMPLES - psamples) / 4
hb = INT(B / 256)
lb = INT(B - (hb * 256))

OUT ctr2, lb
OUT ctr2, hb

'Set trigger level
A = INT(setpoint * 1.28 * -1) + 127 - 7
OUT &H203, A

'Arm timebase in chosen mode

'First create timebase control word
 tbctw = &HF7 AND mask1

'clkie always equals 1
IF clkie = 1 THEN tbctw = tbctw AND &HFB

'Test mode$( PLUS or MINUS )
IF mode$ = "MINUS" THEN tbctw = tbctw AND &H7F


LOCATE 10, 25
PRINT "2. ) Pretrigger Delay "

OUT tbc, tbctw AND &HED
REM out tbc,tbctw


'Wait loop to get pretrigger data
ptdelay = psamples * rate * .000001
A = TIMER + ptdelay + 1

'This loop generates and error when timing through midnight
WHILE (TIMER < A AND INKEY$ = ""): WEND


LOCATE 12, 25
PRINT "3. ) Arm Recorder...wait for trigger"

OUT tbc, tbctw AND &HFE
OUT tbc, tbctw

B$ = ""
A = 1
```

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```
        WHILE (A <> 0 AND INKEY$ = "")
        A = INP(&H205) AND 3

                IF INKEY$ <> "" THEN
                OUT tbc, tbctw OR 8
                FOR J = 1 TO 500: NEXT J
                OUT tbc, tbctw
                END IF
        WEND

        LOCATE 14, 25
        PRINT "4. ) Triggered ...wait until recording complete"

        WHILE (A = 1 AND INKEY$ = "")
        A = INP(&H205) AND 1
        WEND

RETURN

'_____


getstartadd: 'read 18 bit stop address from 3 ports and convert to number
            'only 16 bit stop address from 2 ports for 64 k sample memory

        stopadd = 0

        'bits 16 and 17
        REM sadd1 = INP(physicaladdress(i) + 2) AND &H3
        REM sadd1 = sadd1 * 64 * 1024
        REM stopadd = sadd1

        'bits 8 thru 15
        sadd1 = INP(physicaladdress(I) + 1)
        sadd1 = sadd1 * 256
        stopadd = stopadd + sadd1

        'bits 0 thru 7
        stopadd = INP(physicaladdress(I)) + stopadd

        'Calculate starting address by subtracting samples
        starts(I) = stopadd - SAMPLES - 4

        'Starting address is never negative, so fix it if needed.
        'IF starts(I) < 0 THEN starts(I) = starts(I) + 65536

RETURN

'_____

        'GETDAT and gd1 both get a single value from the recorder memory,
        'this value is returned in the variable DAT.  DAT is a
        'number that ranges from -2048 to +2047.

        'GETDAT will initialize the memory pointer with the value in BRDST.
        'However, this memory pointer need only be initialized one time per
        'record transfer.  Then the calling routine can continuously call gd1
        'and the recorder memory pointer will auto increment after each call.
'_____
```

```basic
getdat:
        IF brdst > memmax THEN brdst = brdst - memmax
        IF brdst < 0 THEN brdst = brdst + memmax

        REM str = INT(brdst / 65536)
        REM brdst = brdst - (str * 64 * 1024)
        strhi = INT(brdst / 256)
        strlo = brdst - (strhi * 256)

        OUT physicaladdress(I), strlo
        OUT physicaladdress(I) + 1, strhi
        REM OUT physicaladdress(i) + 2, str


gd1:
        A = INP(physicaladdress(I) + 3)
        B = INP(physicaladdress(I) + 4)
        B = (B AND &HF) * 256
        DAT = (A + B - 2048) * -1


RETURN

'_____


PLOT:  This routine will plot the arrays to the screen.

        SCREEN 2                    '2 for cga, 3 for hercules and
                                    '9 for ega. (Only required for
                                    'plotting)

        WINDOW (0, 2048)-(SAMPLES, -2048)

        'plot data on screen
        FOR I = 1 TO 2

            GOSUB getstartadd       'Determines the starting point of
                                    'the record in memory
            brdst = starts(I)       'Initializes memory pointer and gets
            GOSUB getdat            'first data point
        PSET (0, DAT)

            FOR J = 1 TO SAMPLES
                GOSUB gd1       'gets sample in dat and auto inc. ptr

                LINE -(J, DAT)
            NEXT J
        NEXT I

        A$ = ""
        WHILE A$ = ""
        A$ = INKEY$
        WEND

RETURN

'_____
```

```
LOAD: 'Load data into an array
      FOR I = 1 TO 2

            GOSUB getstartadd        'Initializes boards for data
            brdst = starts(I)        'downloading and gets first
            GOSUB getdat             'sample

      FOR J = 1 TO (2 * SAMPLES) STEP 2

            GOSUB gd1        'Gets sample and increments pointer
            IF I = 1 THEN
                P1RAW(J) = DAT
                P1RAW(J + 1) = 0!
            END IF
            IF I = 2 THEN
                P2RAW(J) = DAT
                P2RAW(J + 1) = 0!
            END IF

      NEXT J
      NEXT I

RETURN


'_____


HEADER:
      This subroutine collects run information
            CLS                         'Clear screen

            LOCATE 2, 10                'Locates text
            PRINT "RUN DATA INPUT"

            LOCATE 4, 20
            PRINT "Number of run and the port in the form XYY."
            INPUT RUNNO$
            LOCATE 6, 25
            PRINT "RUN NUMBER - "; RUNNO$

            LOCATE 8, 20
            PRINT "7. Input Indicated Oscillation Frequency (Hz)"
            INPUT OMEGA
            LOCATE 10, 25
            PRINT "OSCILLATION FREQUENCY-"; OMEGA; "Hz"

RETURN


'_____  _____


DISK:   'This subroutine creates a file A:SCNXXX.DAT, (where XXX is the
        'RUN NUMBER AND SCANIVALVE PORT), and writes all HEADER DATA,
        'P1RAW and P2RAW to that file.

        CLS
        LOCATE 10, 15
        PRINT "INSERT A FORMATTED DISK IN DRIVE A:"
```

```
LOCATE 15, 15
PRINT "PRESS ANY KEY TO WRITE RUN DATA TO FILE"

A$ = ""
WHILE A$ = ""
A$ = INKEY$
WEND

CLS
LOCATE 10, 10
PRINT "Run data is being written to file A:SCN" + RUNNO$ + ".DAT"

'Open the file:

OPEN "A:SCN" + RUNNO$ + ".DAT" FOR OUTPUT AS #2

'Write header data:

        WRITE #2, RUNNO$, DATES:  'Strings!
        WRITE #2, OMEGA:  'hertz

'Next write pressure data:

FOR I = 1 TO (2 * SAMPLES) STEP 2
        WRITE #2, P1RAW(I):
NEXT I

FOR I = 1 TO (2 * SAMPLES) STEP 2
        WRITE #2, P2RAW(I):
NEXT I

CLS

BEEP
LOCATE 10, 10
PRINT "   RUN COMPLETE AND DATA WRITTEN TO FILE"

RETURN
```

```
PHASE:   This subroutine calculates the phase lag in degrees between
         the pressure signals from Channel No.1 and Channel No.2.

SUMP1 = 0
SUMP2 = 0
SP1P2 = 0
FOR I = 1 TO (2 * SAMPLES) STEP 2
        SUMP1 = SUMP1 + P1RAW(I) * P1RAW(I)
        SUMP2 = SUMP2 + P2RAW(I) * P2RAW(I)
        SP1P2 = SP1P2 + P1RAW(I) * P2RAW(I)
NEXT I

N = SAMPLES
P1 = SQR(2 * SUMP1 / N)
P2 = SQR(2 * SUMP2 / N)
```

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COSDFI = (2 * SP1P2) / (N * P1 * P2)

ARCCOSDFI = 3.141593 / 2 - ATN(COSDFI / SQR(-COSDFI * COSDF + 1))

DFI = ARCCOSDFI * 180 / 3.141593

PRINT "THE PHASE LAG BETWEEN CHANNEL 1 AND CHANNEL 2 IN DEGREES IS :"
PRINT DFI

RETURN

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