AN ADAPTIVE CONTROL ALGORITHM FOR ACQUISITION OF PNEUMATIC COMMUTATOR DATA

PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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This technical report has been reviewed and is approved for publication.

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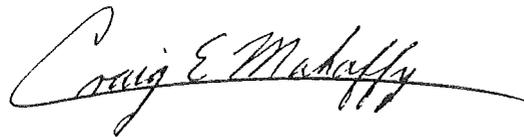
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This report describes and documents an adaptive control algorithm currently used in the Propulsion Wind Tunnel Transonic and Supersonic tunnels for the acquisition of steady-state pressure data using pneumatic commutators. The algorithm employs a classification process to determine whether or not data smoothing is required. If filtering is required, then a self-adjusting arithmetic averaging technique is used. Data obtained using the

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20. ABSTRACT (Continued)

algorithm are acquired subject to both a settling criterion and a time constraint. The report contains a description of the basic instrumentation system and adaptive control algorithm.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65307F. The results were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee. The work was done under ARO Project No. P45U. The authors of this report were Robert G. Chapman, Thomas H. Clay, and James L. Taylor, ARO, Inc. The manuscript (ARO Control No. ARO-PWT-TR-75-90) was submitted for publication on June 23, 1975.

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ILLUSTRATIONS

1.0 INTRODUCTION

Recent trends in wind tunnel testing indicate a growing popularity for pneumatic commutator devices as a means to measure steady-state pressure data. Such devices have one pressure transducer whose pneumatic input is switched by an electrical signal to various pressure orifices. A single transducer is then capable of providing a large number of different pressure measurements with a simple valving arrangement.

In the past, the data acquisition process used in PWT has been to sequentially advance the commutator to an orifice; delay a fixed time to permit the pressure input to the transducer to stabilize; and then digitize the analog signal from the transducer. This process is repeated until all pressures on the commutator have been digitized and the commutator is back in its pre-data acquisition cycle position. The delay time is a fixed quantity which is determined by the worst-case pressure settling time. To minimize the settling time, the pressure orifices connected to the commutator are arranged such that the pressure differential between consecutive ports is minimal. Even with such acceptable engineering practices as these, it is both unreasonable and unlikely that a constant delay time would be acceptable at all environmental testing conditions. If a conservative delay time is used, then the data acquisition time is increased. To reduce the data acquisition time, a compromise in the data accuracy must be made. Hence, the test engineer using a pneumatic commutator faces a dilemma.

This perplexing situation can be avoided if an adaptive step rate is used. With a computer-based data acquisition system such as is currently in use in the Propulsion Wind Tunnel Transonic and Supersonic tunnels, an adaptive control that automatically modifies operating parameters to achieve optimal performance is realizable. This report describes the development and benefits of such a technique devised for use with pneumatic commutators.

2.0 BASIC SYSTEM DESCRIPTION

Figure 1 is a simplified block diagram illustrating the major components of a system designed to acquire pneumatic commutator data. For simplicity, the commutator is shown as a rotary pneumatic switch separated from the pressure transducer. The transducers most often used are differential strain-gage transducers which produce an electrical signal proportional to the pressure
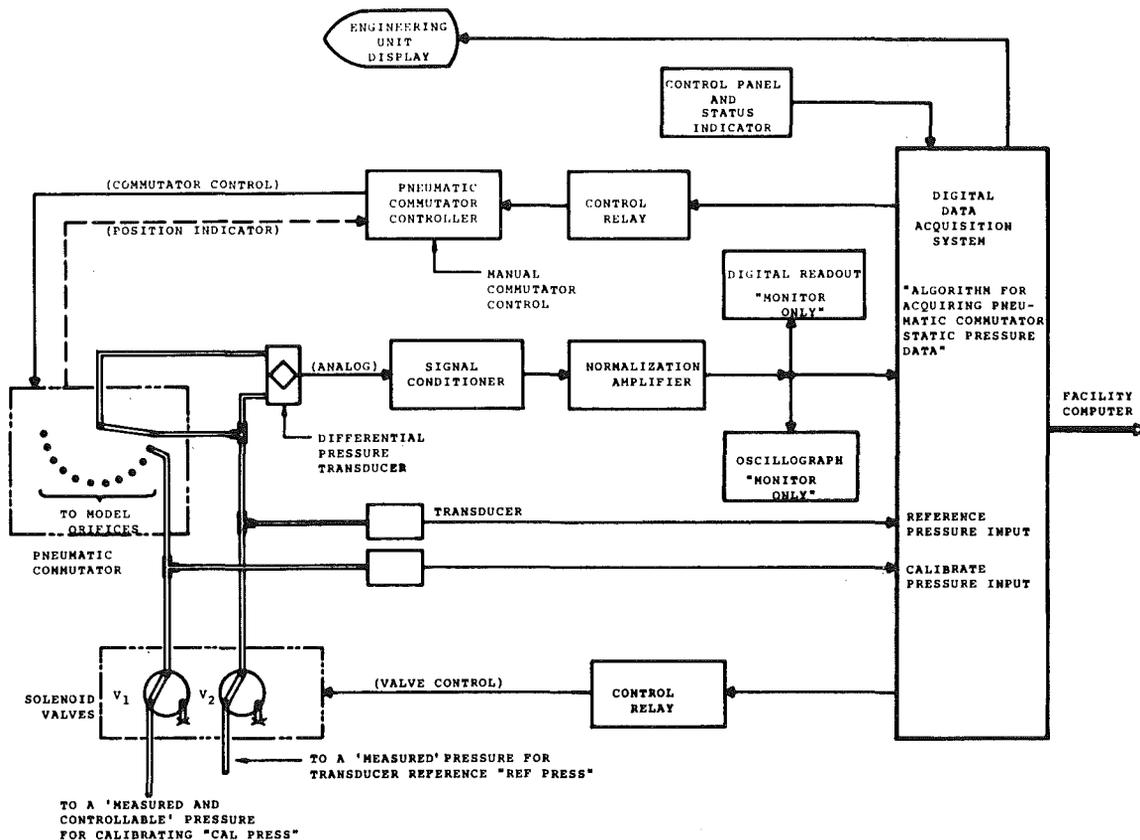
Figure 1. Simplified block diagram of a pneumatic commutator
data acquisition system.

differential applied to the transducer's input ports. The transducer is
connected through a signal conditioner to a variable gain amplifier which
is used to normalize the transducer's output such that the sensitivity
constant is in convenient engineering units. In addition, the amplifier
contains a bandpass filter which is used to provide filtering above 100
Hz. The amplifier's output is connected in parallel to a digital voltmeter,
an oscillograph, and a computer-based data acquisition system. During
periods of data acquisition, the oscillograph is used to provide a contin-
uous record of the commutator's output.

In addition to the digital voltmeter and the oscillograph, the ampli-
fier's output is connected to the Digital Data Acquisition System (DDAS).
The DDAS is illustrated in Fig. 2 and is a computer-based data acqui-
sition system used to acquire steady-state pressure data according to
an adaptive control algorithm which is described in Section 3.0.
Automatic commutator control is accomplished by the DDAS operating
in conjunction with its control relays and a pneumatic commutator
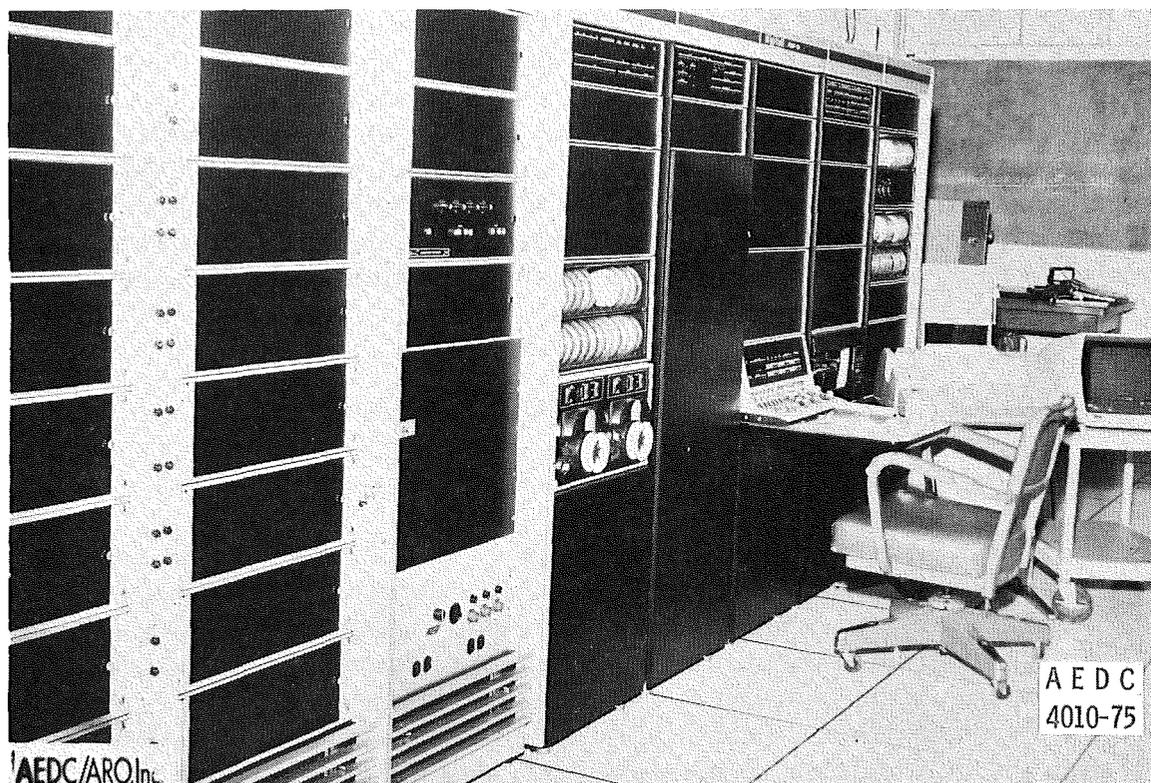
Figure 2. Digital data acquisition system.

controller. Data acquired using the DDAS are transmitted to the facility
computer at the completion of the acquisition cycle.

When using a differential pressure transducer with a commutator,
the general practice is to connect the transducer's reference pressure
to the first port of the commutator and a known variable pressure to the
second port. With the commutator and transducer connected as such, the
transducer's output represents zero differential pressure in its pre-data
acquisition cycle position and the calibration pressure when advanced to
the secort port. Since the reference and calibrate pressures are known
variables which are external inputs to the DDAS, both the transducer's
sensitivity and zero are determined each data acquisition cycle by using
the transducer's output from the first two ports in conjunction with the
reference and calibrate pressures. The computed sensitivities and
transducer zeros are then used to compute the remaining commutator
pressure data. In addition, display of the transducer's sensitivity for
each data acquisition cycle provides a visual check on the commutator's
performance.

A valving arrangement external to the test unit is provided for manual checkout and calibration. By providing a means of applying pressure to either the first or second port commutator positions, both the pneumatic integrity and the system's response can be readily determined. In addition, solenoid valves controlled by the DDAS may be placed in series with the reference and calibrate lines. Upon initiating a data acquisition cycle, the valves are energized. This action traps the reference and calibrate pressures; hence, they remain constant for the duration of the data cycle.

3.0 ADAPTIVE CONTROL TECHNIQUE

3.1 GENERAL REQUIREMENTS

The initial goal in the development of an adaptive control for use with pneumatic commutator devices was to minimize the time delayed on any commutator position subject to a pressure settling criterion. This can be achieved by determining a pressure measurement's rate of change at each commutator position and using the rate-of-change information to govern the delay time. That is, the data acquisition process would be to advance the commutator to the next port, periodically digitize the transducer output to obtain the linear rate of change and use that information to determine if the pressure had stabilized to within some prescribed tolerance. Once the pressure was considered settled, the latest digitized analog signal would be retained, and the commutator would be advanced to select the next pressure. The process is repeated until all pressures have been measured.

With a variable delay time, it is necessary to place some restriction on the maximum time delayed on any commutator position. This constraint modifies the above description such that either the pressure is settled to within a prescribed tolerance or the time constraint is exceeded before the commutator is advanced. In addition to the maximum delay time constraint, each of the two points used in determining the rate of change should consist of an arithmetic average of several digitized transducer readings. Averaging is necessary to smooth out pressure fluctuations which result from any testing environmental changes or aerodynamic phenomena.

Figures 3 and 4 represent typical data acquired from two different test programs in the Propulsion Wind Tunnel Transonic tunnel. The data illustrated in Fig. 3 were obtained from a test program which utilized long tubing lengths to connect the orifice to the commutator. The
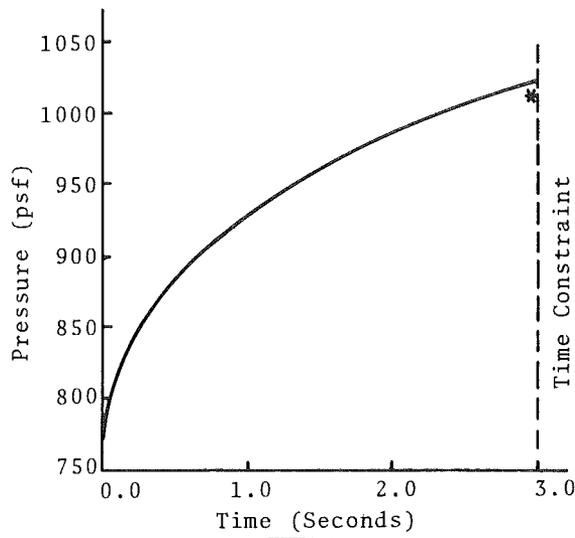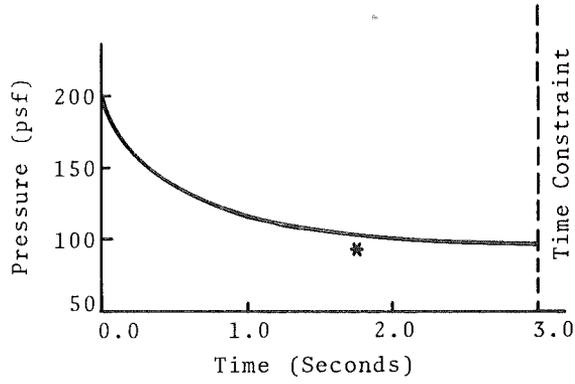
Figure 3. Typical static pressure data acquired using a highly damped pneumatic commutator.
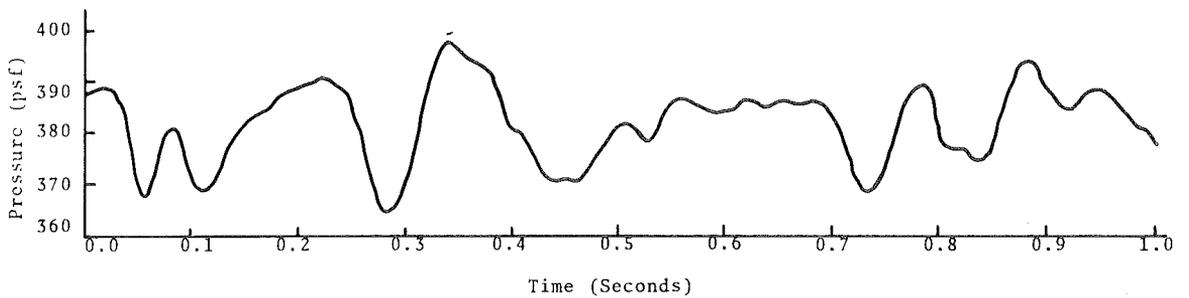
Figure 4. Typical static pressure data acquired using a lightly damped pneumatic commutator.

long tubing lengths served as pneumatic filters and are responsible for the system's highly damped response. In contrast, the data illustrated in Fig. 4 were obtained from a test program utilizing relatively short tubing lengths. Both data sets are representative of the steady-state pressure data which may be encountered when using pneumatic commutator devices.

The algorithm as outlined above is well suited for treating data similar to that illustrated in Fig. 3 but is not generally effective with data obtained from lightly damped systems as shown in Fig. 4. The marked differences between the two data types indicate that a more generalized approach is required. Specifically, the algorithm should be capable of automatically distinguishing between the two data types and then treating each type accordingly. For purposes of further discussion, data from highly damped systems are termed steady state and data from lightly damped systems are termed dynamic.

3.2 DATA CLASSIFICATION

Data may be classified as to steady state or dynamic by analyzing the data for a period of time corresponding to at least one half period of the lowest frequency to be considered. If the lowest frequency to be considered is denoted f_c, then it is necessary to acquire data for a time equal to $1/(2f_c)$. The acquired data are then examined to determine if a fluctuating component is present. This may be accomplished by examining the slope sign between consecutive samples. If the slope between any two samples undergoes a sign change, then the data are classified as dynamic. Otherwise, the data are considered steady state. Data classified as steady state may still contain a fluctuating component, but the frequency will be less than f_c.

In practice the data acquired for the classification process is not a continuous record of the transducer's output but rather is composed of a number of equally spaced discretely digitized samples. If the data acquisition system's sampling rate is denoted f_s and is in samples per second, then the number of samples required for the classification process is given by

$$N = f_s/2f_c \qquad (1)$$

If the samples are denoted S_i, where $i = 1, 2. . .,N$, then the classification data can be considered composed of $N/2$ two-sample averages.

That is, the N samples consist of points P_j, where

$$P_j = (S_i + S_{i+1})/2 \qquad , j = 1, 2, \ldots, N/2 \qquad (2)$$

The difference between consecutive points P_j are denoted as

$$\Delta P_j = P_{j+1} - P_j \qquad , j = 1, 2, \ldots, (N/2-1) \qquad (3)$$

If all the ΔP_j's have the same sign, then the data are considered steady state. However, if a sign change occurs, then the data are considered dyanmic.

It should be noted that an assumption is made in the classification process that if the data contain a fluctuating component, then the fluctuations are basically sinusoidal in nature. This enables one to classify data by simply examing the slope sign over a time segment corresponding to one-half period of the lowest frequency to be considered.

3.3 DATA ACQUISITION PROCEDURE

3.3.1 Steady-State Data

If a slope sign change does not occur within the N samples used in the classification process, then the data are determined to be of steady-state character. Typical data which would be classified steady state are shown in Fig. 3. Following the classification process, data for pressures determined steady state are acquired as follows. Four samples are obtained at the f_s rate and are used to form two points, each of which is an arithmetic average of two samples. The slope between the two points is computed and is compared to the settling criterion. If the magnitude of the computed slope is less than the settling criterion, then the pressure is determined to be settled, and the second point used in the slope calculation is retained for later transmittal to the facility computer. If the slope magnitude is greater than the settling criterion and if the elapsed time expended on this commutator position is less than the maximum time constraint, then the above process is repeated. However, if the time constraint is exceeded, then the last two-sample average is retained for transmittal and is flagged to indicate that the pressure had not settled. The process is repeated for each commutator position.

Two-sample averages are used in the above process as well as in the classification process in order to smooth out any fluctuations which might be introduced in the analog-to-digital conversion.

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Figure 3 illustrates typical steady-state data. The asterisk symbol indicates the point at which the data were either considered settled or had exceeded the maximum time constraint.

3.3.2 Dynamic Data

Typical data which are classified dynamic are shown in Fig. 4. As illustrated, the nature of such data is that the fluctuations are about the average value. The acquisition of dynamic data is not a function of the settling rate, as is the case for steady-state data, but rather is a function of both the frequency and magnitude of the fluctuating component. The primary purpose of the procedure used and described below is to provide sufficient smoothing by using arithmetic averaging such that variations about the average value are minimized.

To determine the effects of arithmetic averaging using different ensemble sizes, data were acquired from a test program which utilized pneumatic commutators having relatively short tubing lengths. At each commutator position, data were acquired at a 120-Hz sampling rate and stored on magnetic tape. By operating on the same data set, the effects of arithmetic averaging using different ensemble sizes, denoted n, could be determined conclusively. The data illustrated in Fig. 4 were processed for different ensemble sizes (n) with the results presented in Fig. 5. It can be seen that, for an n of size 4, the averaged data trend follows the original data trend and is ineffective in smoothing the data. In addition, erroneous results concerning the rate of change may be produced as indicated by the slope between the second and third points on the four-sample average curve. Figure 5 indicates that an effective filter for these data is a sample average of size 30.
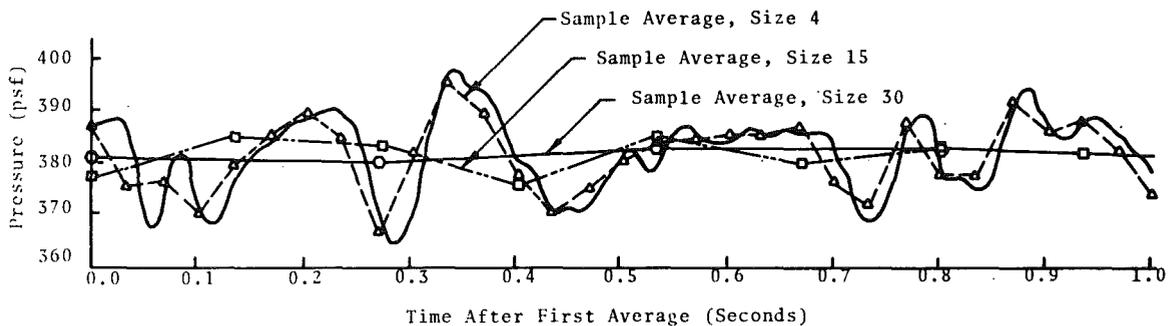
Figure 5. Effects of arithmetic averaging using different ensemble sizes.

Figure 6 also illustrates data processed for different sizes of n and is included to demonstrate the effectiveness of arithmetic averaging. Figures 5 and 6 also illustrate the magnitude of the possible errors involved in data systems which acquire only one digitized transducer output at each commutator position.
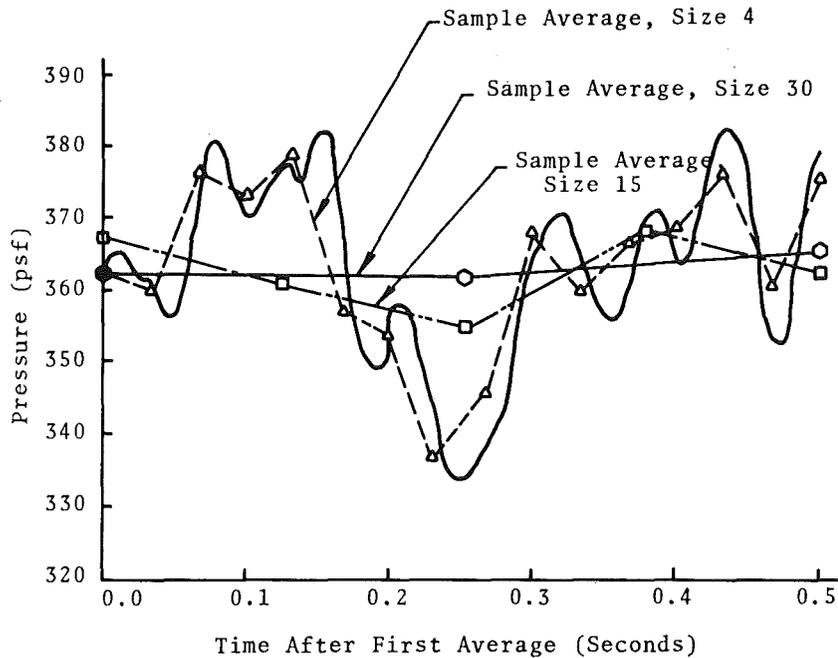
Figure 6. Effects of arithmetic averaging using different ensemble sizes.

If the data are classified dynamic, then filtering is required. Since it is unlikely that the degree of filtering would be constant for all commutator positions at all testing environmental conditions, a self-adjusting arithmetic filtering technique is used. After the data have been classified, two points are formed, each of which is an arithmetic average of n samples. Empirically it was determined that n should be defined as

$$n \geq N/2 \tag{4}$$

The first point (P_1) is defined by using the last n of the N samples which were acquired for the classification process. That is,

$$P_1 = \frac{\sum_{k=1}^{n} S_{N-n+k}}{n} \tag{5}$$

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To define P_2, additional n samples are acquired and are denoted S_i^*, where $i = 1, 2, \ldots, n$. P_2 is then defined as

$$P_2 = \frac{\sum\limits_{i=1}^{n} S_i^*}{n} \qquad (6)$$

The slope between P_1 and P_2 is calculated and compared with the settling criterion. If the computed slope is greater than the settling criterion, then additional filtering is required. The two points defined above are combined to form one point of size 2n. That is, a new P_1 is computed using the previous P_1 and P_2 as

$$P_1 = (P_1 + P_2)/2 \qquad (7)$$

Additional 2n samples are acquired and are used to define a new P_2 as

$$P2 = \frac{\sum\limits_{i=1}^{2n} S_i^*}{2n} \qquad (8)$$

Again the slope is computed and compared with the settling criterion. If the slope is still greater than the criterion, then the points P_1 and P_2 are combined to form a new point P_1. A new P_2 would then be defined by acquiring an additional 4n samples. The process as outlined above continuously adjusts the averaging until either the slope is less than the settling criterion or the expended time becomes greater than the time constraint. The final value used to define a dynamic pressure is the value of P_2.

4.0 SYSTEM OPERATION

4.1 GENERAL OPERATION

Figure 7 is a flow chart of the computer program used with the DDAS to acquire pneumatic commutator steady-state data. As shown, there are two modes of operation. The manual mode is basically a monitoring function which permits any commutator's output to be selected and displayed, whereas the automatic mode is the basic data acquisition mode. In addition to the monitoring function, the manual mode provides a means to flag unused or suspicious ports on any commutator and hence eliminate them from consideration. This process, which is termed bad coding, is necessary to edit invalid measurements
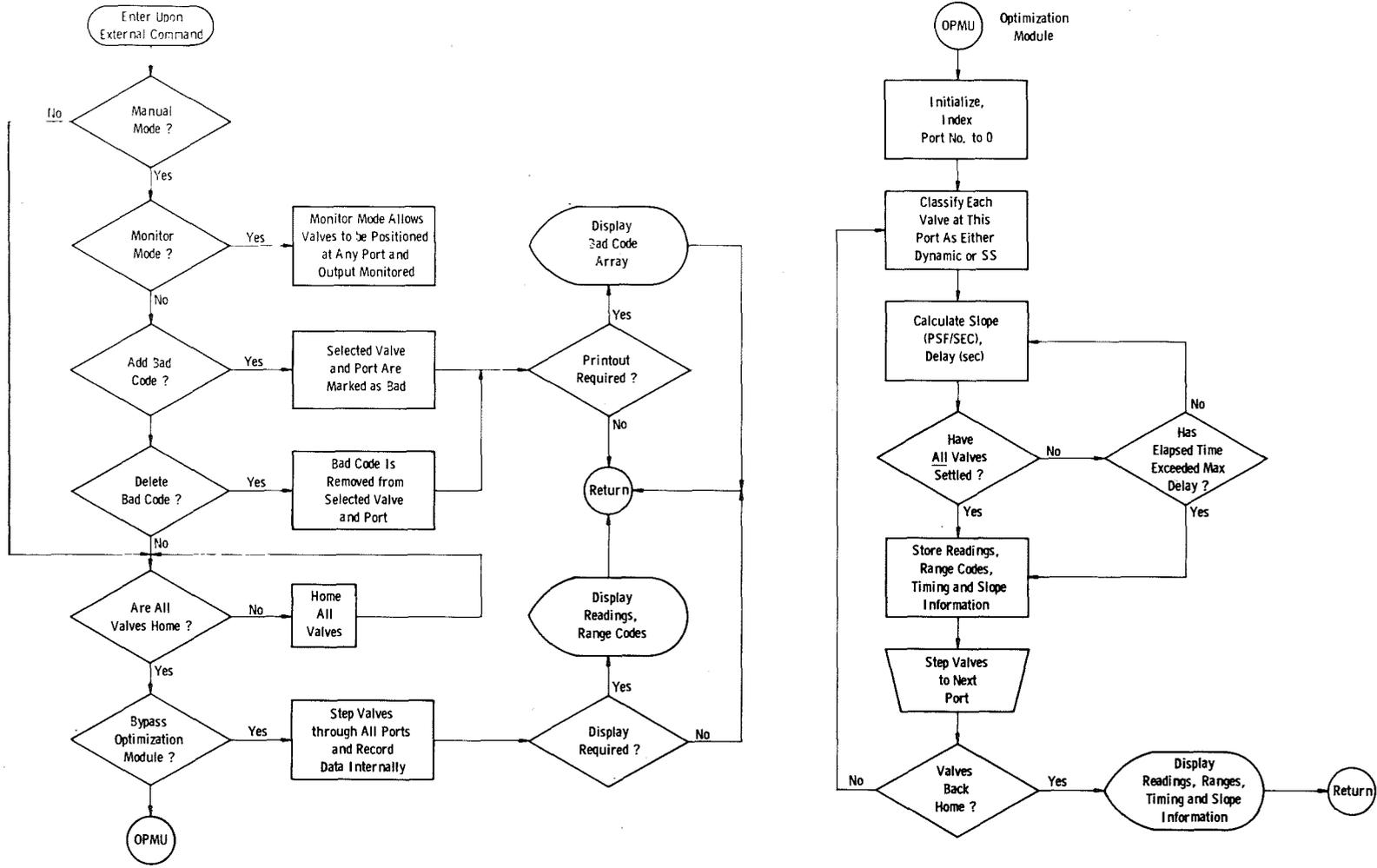
Figure 7. Flow chart of a pneumatic commutator data
acquisition program.

such that they do not influence the algorithm's performance. For
example, it may be necessary due to certain model configurations to
eliminate measurements from consideration during a particular test
phase. The elimination is accomplished by the bad coding process.
If a measurement has been bad coded, then is ignored and does not
affect the optimization algorithm. Figure 8 illustrates a control panel
used in conjunction with the DDAS. In addition to providing a means
for bad coding, the panel provides commutator status lights as well
as a means for inputting the settling criterion and time delay constraint
for use with the optimization algorithm.
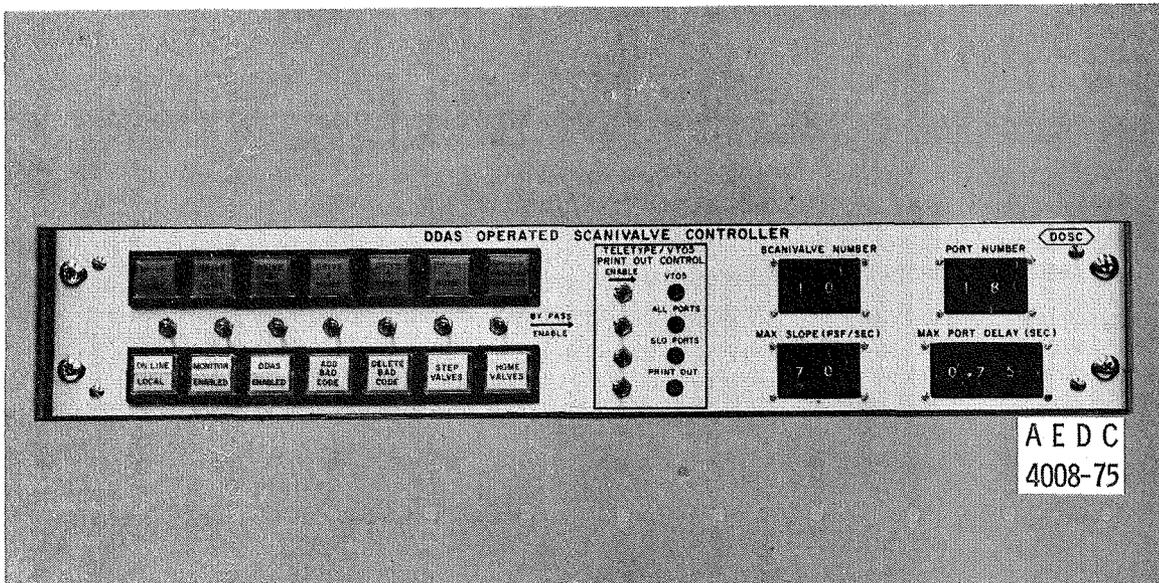
Figure 8. Operating control panel.

As indicated, the automatic mode is the basic data acquisition
mode. When in this mode, it is possible to bypass the adaptive control
algorithm and acquire data using a fixed delay between commutator
positions. While not recommended for data acquisition, the ability to
acquire data in this manner does provide a means for comparing the
data acquisition times between the previously used technique and the
adaptive control algorithm. However, this is not an accurate compar-
ison if any commutators have dynamic data.

Although the description and discussion thus far pertains to only
one commutator, the technique is applicable for a multiple number of
commutators. There are, however, some restrictions imposed on the
algorithm's effectiveness when using more than one commutator. In

the technique described, data from lightly damped systems are distinguished from overly damped systems. Although this classification is necessary if the technique is to be capable of effectively acquiring data from either source, it does place a minimum time restriction on a port position if any of the commutator pressures are considered dynamic at that port position. For example, if a multiple number of commutators are used and if any one pressure is classified as dynamic, then the minimum time spent on that port position is determined by this dynamic pressure. As mentioned previously, acquisition of data from pressures classified dynamic requires at best an additional n samples at the f_s rate, and hence the minimum time spent on that port position would be classification time plus n/f_s. The maximum time spent is determined by the worst case which may be either dyanmic or steady state.

Figure 9 is a simplified flow chart of an adaptive control algorithm which was designed to acquire steady-state pressure data using pneumatic commutators. The settling criterion, time constraint, initial filter size and the lowest frequency to be considered are inputs to the routine. The settling criterion and time constraint inputs are remotely selectable by the test engineer.

4.2 PROGRAM OUTPUTS

4.2.1 Individual Commutator Parameters

For each commutator, the following parameters are computed and displayed at the completion of the data acquisition cycle. NSLO is the total number of slow ports. The term slow port is a misnomer in that the quantity displayed is the sum total of all ports not meeting the slope criterion within the time constraint and may include pressures classified as either steady state or dynamic.

NPSLO is the identification of the port number having the largest slope magnitude.

SLOMAX is the value of the slope computed for the NPSLO port in units of psf/sec.

4.2.2 Composite Commutator Parameters

ET is the total elapsed time from initial entry into the commutator data acquisition routine to its completion.

Input Settling Criterion (psf/sec)

Input Maximum Delay Time Constraint

Input Lowest Frequency to Be Considered – f_c

Sampling Rate = f_s

$N = f_s/2f_c$

Initialize Port No. = 1

(A)

Acquire N Samples $S_1, S_2, ..., S_N$

Define $P_j = \dfrac{S_i + S_{i+1}}{2}$ for $j = 1, 2, ..., \left(\dfrac{N}{2} - 1\right)$

$\Delta P_j = P_{j+1} - P_j$

$T = 0$

Do All ΔP_j Have Same Sign ? No ⟹ Dynamic (C)

Yes ⟹ Steady State

(B)

(B)

Acquire 4 Samples $S_1^\circ, S_2^\circ, S_3^\circ, S_4^\circ$

$P_1 = \dfrac{S_1^\circ + S_2^\circ}{2}$

$P_2 = \dfrac{S_3^\circ + S_4^\circ}{2}$

$\Delta t = 4/f_s$

Slope = $\left(\dfrac{P_2 - P_1}{\Delta t}\right)\left(\dfrac{Valve}{Const}\right)$

Slope < Settling Criterion ? Yes

No

Time = Time + Δt

Time < Constraint ? Yes

(C)

Initialize n = N/2

$P_1 = \dfrac{\sum\limits_{K=1}^{n} S_{N-n+K}}{n}$

Acquire n Samples $S_1^\circ, S_2^\circ, ..., S_n^\circ$

$P_2 = \dfrac{\sum\limits_{i=1}^{n} S_i^\circ}{n}$

$\Delta t = \dfrac{2n}{f_s}$

Slope = $\left(\dfrac{P_2 - P_1}{\Delta t}\right)\left(\dfrac{Valve}{Const}\right)$

Slope < Settling Criterion ? Yes

No

Time = Time + Δt

Time < Constraint ? Yes   No

$P_1 = \dfrac{P_1 + P_2}{2}$

$N = 2n$

Final Value = P_2

Finished ? No   Yes

Increment Port No.

(A)

Compute, Display, Transmit

End

Figure 9. Flow chart of an adaptive control algorithm.

PERCENT SETTLED is the percentage of all ports for all commutators which did satisfy the settling criterion within the time constraint regardless of data classification.

PERCENT DYNAMIC is the percentage of all ports encountered on all commutators which were classified dynamic.

5.0 CONCLUSIONS

The adaptive control routine has proved to be an effective algorithm for acquiring pressure data using pneumatic commutators. The classification process of the algorithm is necessary to achieve the required generality and to ensure a high degree of accuracy in the acquired pressure data. Experience has shown that data systems which obtain only one digitized transducer value for each commutator position are subject to large acquisition errors if the data are of dynamic nature. Such errors are illustrated in Figs. 5 and 6 by the peak-to-peak excursions about the average value and represent errors as large as 10 percent of the final value. Although such errors could be minimized by using a 2 Hz filter before the data acquisition system, the slow response of the filter would degrade the total system performance.

NOMENCLATURE

f_c Cutoff frequency, Hz

f_s Data acquisition sampling rate, Hz

N Number of samples required for classification process

n Ensemble size

P_f The final pressure value

P_j The jth point

ΔP_j The first difference between the j+1 and j^{th} points

S_i The ith transducer sample of the classification process

S_i^* The ith transducer sample after the classification process.