Design and Functional Characteristics of a Model Pressure-Measuring System

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Design of a system for measuring model pressures up to 200 mm Hg absolute with particular emphasis in the 0.10- to 1.0-mm Hg absolute pressure range is described. Twenty-four model pressures can be measured and recorded by the system in six successive time periods of 15 sec after a 75-sec time for pressures to stabilize in the model tubulation. Automatic controls are described by which each of the unknown pressures may be passed successively to three miniature, small-volume transducers of increasing sensitivity. Automatic means are described which prevent any of the transducers from being over-pressurized. Rapid, accurate, calibration procedures using a servo-driven, null-type micromanometer are described. Typical results of pressure-distribution tests obtained at a Mach number (M) of 9.8, freestream pressure (P_∞) of 0.3 mm Hg, reservoir temperature T_0 of 2760°R, and a Reynolds number R_e of 2.0×10^5/ft are presented.

I. Introduction

MEASUREMENT of low absolute pressures has been an area of concern to the Air Force Flight Dynamics Laboratory for a considerable time. Problems associated with short running time of the wind tunnel, stabilization time of the model pressure lines, and the low absolute pressures have pointed to the need for the development of a system, capable of performing this difficult task. A search was therefore initiated to locate a small, low-volume pressure transducer for measurement of pressures from 0.10 to 10.0 mm Hg. The results of this comprehensive survey are contained in Ref. 1.

Because of the nonavailability of small, accurate, low-pressure transducers, use was made of differential pressure transducers, designed originally for use in null-type angle-of-attack and yaw indicators, which were reported originally in Refs. 2 and 3 and later in Ref. 4. This transducer design was used successfully in High-Speed High-Altitude Viscous Effects Program,[5] and in model tests in the Aeronautical Systems Division's Low-Density Wind Tunnel. An interesting and different approach to the transducer development is given in Ref. 6. Pressure-distribution tests conducted on the same model at higher pressure levels in a continuously operating wind tunnel by another testing agency are presented in Ref. 7.

This present project was initiated to provide a system for measuring 24 model pressures in the 0.1- to 200-mm Hg range for use in the pebble bed and continuous air-arc heated Gasdynamics Facilities of the Air Force Flight Dynamics Laboratory. However, prior to installation and actual use, emphasis was given to the 0.1- to 1.0-mm Hg absolute range as a result of specific wind-tunnel operating characteristics.

The use of the miniature, small-volume, pressure transducer helped to make pressure-switching procedures feasible. Calibration techniques, incorporating a servo-driven, null-type micromanometer as the pressure standard in the 0- to 1-mm Hg differential range, permitted accurate and rapid tests of the complete system.

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II. Design

The problem of accurately measuring pressures in both the pebble bed and continuous air-arc heated gasdynamic facilities of the Air Force Flight Dynamics Laboratory are compounded because of short running times in the range of two to three minutes and the low level of absolute pressures to be measured. In the design of a system to meet the needs, one has the choice of mounting transducers in the model, in the sting, in the support struts, in the test cabin, or outside the test cabin. If the transducers and valves are small enough for mounting inside the model, tubulation is short, response time is less, but there are problems of high temperature and vibration effects. Transducers mounted in a sting or support require longer lines with corresponding lower response; however, vibration and high-temperature effects are reduced. Transducers mounted outside the test cabin require still longer lines, responses are slower, but temperature and vibrations effects are greatly reduced. The plan of locating the transducers and valves within the model was ruled out because of space and cooling considerations.

Reference 8 presents useful design data for that portion of the work where no slip is encountered. In these tests, however, emphasis was given to the 0.1- to 1.0-mm Hg range of pressures, where some slip does occur and the flow is in the transitional regime between viscous and molecular flow.

Pressure-stabilization tests were conducted with line lengths required for mounting the transducers at the base of the support struts or outside the test cabin. Although response time is somewhat better for the shorter line, other advantages such as accessibility, ease of calibration, minimization of vibration, and temperature effects resulted in a decision for the location outside the test cabin.

As stated previously, this model pressure-measuring system was designed to measure pressures in the 0.10- to 200-mm Hg range. Three different range transducers were used in this system, namely, 1, 25, and 200 mm Hg to provide the required accuracy of ±2% of the pressure reading over the entire pressure range. The system was designed so that any pressure within the 200-mm Hg range could be applied and measured without over-pressurizing any of the transducers.

Figure 1 is an electrical-pneumatic schematic of one of the four identical subsystems that make up the entire system. One of the six unknown pressures passes through a channel selector valve, through the manifold and then in turn to the 200-, 25-, or 1-mm Hg transducer, unless prevented by the meter relays.

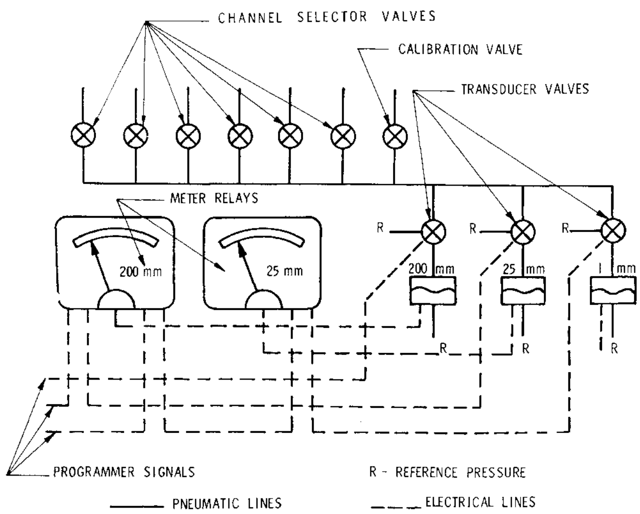


Fig. 1 Pneumatic and electrical flow diagram.

A photograph of the entire system is shown in Fig. 2 as assembled in the laboratory with the control console, six tank calibration system, and the micromanometer. Each tank is provided with pump and bleed valves for pressure setting and a valve for connecting to the pressure measuring manifold. The micromanometer is connected to the measuring manifold.

An unusual feature of this calibration system was the use of large volume tanks for storage of the reference pressure and calibrating pressure. This large 10.4-ft^3 capacity provided excellent stability. Problems associated with setting and maintaining pressures in the 0.1-to 1.0-mm Hg range were simplified by the use of large volume tanks. The reference pressure and the calibration pressures were all measured with the servo-driven, null-type micromanometer, which is described later in more detail.

Each of the four identical subsystems includes a transducer-valve unit similar to that shown in Fig. 3. The model orifice pressure enters through the inlet fitting located back of the valves, it is then passed through the channel selector valve to the small manifold and then through the pertinent valve to either the 200-, 25-, or 1-mm Hg transducer. The reference side of the transducers is open to the case that is maintained at a reference pressure of 0.1 mm Hg absolute. Similarly, the measuring side of the transducers also is supplied with the same respective reference pressure through the transducer valves, except when a pressure is being measured.

The miniature pressure transducers, Fig. 4 are basically the same as those used in miniature, null pressure type, angle-of-

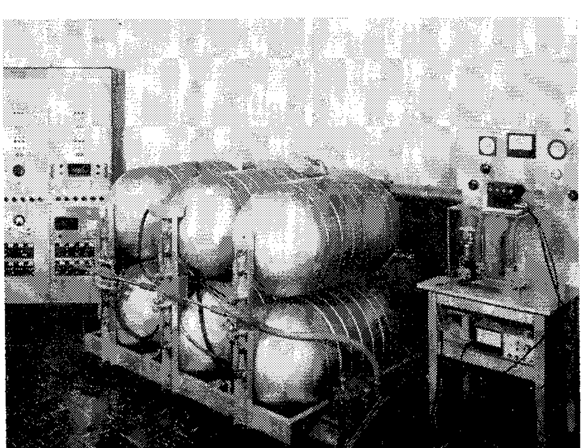


Fig. 2 Model pressure system assembled in the laboratory.

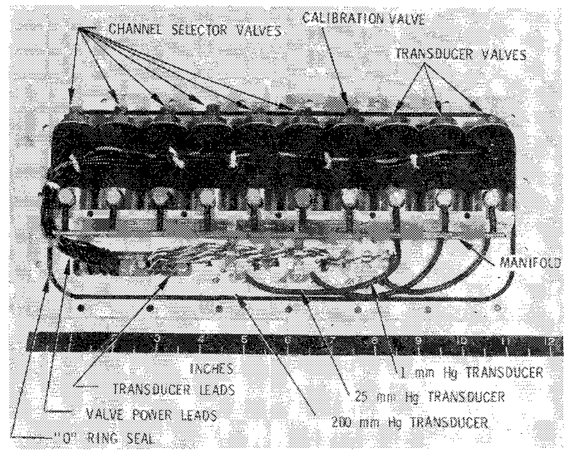


Fig. 3 Transducer valve unit.

attack indicators.[3] The 1.0-mm Hg transducer is 1 in. in diameter and $\frac{1}{4}$ in. thick. A variable-reluctance sensing system measures the deflection of a nonmetallic diaphragm. Early use of nonmetallic diaphragms for instruments is described in Ref. 9.

Figure 5 is a view of the control console with all components identified, whereas Fig. 6 is a view of the four programmer units and master control unit before installation in the control console. The master control unit performs the following functions: Operates the channel selector valves, provides time pulses to simultaneously start all programmer units, and operates the orifice identification indicator lights. The programmer units perform the following functions: Operates the 200-, 25-, and 1-mm Hg valves of the transducer valve units, transfers the 12 transducer outputs to the common preamplifier and readout system, and provides the command signals for printout of each of the 12 transducer outputs at the appropriate time. Each programmer unit also contains two fiber-optic relays, one of which is connected to the 200-mm Hg transducer output, and the other to the 25-mm Hg transducer output. Each in turn provides an over-riding control to the 25- and 1-mm Hg transducer valves, and thus prevents over-pressurization of the transducer.

This system provides the user a high degree of flexibility. The speed of scanning each model pressure with the three different range transducers can be 6, 9, 12, 15, 18, or 21 sec by a simple change of the gear assembly in each of the four programmers. The proportion of time that pressure is applied to the 200-, 25-, or 1-mm Hg transducers can be varied by a simple adjustment to the individual programmer. It

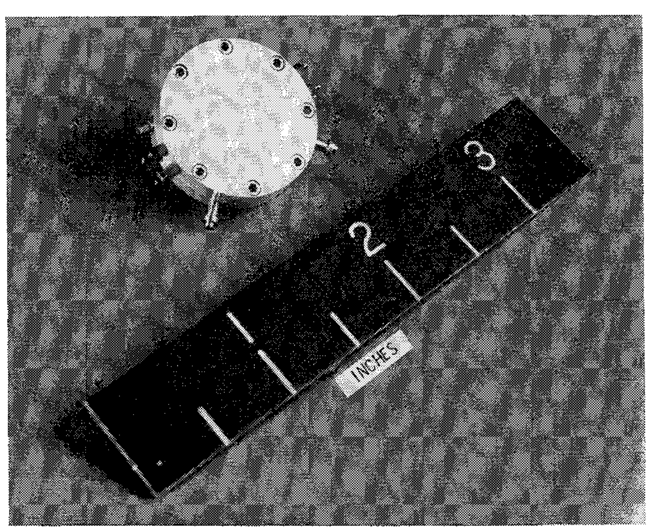


Fig. 4 Miniature pressure transducer.

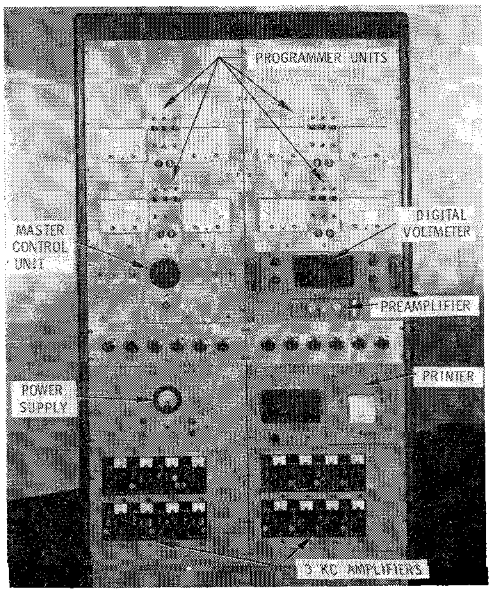


Fig. 5 Control console for the model pressure-measuring system.

is also possible to cut out operation of both the 200- and 25-mm Hg valves and thus use all available time for stabilization of the 1-mm Hg transducer.

Each subsystem, which is made up of a programmer unit and a transducer-valve unit, is pneumatically connected by means of a channel selector valve to six model pressures. Four subsystems are used in the complete system, thus providing capability for measuring 24 individual model pressures. In order to scan these pressures, the master control provides appropriately timed pulses for six cycles of each of the four programmers.

Figure 7 illustrates how the four programmer units function in order that a single channel preamplifier and readout means can be used to scan the 12 individual transducer outputs. The time scale on the bottom of the diagram represents percent of time for one revolution of the programmers, namely, 15 sec. Considering unit one, the block at the left indicates the time the 200-mm Hg valve is open, that is, it opens at time 0 and closes at time 14%. The shaded portion of the same block represents the time the output signal from the 200-mm Hg transducer is connected to the common preamplifier, that is, from 10 to 14%. The arrow at the bottom of the shaded portion represents the time at which the print command signal is given, which in this case is 12%. The center block represents the functioning of the 25-mm Hg transducer system, and the large block to the right represents the 1-mm Hg transducer system. Note that the 1-mm Hg transducer system is given a larger percentage of the time,

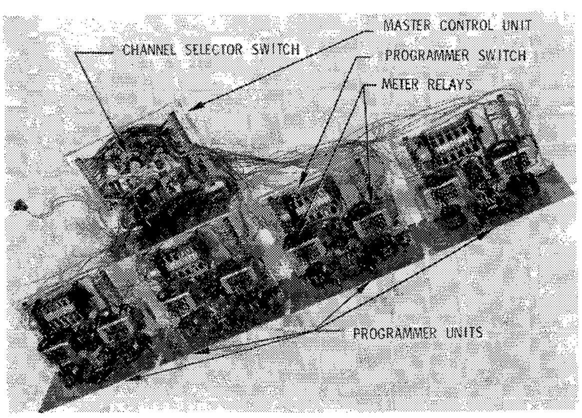


Fig. 6 Four programmer units and master control unit (plan view).

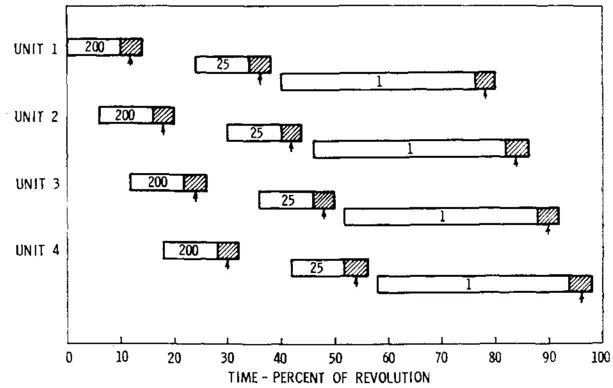


Fig. 7 Programmer block diagram.

because of longer stabilizing times required at the lower pressures. Note also that the staggering of the four units is accomplished in order that the common preamplifier and readout can be shared among the 12 transducers.

The micromanometer shown in Fig. 8 was developed for the specific purpose of filling the need for a pressure standard that could be used for calibrating pressure transducers in the 0- to 1.0-mm Hg range of differential pressures. Two glass vessels are interconnected with a 0.75-in. i.d. glass tube. Metal caps are fitted to the top of each vessel and are sealed with "O" rings. The left-hand vessel is used as the reference pressure side of the micromanometer, whereas the right side is used for the unknown pressure. A molecular vacuum gage was used for measuring the absolute pressure in the reference side of the micromanometer. As shown in Fig. 8, the gage is filled to the proper level with a low vapor pressure solution known as "Octoil."

A float, suspended in the right-hand vessel, electrically senses the level of the solution. This whole vessel system is supported at the right side by pivotal means, whereas the left side is supported by a precision lead screw. A servo actuator is controlled by the amplified error signal from the float position sensor. The actuator causes the left-hand vessel to change its height in relation to that of the right-hand vessel. A digital counter, geared to the lead screw indicates the position of the left-hand vessel, with respect to the right-hand vessel. The output also can be indicated remotely by a simple digital converter and Nixie tube system as shown in Fig. 2. Pressure differential is a direct function of the difference in height of the left and right vessels. This micromanometer has a resolution of 0.001 mm Hg.

In order to obtain optimum tubulation for the installation a series of pressure stabilization tests were conducted. Figure 9a is a graph of stabilization characteristics obtained with

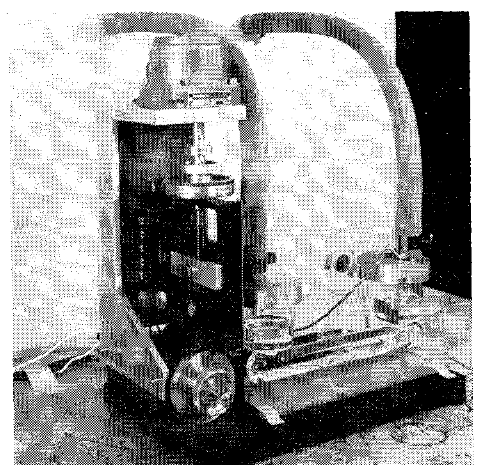
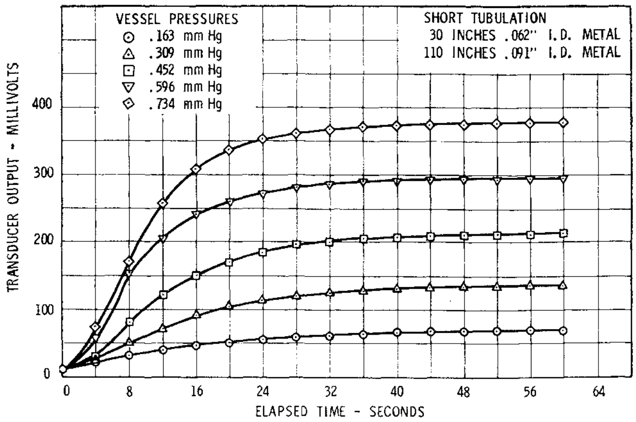
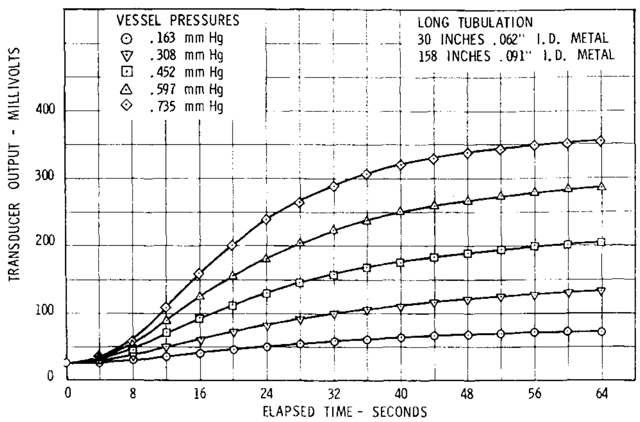


Fig. 8 Null-type micromanometer.



a) **Obtained with short tubulation.**



b) **Obtained with long tubulation.**

Fig. 9 Pressure-stabilization data.

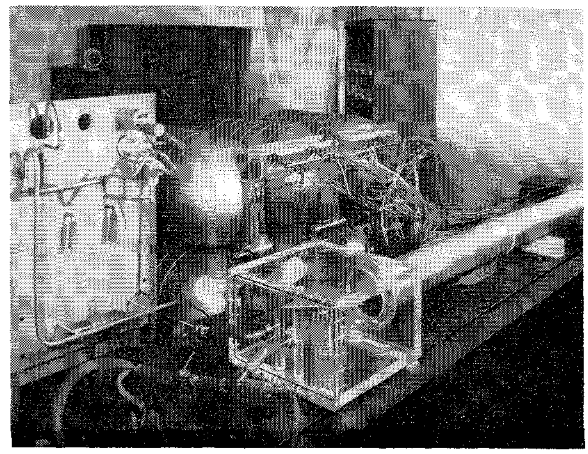


Fig. 11 Equipment used in pressure-stabilization test in the laboratory.

tubulation required for mounting the transducer valve units at the base of the wind-tunnel model crescent support. This required 30 in. of 0.062-in. i.d. and 110 in. of 0.091-in. i.d. tubing. Figure 9b is similar data obtained with longer tubulation required for mounting the transducer valve units just outside the test cabin, i.e., 30 in. of 0.062-in. i.d. and 158 in. of 0.091-in. i.d. tubing.

On the basis of results obtained from the foregoing test, it was decided to mount the transducer valve units outside the test cabin, thus avoiding to a large degree the problems of high temperature, vibration, and accessibility.

The actual installation required considerable flexing of the model pressure lines between the bottom of the crescent support and the penetrations in the side of the test cabin wall. Tests were conducted to determine the feasibility of replacing 26 in. of the 0.091-in. i.d. metal line with either rubber, nylon, or teflon tubing. Figure 10 presents the results of outgassing tests which were made with these various flexible materials, as well as outgassing characteristics of the all metal tubulation.

The intended purpose of these tests was to determine comparative conductance and outgassing characteristics of systems with all-metal tubulation or combinations of metal and nonmetal tubulation. Even though outgassing characteristics were known for the various nonmetallic materials, it was believed that experimental testing of the complete system would provide more accurate information regarding system performance. For each of the tubulation arrangements the system from simulated model orifice to transducer valve was opened to the atmosphere. After waiting three minutes, pressures indicated at the transducer were recorded at one-minute intervals to determine the conductance and outgassing characteristics.

The results of these tests indicated the following order of preference, namely, copper, teflon, nylon, and rubber. In actual use, the outgassing time is important because a large pumping system is required to maintain a pressure of 0.1 mm Hg in the wind tunnel prior to operation. The orifice, tubulation, valving, and transducers must be outgassed before insertion of the model in the high temperature, high Mach number flow.

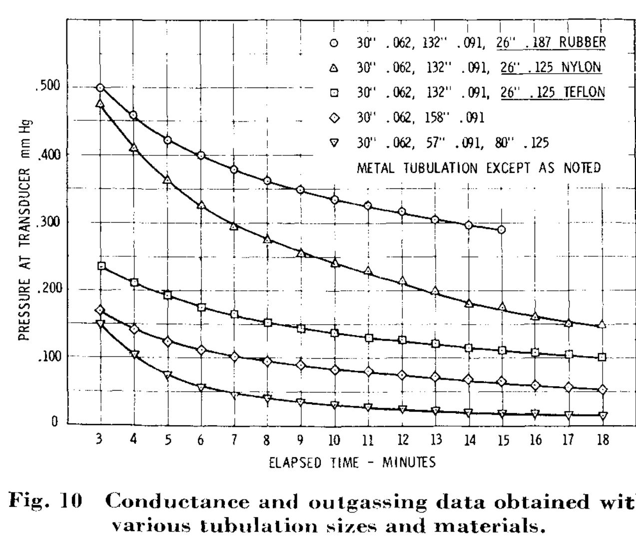


Fig. 10 Conductance and outgassing data obtained with various tubulation sizes and materials.

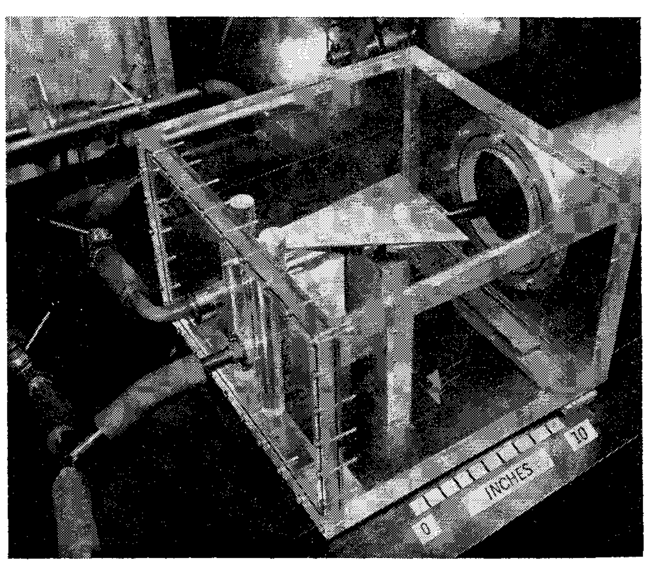


Fig. 12 Model mounted in vacuum vessel for stabilization tests.

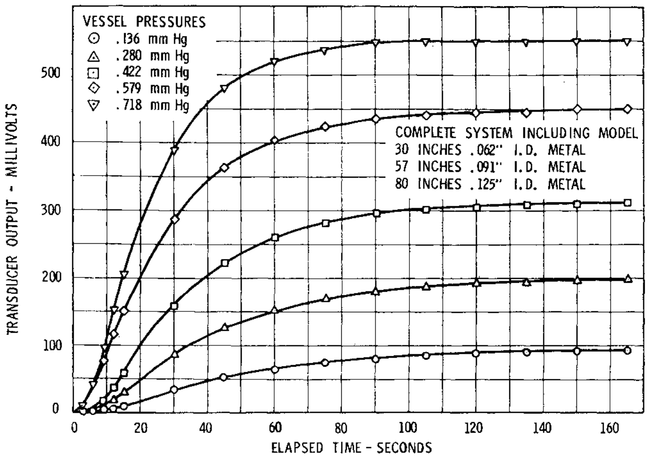


Fig. 13 Pressure-stabilization data obtained with the complete system.

Further improvement was obtained by increasing the diameter from 0.091-in. i.d. to 0.125-in. i.d. for that part of the tubulation from the bottom of the crescent support to the transducer valve units. The final tubulation design for use with the model consisted of 30 in. of 0.062-in. i.d. metal tube, 57 in. of 0.091-in. i.d. metal tube and 80 in. of 0.125-in. i.d. metal tube. Very short lengths of rubber tubing were used for connecting the metal lines to the transducer valve units.

The first use of this model pressure-measuring system was for the measurement of pressures on the expansion side of both a 60° and a 75° swept delta wing. Emphasis was therefore given to the measurement of pressure below 1 mm Hg absolute. In order to be certain that the orifice and tubulation in the model possessed the proper conductance, a special test apparatus was prepared as shown in Fig. 11. The pressure-distribution model, which was to be tested in the wind tunnel, was mounted in the plastic vacuum vessel, Fig. 12. Model pressure lines extended through fittings at the aft end of the large metal cylinder, to the four transducer-valve units. In addition, a calibration line of identical size and length as those connecting the model to the transducer-valve unit, connected the calibration valve of the 4 transducer-valve units to the measuring manifold. Results of stabilization tests of the complete system, including the model are given in Fig. 13.

III. Model Tests

After completion of conductance and outgassing tests the model pressure-measuring system was moved into the facility area. One tank (Fig. 2) was used for storage of the reference pressure, while the other five were set at pressures to provide five different calibration pressures that covered the 1-mm Hg absolute range. Operation of the six pump and bleed valves for setting the pressure level within the six tanks could be accomplished from the facility control room. Operational control of the valves that connect any of the six tanks to the micromanometer was also from the facility control room. The pressure-measuring system was mounted adjacent to the tunnel. The control console, previously described and shown in Fig. 2, also was located in the facility control room. Calibration of the entire system could be accomplished from the facility control room in a period of about 25 minutes.

Figure 14 illustrates a typical calibration of a 1-mm Hg transducer. The calibration curves were obtained by recording the output at various stabilization periods. By using the appropriate calibration curve in the data-reduction process the small errors due to incomplete stabilization during an actual text could be minimized. This procedure was necessary because of the short running time of the wind tunnel, that is, about 150 sec.

Figure 15 is a view of the pressure distribution model installed in the test section. Prior to a test the test cabin pressure was reduced to a pressure of about 0.10 mm Hg and held for sufficient time to evacuate and outgass the 24 model pressure lines. Immediately after flow was established, the model was injected. After stabilization, the automatic control system was energized. Each of the 24 model pressures

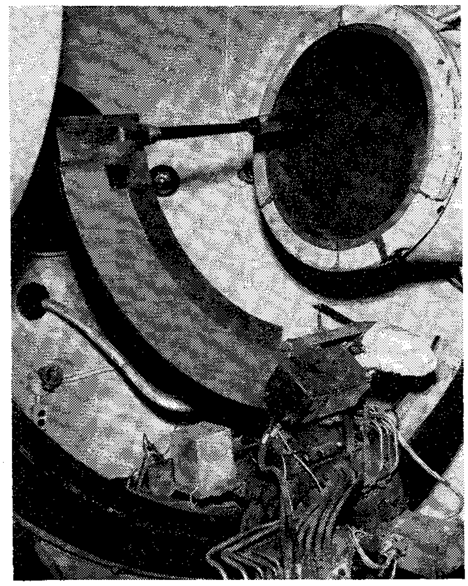


Fig. 15 Pressure-distribution model mounted in the high-temperature wind tunnel.

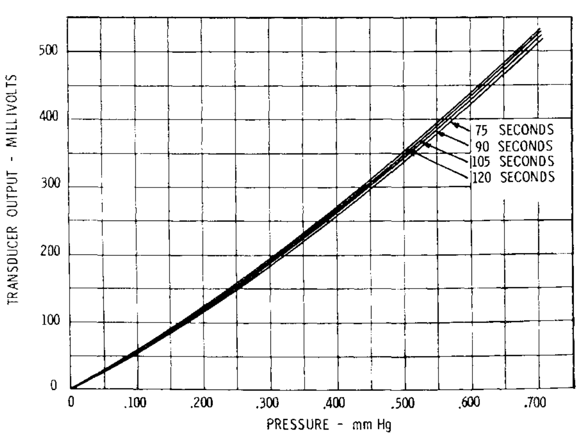


Fig. 14 Typical calibration of 1-mm Hg transducer.

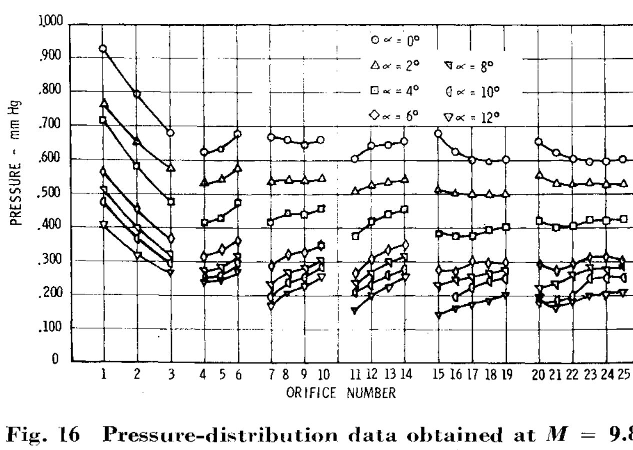


Fig. 16 Pressure-distribution data obtained at $M = 9.8$, $T_0 = 2760$, $R_l = 2.0 \times 10^5$/ft.

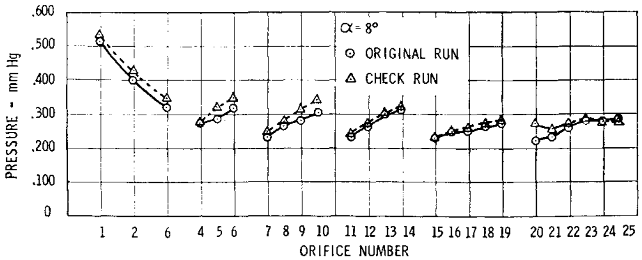


Fig. 17 Comparison of pressure-distribution data obtained from two repeat runs.

was sequentially scanned by one of the four subsystems in six successive steps. The output of the pressure transducers was printed out in digital form on paper tape.

IV. Results

The pressure distribution data obtained from the 75° swept wing model with a blunt leading edge is shown on Fig. 16. Conditions for this test were as follows: $M = 9.8$, $P_\infty = 0.3$ mm Hg, $T_0 = 2760°$R, and $R_e = 2.0 \times 10^5$/ft. Model angles of attack from 0° to 12° were investigated and the range of pressures measured was from 0.145 to 0.925 mm Hg absolute.

Figure 17 shows the average difference in measured orifice pressures of approximately 0.025 mm Hg for the comparison of the two sets of repeat data. These data were not corrected for the small variations in tunnel conditions.

To obtain the highest degree of accuracy, calibrations of the system were performed daily prior to test. Figure 18 shows typical data obtained from a 1-mm Hg transducer on three successive days while Fig. 19 shows similar data obtained from a 200-mm Hg transducer on four successive days.

Because of the inherent problems of conductance, outgassing, and leakage associated with establishing very low pressures throughout a pressure system, reference pressures were maintained at levels which were only low enough to be below the lowest model pressure.

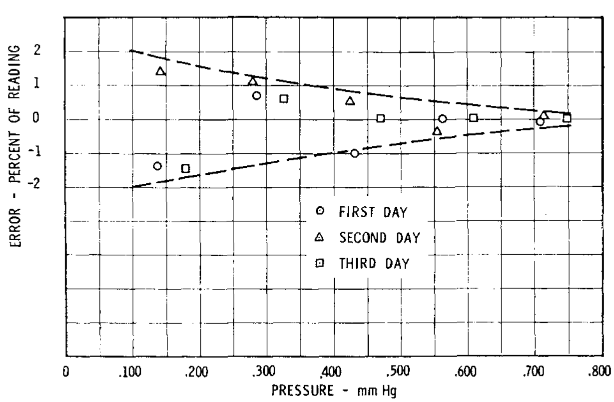


Fig. 18 Calibration data obtained from one of the 1-mm Hg transducers on three successive days.

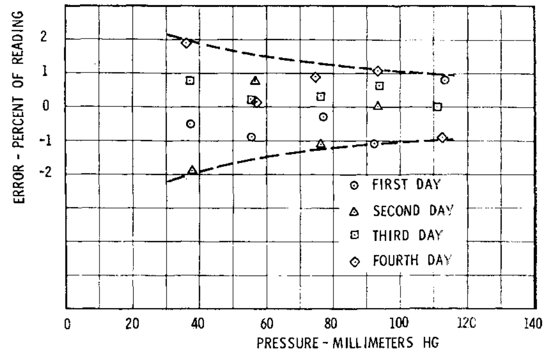


Fig. 19 Calibration data obtained from one of the 200-mm Hg transducers on four successive days.

V. Conclusions

A rapid, accurate, low-pressure measuring system was designed, developed, and proven for facilities operating for periods of approximately two minutes. The range of the measuring system was from 0.1 to 200 mm Hg with accuracies of approximately ±2.0% of the reading. The system provided sequential, fast, scanning with associated protective means to the sensitive transducers.

The short calibration times were made possible by the use of large volume tanks for storage of known calibration pressures, by a completely automated control system, and by a fast response, servo-driven, null-type micromanometer. The small-volume, high-accuracy pressure transducers played an important role in the ability of this system to respond to low pressure in the short operating time of the wind tunnel.

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