ANALYSIS OF A DYNAMIC PRESSURE MEASURING SYSTEM

by

Roger Allen Blevins

Thesis submitted to the Graduate Faculty of the Virginia Polytechnic Institute in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Agricultural Engineering

Approved:

Dr. J.P.H. Mason, Chairman

Dr. C. J. Hurst

Prof. U. E. Earp

Dr. J. V. Perumpral

May 1970

Blacksburg, Virginia
ACKNOWLEDGEMENTS

The author is indebted to the National Science Foundation for the fellowship granted to him. Similar appreciation is extended to the United States Department of Agriculture, Agricultural Research Service, Agricultural Engineering Research Division, Livestock Engineering and Far Structures Research Branch and to the Research Division, Virginia Polytechnic Institute, for research assistantships granted during the course of this investigation. Without financial aid that was received from these sources, the pursuit of this investigation would have been greatly lengthened.

The author is appreciative to Dr. J. P. H. Mason for having served as the graduate committee chairman. Faithful and dependable guidance was extended by Dr. Charles J. Hurst, Dr. Donald D. Hamann, and Professor Unus F. Earp and for this the author is indeed grateful. Appreciation is due to Dr. C. B. Ling for serving on the thesis advisory committee and to Dr. J. V. Perumpral for serving on the reviewing committee.

Special acknowledgement is due to Professor Unus F. Earp for the photographs of instrumentation found in this thesis.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Subject</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Wind Pressure Recordings</td>
<td>2</td>
</tr>
<tr>
<td>REVIEW OF LITERATURE</td>
<td>4</td>
</tr>
<tr>
<td>Interconnecting Tubing</td>
<td>4</td>
</tr>
<tr>
<td>Mechanical Models of Transducers</td>
<td>8</td>
</tr>
<tr>
<td>Measurement and Recording System</td>
<td>8</td>
</tr>
<tr>
<td>Frequency Response</td>
<td></td>
</tr>
<tr>
<td>OBJECTIVES</td>
<td>10</td>
</tr>
<tr>
<td>INVESTIGATION</td>
<td>11</td>
</tr>
<tr>
<td>The Interconnecting Air Column</td>
<td>11</td>
</tr>
<tr>
<td>The Transducer</td>
<td>17</td>
</tr>
<tr>
<td>The Preamplifier and Power Amplifier</td>
<td>20</td>
</tr>
<tr>
<td>The Galvanometer</td>
<td>22</td>
</tr>
<tr>
<td>System Operational Transfer Function</td>
<td>23</td>
</tr>
<tr>
<td>Air Column Oscillations</td>
<td>25</td>
</tr>
<tr>
<td>The Transducer Mountings</td>
<td>28</td>
</tr>
<tr>
<td>PRESENTATION AND DISCUSSION OF RESULTS</td>
<td>30</td>
</tr>
<tr>
<td>System Frequency Analysis</td>
<td>30</td>
</tr>
<tr>
<td>Air Column Effects</td>
<td>35</td>
</tr>
<tr>
<td>The Transducer Mounting</td>
<td>35</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>37</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>39</td>
</tr>
<tr>
<td>RECOMMENDATIONS</td>
<td>40</td>
</tr>
<tr>
<td>Subject</td>
<td>Page</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>41</td>
</tr>
<tr>
<td>APPENDIX I</td>
<td>43</td>
</tr>
<tr>
<td>APPENDIX II</td>
<td>47</td>
</tr>
<tr>
<td>Appendix II-A</td>
<td>48</td>
</tr>
<tr>
<td>Appendix II-B</td>
<td>51</td>
</tr>
<tr>
<td>Appendix II-C</td>
<td>53</td>
</tr>
<tr>
<td>VITA</td>
<td>56</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>An oscillogram of six surface pressures taken when wind velocity ranged from 30 to 35 mph. Wind direction was perpendicular to the windward wall.</td>
</tr>
<tr>
<td>2.</td>
<td>Time varying wind pressure measuring and recording system.</td>
</tr>
<tr>
<td>3.</td>
<td>Block diagram of wind pressure measuring system components.</td>
</tr>
<tr>
<td>4.</td>
<td>Transducer with sensing port and interconnecting tubing.</td>
</tr>
<tr>
<td>5.</td>
<td>(A) Transducer with interconnecting tubing. (B) Weighted average diameter air column with terminal volume.</td>
</tr>
<tr>
<td>6.</td>
<td>Schematic of Statham, Inc., PM5TC±0.3 psid - 350 pressure transducer.</td>
</tr>
<tr>
<td>7.</td>
<td>Underdamped free oscillation of transducer diaphragm in air.</td>
</tr>
<tr>
<td>8.</td>
<td>(A) Pressure measuring system component transfer function. (B) Pressure measuring system operational transfer function.</td>
</tr>
<tr>
<td>9.</td>
<td>Strip chart recording of 89.25&quot; air column oscillations.</td>
</tr>
<tr>
<td>10.</td>
<td>Strip chart recording of 18.75&quot; air column oscillations.</td>
</tr>
<tr>
<td>11.</td>
<td>Frequency response curve for pressure measuring system with and without air column.</td>
</tr>
<tr>
<td>12.</td>
<td>System response curves within usable frequency range.</td>
</tr>
<tr>
<td>13.</td>
<td>Spring constant curve for transducer diaphragm.</td>
</tr>
<tr>
<td>14.</td>
<td>The transducer static sensitivity curve.</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>I. Transducer Force - Deflection Data</td>
<td>49</td>
</tr>
<tr>
<td>II. Values of Logarithmic Decrement</td>
<td>52</td>
</tr>
<tr>
<td>III. Test Values of Transducer Output in Millivolts vs. Input in Inches of Water Column</td>
<td>54</td>
</tr>
</tbody>
</table>
## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>System amplitude ratio</td>
<td>No units</td>
</tr>
<tr>
<td>a</td>
<td>Cross sectional area of air column</td>
<td>Sq. ft.</td>
</tr>
<tr>
<td>c</td>
<td>Acoustic velocity</td>
<td>Ft./sec.</td>
</tr>
<tr>
<td>c_t</td>
<td>Damping constant of transducer in air</td>
<td>Lb. sec./ft.</td>
</tr>
<tr>
<td>d</td>
<td>Diameter of air column</td>
<td>Ft.</td>
</tr>
<tr>
<td>e_i(S)</td>
<td>Laplace transform of transducers output signal</td>
<td>Millivolts(s)</td>
</tr>
<tr>
<td>e_o(S)</td>
<td>Laplace transform of galvanometer</td>
<td>Millivolts(s)</td>
</tr>
<tr>
<td>e_i(t)</td>
<td>Output voltage signal of transducer bridge</td>
<td>Millivolts(t)</td>
</tr>
<tr>
<td>e_o(t)</td>
<td>Voltage output of D-C amplifier</td>
<td>Millivolts(t)</td>
</tr>
<tr>
<td>F_o</td>
<td>Amplitude of forcing function on transducer mounting</td>
<td>Lb.</td>
</tr>
<tr>
<td>K_a</td>
<td>D-C amplifier gain</td>
<td>No unit</td>
</tr>
<tr>
<td>K_g</td>
<td>Static voltage sensitivity of galvanometer</td>
<td>In./millivolt</td>
</tr>
<tr>
<td>K_t</td>
<td>Static sensitivity of the transducer</td>
<td>Millivolt/psi d</td>
</tr>
<tr>
<td>Keq.</td>
<td>Equivalent spring constant of transducer</td>
<td>Lb./ft.</td>
</tr>
<tr>
<td>L</td>
<td>Length of interconnecting air column</td>
<td>Ft.</td>
</tr>
<tr>
<td>M_eq.</td>
<td>Equivalent dynamic mass of transducer</td>
<td>Lb. sec.²/ft.</td>
</tr>
<tr>
<td>P_i(S)</td>
<td>Laplace transform of the input pressure function</td>
<td>Psid(s)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Meaning</td>
<td>Units</td>
</tr>
<tr>
<td>------------</td>
<td>-------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>$P_0(S)$</td>
<td>Laplace transform of the output pressure function</td>
<td>Psid(s)</td>
</tr>
<tr>
<td>$P_1(t)$</td>
<td>Time varying wind velocity head</td>
<td>Psid(t)</td>
</tr>
<tr>
<td>$P_0(t)$</td>
<td>Time varying pressure at transducer due to $P_1(t)$</td>
<td>Psid(t)</td>
</tr>
<tr>
<td>$Q$</td>
<td>Transducer terminal volume</td>
<td>Cu. ft.</td>
</tr>
<tr>
<td>$R$</td>
<td>Frictional resistance of air column</td>
<td>Lb. sec./ft.</td>
</tr>
<tr>
<td>$S$</td>
<td>Laplace transform variable</td>
<td>No units</td>
</tr>
<tr>
<td>$X(t)$</td>
<td>Time varying displacement of transducer mounting</td>
<td>Inch (t)</td>
</tr>
<tr>
<td>$X_0(s)$</td>
<td>Laplace transform of strip recording displacement</td>
<td>Inch (s)</td>
</tr>
<tr>
<td>$X_0(t)$</td>
<td>Strip chart recorded displacement due to $P_1(t)$</td>
<td>Inch (t)</td>
</tr>
<tr>
<td>$\alpha_g$</td>
<td>Damping ratio of the galvanometer</td>
<td>No units</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Damping ratio of the transducer</td>
<td>No units</td>
</tr>
<tr>
<td>$\alpha_{ac}$</td>
<td>Damping ratio of the air column</td>
<td>No units</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Frequency of oscillating velocity head</td>
<td>Radians/sec.</td>
</tr>
<tr>
<td>$\omega_{ng}$</td>
<td>Undamped natural frequency of the galvanometer</td>
<td>Radians/sec.</td>
</tr>
<tr>
<td>$\omega_{nt}$</td>
<td>Undamped natural frequency of the transducer</td>
<td>Radians/sec.</td>
</tr>
<tr>
<td>$\omega_{nac}$</td>
<td>Undamped natural frequency of the air column</td>
<td>Radians/sec.</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of air</td>
<td>Slugs/cu. ft.</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity of air</td>
<td>slugs/ft.sec.</td>
</tr>
<tr>
<td>$\psi$</td>
<td>Logarithmic decrement</td>
<td>No units</td>
</tr>
<tr>
<td>$\phi$</td>
<td>System phase angle lead</td>
<td>Degree</td>
</tr>
</tbody>
</table>
INTRODUCTION

A study of dynamic effects of wind pressures on low profile structures was conducted by a previous investigator (12)* at the Virginia Polytechnic Institute, Department of Agricultural Engineering. Both the magnitude and frequency of oscillations of the wind velocity head were of interest in these investigations.

A prototype building sixteen feet square was erected and mounted on a turntable to allow orientation of desired surfaces to prevailing winds. A 15 degree slope gable roof covered the building. All surfaces of the test structure (exterior and interior) were of light plywood construction.

Wind pressures in this previous investigation were measured using one-eighth inch pressure ports mounted flush with building exterior surfaces. These ports were located in all six exterior surfaces (walls and roofs). Pressure data was transmitted via one-quarter inch inside diameter plastic tubing to transducers mounted on interior wall surfaces. Transducers mounted on the walls near their respective pressure ports were orientated with their sensing axis vertical. Statham Instruments, Inc., model PM5TC differential pressure transducers with a range of ± 0.3 psid (pounds per square inch differential) measured the pressure. The transducer bridge output voltage signals were amplified with a Honeywell, Inc., Accudata 104 D-C amplifier, while

*Numbers in parentheses refer to Bibliography.
indication and recording was accomplished with a Honeywell Model 1508
galvanometer oscillograph (Appendix I).

Wind Pressure Recordings

Some pressure recordings resulting from the wind studies indicated
frequencies of oscillation far in excess of what was expected. Most
of the higher frequency recordings were obtained on the windward and
leeward roofs (Figure 1), but several high frequency recordings were
also taken on the windward wall. Some of the recordings indicated the
wind pressure was oscillating to either side of the zero pressure line
with frequencies in excess of one-hundred Hz (cycles per second). Re-
cordings of about 20 Hz oscillations were also found in abundance.
Higher frequencies of pressure oscillations were not recorded simultan-
eously at several other recording stations. This investigation of the
pressure measuring system was prompted by the occurrence of the high
frequency pressure oscillations recorded on some of the building
surfaces.
Figure 1. An oscillogram of six surface pressures taken when wind velocity ranged from 30 to 35 mph. Wind direction was perpendicular to the windward wall.
REVIEW OF LITERATURE

A dynamic pressure measuring system should exactly record the pressure phenomenon acting on it on desired coordinates, but this is not practical. The extent to which a dynamic pressure measuring system records a transient pressure is dependent on several inherent system characteristics (7). Some of these characteristics are: (a) energy required to actuate the pressure pickup, (b) mechanical and electrical frequency response of each element of the system, (c) thermal and electrical stability of components, (d) gage calibration. Complete knowledge of system response, therefore, requires close examination of each element within the system.

Interconnecting Tubing

The unbonded strain gage pressure transducer finds wide application in the measurement of transient pressures. These gages have been available for a number of years and have a surprisingly large frequency range (14). The flush diaphragm of the transducer is mounted in a plane and offers a good surface for measuring pressures.

Often, because of environmental conditions like temperature, vibration, and shock the transducer is located some distance from the source of the dynamic pressure. When this is done, an interconnecting tube is generally used to transmit the pressure from the point of measurement to the surface of the sensing element (transducer diaphragm). The interconnecting tube can severely limit the frequency response of pressure measurement systems, and should be avoided if possible (5).
Because of the frequent use of interconnecting tubes in transmitting time varying air pressures, a great deal of work has been done in describing the dynamic characteristics of air columns (3, 4, 9, 11, 13, 14, 17, 20).

Reid and Kops (14), with an experimental set-up, obtained magnification ratio (ratio of input signal amplitude to signal amplitude received by transducer) versus source frequency curves. The interconnecting tube used was 0.06 inches inside diameter and 4.6 inches long, terminating in a transducer volume 0.5 inches diameter and 1.0 inches long. The magnitude of the oscillating pressure source was ± 0.15 psi. Test results from this volume terminated air column indicated the presence of a second-order resonant pneumatic system with a damping ratio (ratio of actual to critical of 0.32). An attempt by Reid and Kops to increase the usable frequency range of the system by decreasing the transducer volume proved of little value. The air column natural frequency was increased, but with the resulting smaller value of damping larger amplification occurred in the resonant region. By introducing a smaller tube at the sensing end of the transmission tube, they found that violent oscillations that took place in the transmission tube were attenuated. Further restriction of the sensing end tube diameter resulted in undesirable effects. In some cases they found it more beneficial to provide a coarse acoustically absorbent lining within the main tube to reduce oscillations at resonance.

Schuder and Binder (17) developed an equation to give pressure-time relationships in an instrument volume following a sudden change
at the sensing end of the connecting tube. Hougen et al. (9) extended
the analysis of Schuder and Binder to develop a second-order linear
relationship (transfer function) between the output pressure \( P_o(S) \) and
the input pressure \( P_i(S) \). In practice, as the ratio of the inside
diameter to transmission line length becomes small, radial gradients
become less significant. Under these conditions the following simple
model adequately depicts transmission line dynamics:

\[
\frac{P_o(S)}{P_i(S)} = \frac{1}{S^2 + \frac{2\alpha ac}{\omega_{nac}} + 1}
\]

[1]

In Equation 1, \( S \) is the Laplace transform variable; \( P_o \), pressure at the
terminal volume end of the transmission tube; \( P_i \), pressure at the tube
sensing end; \( \alpha_{ac} \), ratio of actual to critical damping; and \( \omega_{nac} \),
the undamped natural frequency. If \( L \) is the tube length; \( C \), acoustic
velocity; \( a \), cross sectional area; \( Q \), transducer terminal volume; \( R \),
frictional resistance; and \( \epsilon \), fluid density; the values of \( \alpha_{ac} \) and
\( \omega_{nac} \) are defined as follows:

\[
\alpha_{ac} = \frac{RL}{23c} \left( \frac{1}{2} + \frac{Q}{aL} \right)^{1/2}
\]

[2]

\[
\omega_{nac} = \frac{C}{L \left( \frac{1}{2} + \frac{Q}{aL} \right)^{1/2}}
\]

[3]

Equations 1, 2, and 3 were tested experimentally by Hougen
et al. (9), and were found to represent transmission line dynamics adequately in the frequency range where the largest time constants define the response.

An analysis of pneumatic transmission tubing dynamics based on a system of evenly distributed fixed parameters and considerable experimental work was performed by Rohmann and Crogan (15).

Moise (13) linearized one dimensional momentum and continuity equations to obtain equations of the form used for electrical transmission lines containing distributed resistance, inductance, and capacitance. His experimentation was conducted with one-quarter inch tubing in lengths of 200, 500, and 1000 feet. Two terminal volumes of 117 and 445 cubic inches were used.

The work of Bradner (3) was done earlier than other similar work (11,13,15). His experimentation was conducted with transmission line lengths up to 2000 feet and diameters of 0.125, 0.188, and 0.305 inches. The authors used equations 1, 2, and 3 developed by Hougen et al. (9) to predict the frequency response of the air column studied in this investigation. Work done by Reid and Kops (14) prompted experimentation of filling the interconnecting tubing with glass wool packing in an effort to increase system damping. Experimentation performed by other investigators (3,13,15) was useful in establishing a feel for magnitudes of time lags experienced with different lengths and diameters of interconnecting tubing.
Mechanical Models of Transducers

The unbonded strain gage pressure transducer is available in a variety of factory built units. In the Statham Instruments, Inc., unit (8), the pressure is converted to force by a flexible metallic bellows for the range zero to 50 psi.

Several methods for dynamic calibration of pressure transducers have been employed, especially on instruments used to measure rapidly varying pressures (10,16). Often expensive equipment and considerable time is required to dynamically calibrate transducers, so other methods of calibration are attractive. Often it is possible to develop a mechanical model that idealizes the dynamic behavior of a transducer (6). From the differential equation that describes the motion of the transducer armature, a transfer function can be obtained, which establishes a known functional relationship between electrical output and pressure input. Response of the transducer to inputs of varying frequency can then be predicted with relative ease.

Measurement and Recording System Frequency Response

If the dynamic behavior of all components of a pressure measuring and recording system can be described by differential equations, a system operational transfer function can be obtained (5). From this transfer function the output amplitude ratio can be determined as a function of frequency of oscillation of the pressure in the medium. The usable frequency range of the system can then be defined if the maximum amplitude errors that can be tolerated are known. If wind
direction or some other parameter is being measured and recorded simultaneously with pressure, the phase angle relationships should be known. These phase angle relationships as a function of source frequency also can be readily calculated from the system operational transfer function.
OBJECTIVES

The objectives of this investigation were:

1. To study the frequency response of the wind pressure measuring system, including the interconnecting tube, transducer, D-C amplifier, and galvanometer oscillograph.

2. To investigate the effects of air column vibration and external excitations on pressure data.

3. To recommend system modifications which would allow better pressure data recording.
INVESTIGATION

The pressure measuring system used to record wind pressures on low profile structures (Figure 2) included an interconnecting air column, transducer, D-C amplifier, and galvanometer oscillograph. Because the transducers were rigidly mounted to the walls, an additional input to the transducer from the transducer mounting is included in the system block diagram (Figure 3).

It is within the scope of this investigation to (a) develop the necessary transfer functions for components of the pressure measuring system, (b) develop a system operational transfer function, and (c) investigate transducer mounting inputs and air column effects on pressure data.

The Interconnecting Air Column

An interconnecting air column was used to transmit the pressure signals to the transducer terminal volume (Figure 4). The air column was contained along its length by 3 sections of tubing, each with a different inside diameter (Figure 5a). An equivalent weighted average diameter was used in calculations (Figure 5b) and was determined from the equation

\[ d = \left( \frac{\sum l_i d_i^2}{\sum l_i} \right)^{1/2}, \]

where \( l_i \) is the length of a section of tubing and \( d_i \) is its inside diameter.
Figure 2. Time varying wind pressure measuring and recording system.
\( P_i(t) \) - Time varying wind pressure on building exterior surfaces

\( P_o(t) \) - Time varying pressure as sensed by transducer diaphragm

\( X(t) \) - Time varying displacement of transducer mounting

\( e_i(t) \) - Output voltage signal of transducer bridge

\( e_o(t) \) - Output of D-C amplifier

\( X_o(t) \) - Strip chart recorded displacement

Figure 3. Block diagram of wind pressure measuring system components.
Figure 4. Transducer with sensing port and interconnecting tubing.
Figure 5a. Transducer with interconnecting tubing.

Figure 5b. Weighted average diameter air column with terminal volume.
The transfer function presented by Hougen et al. (9) was used to represent the air column. Values of \( Q = 0.306 \) cubic inches, \( d \) (weighted average diameter of air column cross section) = 0.213 inches, and \( L = 18.75 \) inches were used in Equations 2 and 3 to arrive at values of \( \alpha_{ac} = 0.012 \) and \( \omega_{nac} = 738 \) rps (radians per second). The value of the flow resistance, \( R \), used was obtained from the Hagen-Poiseuille law,

\[
R = \frac{32\mu}{d^2} \tag{4}
\]

where \( \mu = 4 \times 10^{-7} \) slugs per foot second was the dynamic viscosity of air at 75 degrees F(17).

A measured value of \( \omega_{nac} \) (Figure 10) for this air column was found to be 691 rps. The difference between the recorded and calculated values of \( \omega_{nac} \) can be attributed to two sources of error:

1. The interconnecting air column was composed of three different diameter tubings. An equivalent weighted average diameter was used in calculations.

2. The percentage difference between actual and calculated values of \( \omega_{nac} \) is greater for short lengths of air column. As the ratio of inside diameter to length of air column decreases (longer tubing for a constant diameter) the actual and calculated values show closer agreement (9).

The transfer function used to describe the interconnecting air column (Equation 1) with calculated values of the system parameters \( \alpha_{ac} \) and \( \omega_{nac} \) inserted was as follows:
\[
\frac{P_o(s)}{P_i(s)} = \frac{1}{(\frac{s}{738})^2 + 0.024s + 1}
\]  \hspace{1cm} [5]

The Transducer

The Statham Instruments, Inc., model PM5TC ± 0.3 psid - 350 differential pressure transducer (Appendix I) was of the resistive, balanced, completely unbonded construction (Figure 6). A flexible metallic bellows isolated the totally enclosed gage elements from the pressure medium being measured. In addition, the bellows acted as a spring opposing displacement of the diaphragm by pressure. An armature actuated by pressure exerted on the diaphragm strained the gage filaments. Support springs isolated the armature from the frame and allowed movement of the armature in a plane. The armature movement was limited in displacement by fixed stops in the sensing directions.

Because of its design, the unbonded strain gage transducer armature dynamics was described by a linear homogeneous second-order differential equation with constant coefficients.

\[
Meq \frac{d^2x}{dt^2} + c_t \frac{dx}{dt} + Keq x = F_o \sin \omega t,
\]  \hspace{1cm} [6]

In Equation 6, \(F_o \sin \omega t\) was the time varying force acting on the diaphragm due to a pressure \(P_o \sin \omega t\) on the diaphragm cross section. \(Meq\), the equivalent mass of the system, included the total armature and diaphragm masses and a portion of the bellows, gage filaments and support spring masses. \(c_t\) was the damping coefficient of the diaphragm in air, and \(Keq\) was the equivalent spring constant of the bellows, support
Figure 6. Schematic of Statham, Inc., PMSTC + 0.3 psid - 350 pressure transducer.
springs, and one-half the gage filaments acting in parallel.

It was of interest to know if the coefficient $K_{eq}$ of Equation 6 was reasonably linear within the designed pressure range of the transducer. This was accomplished by loading the transducer diaphragm uniformly (transducer, mounted with sensing axis vertical), and measuring with an Ames dial gage the resulting deflections of the diaphragm center. Loading was increased several times, and values of deflection and weight were recorded (Appendix IIa). The slope of the least squares fitted straight line to the resulting data indicated $K_{eq}$ to be 338 lbs./in. and linear over the range measured.

The value of the damping coefficient $c_t$ was not needed. The value of $\alpha_{ac}$, the damping ratio for the transducer in air, was determined. Since $c_t$ was equal to the product $2\alpha_{ac} \cdot Meq_{nac}$ and since $Meq_{nac}$ was a constant, it was sufficient to establish $c_t$ as a constant by showing $\alpha_{ac}$ to be a constant.

The value of $\alpha_{ac}$ was determined experimentally. The transducer was first mounted rigidly with its sensing axis vertical. The armature and bellows were then set into motion by striking the transducer frame in its axial direction. Voltage output from the gage bridge resulted from the underdamped free oscillation of the armature and diaphragm. Voltage was amplified and recorded with a model 1508 Honeywell, Inc., galvanometer oscillograph, and a Honeywell, Inc., type M1650 fluid damped galvanometer.

A strip recording with a chart speed of 40 inches per second (Figure 7) was used to determine the effective damping present. From
the chart, values of logarithmic decrement, $\psi$ (the natural logarithm of the ratio of two successive amplitude peaks) were determined. Values of logarithmic decrement were calculated from amplitudes after 30 and 60 successive cycles (19). The values were 0.0445 and 0.0447 respectively (Appendix IIb) and indicated that the logarithmic decrement was constant over a number of oscillations. The value of the damping ratio calculated from the value of logarithmic decrement was 0.0072.

The value of the damped natural frequency of the transducer was determined from a strip recording (Figure 7). Since the effective damping present was negligible, the value of $\omega_{nt}$ was essentially equal to the frequency measured from the chart. This was found to be 2120 rps.

The static sensitivity, $K_t$, of the transducer was determined experimentally (Appendix IIc). Static pressures in increments of 0.05 inches of water column were imposed on the transducer bellows with a E. Vernon and Hill type "C" Micro-Manometer. Voltage outputs from the gage bridge were measured with a Hewlett and Packard Digital Voltmeter model 3440A with a Hewlett and Packard D-C multifunction unit model 3444A. The digital readout to 0.01 MV was sufficient for the determination. The value of $K_t$ determined was 73.2 MV. per psid.

The Preamplifier and Power Amplifier

A Honeywell, Inc., Accudata 104 D-C amplifier was used to amplify the transducer bridge output (Appendix I). Specifications on the amplifier that were of interest in the frequency response investigation
Figure 7. Underdamped free oscillation of transducer diaphragm in air.
were as follows: (a) with a resistive load greater than 38 ohms, a
capacitive load less than 1 μfd and standard gain, the frequency
response is +1% to 10 kHz up to full-scale output, and +5% D.C.
to 20 kHz up to 80% full-scale output; and (b) phase shift less than
10 degrees from D.C. to 10 kHz.

The natural frequencies of the other elements of the system were
as follows: air column, 117.6 Hz; transducer, 337.5 Hz; and galvanom-
eter, 1650 Hz. The frequency response of the amplifier in the usable
frequency range of the other components (10% allowable amplification
ratio error) was not limiting. In the usable system frequency range,
the maximum phase shift caused by the amplifier was 1.5 minutes. The
amplitude error in this range would not be detectable. For these
reasons, frequency response of the amplifier was not included in the
system analysis.

The Galvanometer

The galvanometer employed was a Honeywell, Inc., Series "M"
Sub-Miniature type with fluid damping (Appendix I). The model number
M1650 designated its undamped natural frequency at 1650 Hz. At 120
degrees F, the damping ratio of this instrument was 0.64. This
damping ratio was maintained by keeping the galvanometer damping fluid
constant at 120 degrees F.

The transfer function for a galvanometer of this type (5) was

\[
\frac{X_o(S)}{e_o(S)} = \frac{K_g}{S^2 + \frac{2\zeta \omega_n S}{\omega_n^2} + 1} \quad [7]
\]
where \( K_g \) was the galvanometer voltage sensitivity with an 11.8 inch optical arm. The specified value of \( K_g \) (Appendix I) for this galvanometer was 4.49 inches per volt.

**System Operational Transfer Function**

For frequency analysis, the pressure measuring system was best described in terms of its operational transfer function. Individual system components were first represented by their transfer function (Figure 8a). Since the output impedance of each component was considerably lower than the input impedance of the following elements in the system, negligible loading existed between elements. Under this condition (5), the system operational transfer function was the product of the transfer functions of individual elements (Figure 8b). The operational transfer function that adequately described the entire measurement system was then as follows:

\[
\frac{X_o(s)}{P_i(s)} = \frac{K_t K_a K_g}{\gamma_1 \gamma_2 \gamma_3}
\]

where

\[
\gamma_1 = \frac{s^2}{\omega_{nac}^2} + \frac{2\omega_{ac}}{\omega_{nac}} + 1
\]

\[
\gamma_2 = \frac{s^2}{\omega_{nt}^2} + \frac{2\omega_t}{\omega_{nt}} + 1
\]
\[ \gamma_3 = \frac{S^2}{\omega_{ng}^2} + \frac{2\alpha S}{\omega_{ng}} + 1 \]

**Air Column Oscillations**

Since the air column was imposing severe limitations on the system, it was necessary to expand its useful frequency range.

The natural frequency of the air column was calculated using Equation 3. Tests were conducted with two different lengths of tubing to determine how closely the equation predicted values of natural frequency. A four-bladed fan rotating at 1085 revolutions per minute generating 72.4 pressure oscillations per second and located 16 inches from the pressure port was used to excite the air columns. Strip chart recordings made at 2 inches per second (Figures 9, 10) revealed the resulting air column oscillations. Forty inch-per-second charts were used to determine the predominant air column frequencies of oscillation. Results of these tests were tabulated for comparison.

<table>
<thead>
<tr>
<th>Air Column Length</th>
<th>Measured Frequency</th>
<th>Calculated Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.75&quot;</td>
<td>31.1 Hz</td>
<td>31.9 Hz</td>
</tr>
<tr>
<td>39.25&quot;</td>
<td>110 Hz</td>
<td>117.6 Hz</td>
</tr>
</tbody>
</table>

In an attempt to extend the useful range of air columns by increasing damping, two approaches were tried: (a) filling the interconnecting tubing with a damping fluid (water), and (b) inserting a glass wool packing in the tube.
Figure 9. Strip chart recording of 89.25'' air column oscillations.
Figure 10. Strip chart recording of 18.75" air column oscillations.
The interconnecting tubing was bent in a U shape to contain the water. This transmitting liquid filled the transducer terminal volume and acted as a damping medium for the transducer diaphragm as well as eliminating the compressible air column. This approach was not found satisfactory. The fluid mass oscillated in the tubing and resulted in very large values of peak pressure being recorded.

Filling the tubing with a fibrous material proved of great benefit in eliminating the air column oscillations only after packing the material to a sufficient density. At one point, the air column oscillations were eliminated to the extent that oscillations of the transducer diaphragm were predominant in strip chart recordings. At this point, however, the recorded pressure of the air source was not detectable.

It was felt that these methods of increasing damping could have been used with success. However, it would have been very difficult to describe adequately the dynamics of either of those systems to dismiss the necessity of dynamic calibration.

The Transducer Mountings

The transducer mountings (Figure 3) were shown to be a second transducer input. Transducers were mounted rigidly to inside surfaces of the exterior walls of the test structure, with their sensing axis vertical. The diaphragms were perpendicular to the direction of wind pressure being measured.

The transducers could pick up vibration since they were rigidly mounted to the walls. The wall was in effect a spring mass system
with damping. Oscillating wind pressure provided a forcing function. Under most conditions, the resulting displacement input perpendicular to the sensitive axis of the transducer would not be detrimental. If the wind-generated forcing function approached the wall system natural frequency, however, the resulting displacement could have been significant, since air offered little damping to the system.

The damped natural frequencies of the walls were determined to see if their fundamental undamped natural frequencies were within the usable frequency range of instrumentation. The fundamental damped natural frequencies of the side walls and roof slopes were measured with a vibration pick-up mounted in the center (longitudinally and vertically) of each exterior surface. Surfaces were deflected at vibration pick-up mounting points and released. The underdamped free oscillation of the surface was then recorded. The fundamental undamped natural frequencies were determined from the recordings.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Undamped Fundamental Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward and leeward roof slopes</td>
<td>29.5 Hz</td>
</tr>
<tr>
<td>Windward and leeward walls</td>
<td>19.5 Hz</td>
</tr>
</tbody>
</table>
PRESENTATION AND DISCUSSION OF RESULTS

The system operational transfer function made possible response analysis for standard inputs. The analysis was used to determine the useful frequency range of the pressure measuring system.

System Frequency Analysis

To allow comparison of the quality of measurement of systems under dynamic conditions, they are usually subjected to standard inputs. The standard input used in this investigation was sinusoidal. The steady state response (response after all transients have died out for a stable system) to the sinusoidal pressure input \( P_1 \sin \omega t \) yielded the amplitude ratio and phase angle relationships between the input and output.

Insertion of numerical values in Equation 8 yielded the system transfer function:

\[
\frac{X_o(s)}{P_1(s)} = \frac{0.342 K_a}{\gamma_1 \gamma_2 \gamma_3} \quad [9]
\]

where

\[
\gamma_1 = \left(\frac{s}{738}\right)^2 + \frac{0.0244s}{738} + 1
\]

\[
\gamma_2 = \left(\frac{s}{2120}\right)^2 + \frac{0.0144s}{2120} + 1
\]

\[
\gamma_3 = \left(\frac{s}{10,400}\right)^2 + \frac{1.28s}{10,400} + 1
\]
Replacing \( S \) with \( i\omega \) to find the complex relationships between the input and output when the input was subjected to a sinusoidal pressure variation gives:

\[
\frac{X_o(i\omega)}{P_1(i\omega)} = \frac{0.342K_a}{(\theta_1+i\beta_1)(\theta_2+i\beta_2)(\theta_3+i\beta_3)} \tag{10}
\]

where

\[
\theta_1 = 1 - \left(\frac{\omega}{738}\right)^2
\]

\[
\theta_2 = 1 - \left(\frac{\omega}{2120}\right)^2
\]

\[
\theta_3 = 1 - \left(\frac{\omega}{10,400}\right)^2
\]

\[
\beta_1 = \frac{0.024\omega}{738}
\]

\[
\beta_2 = \frac{0.0144\omega}{2120}
\]

\[
\beta_3 = \frac{1.28\omega}{10,400}
\]

This complex relationship can be separated to obtain the amplitude ratio as a function of frequency:

\[
\frac{X_o}{P_1 K_a} = \frac{1}{(\theta_1^2 + \beta_1^2)^{1/2}(\theta_2^2 + \beta_2^2)^{1/2}(\theta_3^2 + \beta_3^2)^{1/2}} \tag{11}
\]

and the phase angle as a function of frequency:
\[ \phi = - \left( \tan^{-1} \left( \frac{\beta_1}{\phi_1} \right) + \tan^{-1} \left( \frac{\beta_2}{\phi_2} \right) + \tan^{-1} \left( \frac{\beta_3}{\phi_3} \right) \right) \]  

[12]

where \( \phi \) is defined as the leading phase angle between input and output.

The frequency response curves (Figure 11) of the system were determined from Equations 11 and 12 by incrementing values of \( \omega \) and calculating corresponding values of amplitude ratio \( \frac{X_o}{342P_kK_a} \) and phase shift \( \phi \). Values of \( \omega \) were incremented by computer from 50 to 2500 rps in increments of 50 rps. The curves of Figure 11 indicated this was in excess of the natural frequency of the transducer. Interest in the plot of Equations 11 and 12 beyond this value was academic and was not shown.

With the system including an air column, the amplitude response was acceptable (± 10% attenuation) only to 34.2 Hz. The amplitude ratio at this point was 1.104, and the driving frequency was 29.1% of the undamped natural frequency of the air column.

Values for the amplitude ratio and phase angle (Figure 12) were then determined in much greater detail (increments of 5 rps) over the system's usable frequency range of zero to 214 rps. The curves indicated that the system phase lag in the usable frequency range was less than 2 degrees. This phase shift was considered of no significance, as corrections would not be attempted with phase shifts of that magnitude.

The amplitude error became unattractive rapidly after a frequency ratio of 0.30 of the air column undamped natural frequency. It would
Figure 11. Frequency response curve for pressure measuring system with and without air column.
Figure 12. System response curves within usable frequency range.
have been very difficult to try to make corrections in data for oscillations above that value, because of non-linear effects.

**Air Column Effects**

The air column which was introduced into the measurement system by employment of an interconnecting tube severely limited system frequency response.

A frequency response analysis for the system excluding the air column was also plotted (Figure 11). Two observations were readily apparent from the curves of amplitude ratio and phase angle versus frequency:

1. The usable frequency range was more than doubled (34.2 Hz to 99.4 Hz) by elimination of the air column. Errors in amplitude above that frequency (effects of non-linearity) were not as severe as with the air column.

2. The phase angle response was linear and acceptable in the range zero to 1800 rps.

**The Transducer Mounting**

The transducer mountings exhibited fundamental undamped natural frequencies within the usable frequency range of the transducer and air column. Since the time varying pressure being measured simultaneously acted as a forcing function for the transducer mountings (walls), serious inputs from this source could have occurred.

A comparison of the fundamental undamped natural frequencies of the transducer mountings and the usable frequency ranges of the walls
with and without the air column was made.

<table>
<thead>
<tr>
<th>System Usable Frequency Range</th>
<th>Transducer Mountings</th>
</tr>
</thead>
<tbody>
<tr>
<td>With air column - 34.2 Hz</td>
<td>Wall Frequency: 19.5 Hz</td>
</tr>
<tr>
<td></td>
<td>Roof Slope Frequency: 29.5 Hz</td>
</tr>
<tr>
<td>Without air column - 99.4 Hz</td>
<td>Wall Frequency: 19.5 Hz</td>
</tr>
<tr>
<td></td>
<td>Roof Slope Frequency: 29.5 Hz</td>
</tr>
</tbody>
</table>

The fundamental natural frequencies of both the walls and roofs were well within the usable frequency range of the pressure measuring system, with or without the air column. This is undesirable since vibration inputs from the transducer mountings, when they are forced to oscillate at or near their fundamental frequencies, could be quite large. Negligible damping present with the transducer mountings in air contributed to make this extraneous source of error more significant.

Several recordings made of wind pressures acting on exterior wall surfaces indicated oscillations of about 20 Hz. Since the fundamental frequencies of the walls were 19.5 Hz, the frequency of oscillation measured could well have been wall vibration.
SUMMARY

A mechanical model of each of the pressure measurement system components enabled adequate definition of the frequency response without having to resort to dynamic calibration.

The air column dynamics were described with the second order model transfer function presented by Hougen et al. (9). Recorded values of frequencies of oscillation of air columns compared favorably with those calculated from Equation 3. The calculated amount of damping present in the oscillating air column was small.

The dynamics of a Statham, Inc., model PM5TC unbonded strain gage differential pressure transducer were described by a second order linear differential equation with constant coefficients. The constant coefficients of the differential equation were shown to be valid from experimentally determined values of logarithmic decrement and spring constant. A static calibration of the pressure transducer indicated the static sensitivity curve was also linear.

Because of the small amount of phase shift and amplitude errors produced by the D-C amplifier, its dynamic response was not included in the analysis. Both the phase shift and amplitude error were very small in the usable range of the system.

Since negligible loading existed between components of the measurement system, the system operational transfer function was the product of the individual component transfer functions. This transfer function allowed frequency analysis of the system without resort to
a dynamic calibration method which could have been both difficult and expensive. With the system operational transfer function, system response to transient inputs could also be studied.

Frequency analysis indicated the air column severely limited the frequency response of the measurement system. System response could have been increased by increasing damping in the oscillating air column. Several methods were tried in an attempt to increase the value of damping, but were not found to be satisfactory. Elimination of the air column was found to increase the usable frequency range of the instrumentation from 34.2 Hz to 99.4 Hz.

The transducer mountings used were found to be possible sources of additional input to the transducer. Vibration input from the mountings could have had significant influence on strip recordings, especially if the oscillating frequency of the wind velocity head approached the fundamental undamped natural frequency of the vibrating wall system (mounting). The fundamental undamped natural frequencies of the walls and roofs were found to be within the otherwise usable frequency range of the pressure measuring instrumentation.
CONCLUSIONS

1. The pressure measuring system was adequately represented by a system operational transfer function. This transfer function permitted a frequency response analysis of the system.

2. A source of error was present because the transducers were rigidly attached to the wall surfaces.

3. The value of recordings made with the present system was severely limited due to air column effects and possible additional inputs from wall vibration.
RECOMMENDATIONS


2. The interconnecting tubing should be eliminated from the system by flush mounting of the transducer bellows with the exterior surfaces of the test structure.

3. To eliminate vibration pick-up, walls of the test structure should be stiffened structurally to increase their fundamental undamped natural frequency to a value greater than the system usable frequency range.
BIBLIOGRAPHY


APPENDIX I - Published specifications on components of the pressure measuring system.

1. Transducer*
   Type - Differential pressure transducer
   Model - Statham Model PM5TC
   Ranges - ± 0.3 psid
   Maximum psid Positive - +3.5
   Maximum psid Negative - -3.5
   Excitation - 12 volts AC or DC
   Nominal full scale output ± 23 M.V.
   Transduction - Resistive, balanced, complete unbonded strain gage bridge
   Positive pressure media - non-corrosive gases and/or fluids
   Nominal bridge resistance - 350 ohms
   Resolution - Indefinite

2. D-C Amplifier**
   Model - Honeywell Accudata 104 D-C amplifier
   Input voltage for full scale output - 10mv to 250 mv.
   Input impedance - 10 meghms minimum at D.C.
   Output impedance - Less than 500 milliohms from D.C. to 10 K.C.
   Source of resistance - 0 - 1000 ohms with up to 1000 ohms unbalance
   Gain - 10-50 in the "50" position of the gain range control
   50-250 in the "250" position of the gain range control

*Taken from Statham Instruments, Inc., Specification Number 12114.

**Taken from Honeywell, Inc., Technical Manual Number 759960A, August 1965.
Calibrated gain steps (with vernier in calibrated position),
10, 20, 30, and 50 in the "50" position of the gain range
control 50, 100, 150, and 250 in the "250" position of
the gain range control.

Frequency response (resistive load greater than 38 ohms and
and capacitive load less than 0.1 ufd) ± 1% DC to 10 KC,
up to full scale output ± 5% DC to 20 KC, up to 80% of
full scale output.

Phase shift - less than 10° from DC to 10 KC.

3. Visicorder Oscillograph*

Model - Honeywell, Inc., Model 1308,

Recording frequency - 0 to 5000 CPS, depending on the galvanometer
employed.

Writing speed - legible traces to beyond 25,000 inches per second
spot velocity.

Linearity - ± 2% of reading with deflection of four inches or
less, when initially calibrated at the average left and
right 3-inch deflection.

Time lines - 100, 10, 1.0, and 0.1 lines/second, ±2% at 117 volts
AC, operates only in record mode.

Gridlines - 0.1-inch spacing, every fifth line heavier. Two mm
spacing for metric system with every fifth line heavier.

Recording channels - Up to 24 active channels plus four auxiliary
channels.

Recording lamp - 100 watt, high pressure mercury arc, two elec-
trode, vertically mounted.

Chart speeds - Twelve speeds from 0.1 to 80 inches/sec., or the
equivalent in millimeters.

Operating temperature - Basic visicorder with fluid-damped
galvanometers +50° to 115°F.

4. Galvanometer*

Damping - Fluid damped to 64% critical damping.
Undamped natural frequency - 1650 Hz.
Flat (+5%) frequency response - 1000 Hz.
Nominal coil resistance - 24.0 ohms.
Voltage sensitivity - 4.49 in./volt.
Maximum peak to peak deflection with ±2% linearity - 8 inches.

APPENDIX II
APPENDIX II-A - Determination of the Transducer Spring Constant

Apparatus - .0001" Ames dial gage, laboratory balance scale, transducer mounting Apparatus, weights.

Procedure Sequence
1. Transducer was mounted on apparatus with the sensing axis vertical.
2. The mass of several small weights was determined with the laboratory balance scale.
3. The spring loaded sensing stem of the dial gage was mounted with the stem on the center of the transducer diaphragm.
4. Dial gage was positioned to deflect its sensing stem 0.0010".
5. Weights were placed to uniformly load the diaphragm.
6. Values of weights and corresponding deflections of the diaphragm were recorded (Table IY).
7. A least squares polynomial of degree one was fitted to the data (Table I) with the aid of a computer program. The resulting equation that best fitted the data was

\[ Y = 153.45X + .7902, \]

where Keq = 153.45 grams per .001" displacement was the resulting spring constant (Figure 13).
Table I. Transducer force - deflection data.

<table>
<thead>
<tr>
<th>Deflection $\times 10^3$ in.</th>
<th>Applied Weight Grams</th>
<th>Deflection $\times 10^3$ in.</th>
<th>Applied Weight Grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>.51</td>
<td>80.04</td>
</tr>
<tr>
<td>.08</td>
<td>13.60</td>
<td>.61</td>
<td>94.50</td>
</tr>
<tr>
<td>.20</td>
<td>30.30</td>
<td>.73</td>
<td>107.8</td>
</tr>
<tr>
<td>.30</td>
<td>46.67</td>
<td>.76</td>
<td>120.6</td>
</tr>
<tr>
<td>.39</td>
<td>62.95</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 13. Spring constant curve for transducer diaphragm.

\[ Y = 153.4X + 0.7902 \]

Least Squares First Degree Polynomial
APPENDIX II-B - Determination of the Transducer Damping Ratio


Procedure

1. Transducer bridge output was the input to the D-C amplifier and recorder above.
2. Transducer gage power was set to supply maximum bridge voltage.
3. Transducer was mounted with the axis vertical.
4. Frame of transducer was struck to excite the armature and diaphragm.
5. The transducer bridge voltage output from the resulting underdamped free oscillation was amplified and recorded on a strip chart (Figure 7).
6. Values of the logarithmic decrement $\psi$ were calculated after thirty and sixty successive amplitudes (Table V) with the equation

$$\psi = \frac{1}{n} \ln \frac{X_0}{X_n},$$

where $X_0$ is the amplitude at an arbitrary reference point and $X_n$ is the amplitude after $n$ successive amplitudes.
7. The damping ratio $\alpha_t$ was then calculated from the equation

$$\alpha_t = \left(\frac{1}{\left(\frac{2\pi}{\psi}\right)^2 + 1}\right)^{1/2}.$$
Table II. Values of logarithmic decrement

<table>
<thead>
<tr>
<th>n</th>
<th>$X_1$</th>
<th>$X_n$</th>
<th>$\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>19</td>
<td>5.62</td>
<td>0.0445</td>
</tr>
<tr>
<td>60</td>
<td>19</td>
<td>1.30</td>
<td>0.0447</td>
</tr>
</tbody>
</table>
APPENDIX II-C - Determination of Transducer Static Sensitivity.

Apparatus

Hewlett and Packard Digital Voltmeter model 3440A, Hewlett and Packard D-C multifunction unit model 3444A, E. Vernon and Hill type "C" Micro-Manometer, Statham Instruments, Inc., model PM5TC + 0.3 psid-350 pressure transducer, Honeywell, Inc., bridge power and gage power control units.

Procedure

1. The bridge output was fed into the digital voltmeter.
2. Tubing was supplied to hook the pressure side of the precision manometer to the transducer terminal volume. Connected to this line was a short tubing to a pressure source.
3. The transducer bridge sensitivity was set at 50.
4. Pressure applied to the transducer was incremented in amounts of one-fourth inch of water column.
5. The applied pressures and the resulting transducer bridge output voltages were recorded.
6. A least squares polynomial of degree one was fitted to the data (Table III) by means of a computer program. The resulting equation that best fitted the data was

\[ Y = 2.959 \, X - 0.0542 \]

where \( K_t = 2.959 \) millivolts per inch water column was the resulting transducer sensitivity (Figure 14).
Table III. Test values of transducer output in millivolts Vs. input in inches of water column.

<table>
<thead>
<tr>
<th>H₂O</th>
<th>M.V.</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>9.53</td>
</tr>
<tr>
<td>.67</td>
<td>.25</td>
<td>10.25</td>
</tr>
<tr>
<td>1.41</td>
<td>.50</td>
<td>11.09</td>
</tr>
<tr>
<td>2.18</td>
<td>.75</td>
<td>11.82</td>
</tr>
<tr>
<td>2.91</td>
<td>1.00</td>
<td>12.50</td>
</tr>
<tr>
<td>3.62</td>
<td>1.25</td>
<td>13.27</td>
</tr>
<tr>
<td>4.42</td>
<td>1.50</td>
<td>14.01</td>
</tr>
<tr>
<td>5.17</td>
<td>1.75</td>
<td>14.73</td>
</tr>
<tr>
<td>5.87</td>
<td>2.00</td>
<td>15.47</td>
</tr>
<tr>
<td>6.57</td>
<td>2.25</td>
<td>16.22</td>
</tr>
<tr>
<td>7.31</td>
<td>2.50</td>
<td>17.00</td>
</tr>
<tr>
<td>8.07</td>
<td>2.75</td>
<td>17.70</td>
</tr>
<tr>
<td>8.79</td>
<td>3.00</td>
<td>18.47</td>
</tr>
</tbody>
</table>
Figure 14. The transducer static sensitivity curve.

\[ Y = 2.959 X - 0.0542 \]

Least Squares First Degree Polynomial
Roger Allen Blevins was born in Abingdon, Virginia, May 17, 1944, the son of Charles Edward and Margaret Elizabeth Blevins. After attending elementary school at Abingdon Elementary and William King Elementary, and Abingdon High School, he was graduated in June of 1962. He entered the Virginia Polytechnic Institute in September of 1962. During his undergraduate studies, he was employed as a cooperative student with the Power Marketing Division of the Tennessee Valley Authority. In June, 1967, he was graduated with a Bachelor of Science degree in Agricultural Engineering.

He entered the graduate school of the Virginia Polytechnic Institute in June of 1967 with financial assistance from a National Science Foundation Fellowship. After completing the course work requirements for the Master of Science degree in Agricultural Engineering in August of 1968, he accepted employment with the Aluminum Company of America, Alcoa, Tennessee. While working as a staff plant engineer with Alcoa, he completed his thesis investigation. He completed requirements for a Master of Science degree in Agricultural Engineering in May, 1970.

He is married to the former Julia Ann Byrd of Ozark, Alabama.

Roger A. Blevins
ANALYSIS OF A DYNAMIC PRESSURE MEASURING SYSTEM

by

Roger Allen Blevins

ABSTRACT

A dynamic pressure measuring system composed of long connecting tube, transducer, D-C amplifier and galvanometer oscillograph were used in a wind study conducted by the Department of Agricultural Engineering, Virginia Polytechnic Institute. The instrumentation was used to measure and record dynamic pressures due to wind velocity. Data recorded in that study indicated velocity head pressure oscillations on some surfaces of the test structure in excess of 100 Hz. This investigation was undertaken to see if the recorded oscillations could have been generated in the measuring system or if they were truly wind-pressure variations.

Components of the pressure measuring system were modeled by transfer functions. From these transfer functions, a system operational transfer function was determined and used to define system frequency response.

The frequency analysis indicated the system was severely limited in response by the oscillating air column constrained within the interconnecting tube. The usable frequency range of the system (+ 10% tolerable amplitude error allowable) was found to go from zero to 34.2 Hz. By eliminating the air column this frequency range could
have been extended to 99.4 Hz. Phase shifts in these frequency ranges were found to be negligible.

Transducers were mounted rigidly to exterior walls of the test structure. The measured fundamental natural frequencies of these walls (transducer mountings) were found to be well within the usable frequency range of the instrumentation; and, therefore, a source of vibration pickup.

To improve the measuring system reliability, recommendations were made to eliminate the air column and stiffen the transducer mountings.