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OPTICAL ZERO-DIFFERENTIAL PRESSURE SWITCH AND ITS EVALUATION IN A MULTIPLE-PRESSURE MEASURING SYSTEM

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16. Abstract

The design of a clamped-diaphragm pressure switch is described in which diaphragm motion is detected by a simple fiber-optic displacement sensor. The switch was evaluated in a pressure measurement system where it detected the zero crossing of the differential pressure between a static test pressure and a tank pressure that was periodically ramped from near zero to full-scale gage pressure. With a ramping frequency of 1 hertz and a full-scale tank pressure of 69 N/cm^2 gage (100 psig), the switch delay was as long as 2 milliseconds. Pressure measurement accuracies were 0.25 to 0.75 percent of full scale. Factors affecting switch performance are also discussed.

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OPTICAL ZERO-DIFFERENTIAL PRESSURE SWITCH AND ITS EVALUATION IN A MULTIPLE-PRESSURE MEASURING SYSTEM

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SUMMARY

The design and evaluation of an optical zero-differential pressure switch are described. It was designed to detect the zero crossing of a differential pressure applied to the switch. This is done by detecting the motion of a clamped diaphragm with a simple fiber-optic displacement sensor that is an integral part of the switch. The fabrication and operating characteristics of this displacement sensor are also described.

The switch was evaluated in a 16-channel pressure measuring system. In this system, each test-pressure line was connected through one of the pressure switches to a common tank. Two calibration-pressure lines were connected through two pressure switches to the tank. Also connected to the tank was a linear pressure transducer. The pressure in the tank was periodically ramped from near zero gage pressure to some full-scale value, and the transducer output was recorded for each switch zero crossing. After each ramp, the test pressure applied to each switch was determined from the transducer output corresponding to its zero crossing and the transducer outputs corresponding to the zero crossings of the two calibration-pressure switches. The system operated at a 1-hertz ramp frequency over two pressure ranges: 0.7 to 10 N/cm^2 gage (1 to 15 psig) and 2 to 69 N/cm^2 gage (3 to 100 psig). Measurement accuracies of 0.25 and 0.75 percent of full scale, respectively, were achieved over these two pressure ranges. Pressure switch delays as long as 2 milliseconds were observed. Factors affecting this delay time are discussed.

INTRODUCTION

Aerodynamic research conducted in wind tunnels and engine test facilities at the NASA Lewis Research Center requires the measurement of many thousands of channels of both steady-state and dynamic pressure. Since precision pressure transducers are expensive, the cost of providing a transducer for every channel becomes prohibitive. For steady-state pressure measurements, special systems have been developed that yield a lower cost per channel than the transducer-per-channel approach.

One such approach for measuring many pressure channels is used in both the digital automatic pressure recorder (DAMPR) (refs. 1 and 2) and the parallel pressure multiplexer (PPM) (ref. 3). In these systems, each pressure channel is connected through a pressure switch to a tank in which the pressure is periodically ramped to full scale. When the differential pressure across a given pressure switch is zero (the zero-crossing point), the time at that moment is recorded. A pressure ramp whose pressure-versus-time function is known is obtained by sonic flow through an orifice into the tank. In the DAMPR system a low and a high reference pressure are applied to two sets of pressure switches in the tank, thus providing reference time marks during the ramp. The pressure of a given channel is determined from the switching time of that channel relative to the time marks. Although in a slightly different manner, the pressure of a given channel in the PPM is also determined from the switching time of the corresponding pressure switch. The DAMPR system achieves a measurement accuracy of 0.1 percent of full scale at a tank-pressure ramp frequency of 0.02 hertz, and the PPM system is designed for an accuracy of 1 percent at a tank-pressure ramp frequency of 4 hertz. The most serious problem with both the DAMPR and PPM systems has been the pressure switch. The existing switches are difficult to fabricate and/or switch performance is not reproducible.

This report describes the results of work aimed at overcoming the pressure-switch problems. A new optical pressure-switch design is described, along with its evaluation in a 16-channel pressure measuring system similar to the DAMPR and PPM systems. This system is called the MPM (for multiple-pressure measuring) system to distinguish it from the DAMPR and PPM systems. Pressure measurements with the MPM system were made over two pressure ranges: 0.7 to 10 N/cm^2 gage (1 to 15 psig) and 2 to 69 N/cm^2 gage (3 to 100 psig). Only steady-state pressures were measured. The tank-pressure ramp frequency for the two ranges was 1 hertz. Various configurations of a simple optical displacement sensor that is an integral part of the pressure switch were also investigated. The results presented herein should be of interest to those engaged in the design of pressure switches or systems to measure multiple pressures.

DESCRIPTION OF PRESSURE SWITCH

The characteristics of an ideal pressure switch for the pressure measuring application are as follows: First, a negligible differential pressure should be required to switch the diaphragm between the two positions of maximum deflection. Second, the switch output should have a negligible delay time in responding to a change in sign of the differential pressure. Third, the pressure switch must be able to withstand high differential pressures for millions of cycles without damage. Finally, the switch must be simple and inexpensive to make.

Numerous pressure-switch designs were fabricated and tested. The most-promising pressure switch is illustrated in a cross-sectional view in figure 1 and shown in figure 2. It is a clamped-diaphragm design with a beryllium-copper diaphragm 38 millimeters in diameter and 38 micrometers thick. The diaphragm is sandwiched between two ring-shaped Teflon gaskets 38 millimeters in outside diameter by 13 millimeters in inside diameter by 51 micrometers thick, giving an effective diaphragm diameter of 13 millimeters. The gasket-diaphragm sandwich is clamped between two round, brass end plates 9.5 millimeters thick. Standard brass fittings, silver soldered to these plates, provide the gas connections. The diaphragms were photoetched from a roll of 51-millimeter-wide, "half-hard" strip stock. Other than cleaning, no other treatment was provided. The Teflon gaskets were cut (including the bolt holes and the 13-millimeter center hole) in cookie-cutter fashion by using hardened tubing with sharpened edges. Hole registration was maintained by positioning the cutters with a metal block having appropriate guide holes.

Each end plate contains 0.76-millimeter-diameter holes through which gas from the test side and the tank side can reach the corresponding side of the diaphragm. The effect of the number and placement of these holes on switch performance is discussed later. The diaphragm is supported by one or the other of the end plates, depending on the direction of the differential pressure. This reduces the tensile loading on the diaphragm to a small fraction of what it would be if the diaphragm were supporting the entire pressure load. Thus, the diaphragm can be made very thin, and the resulting differential pressure required to move the diaphragm away from one end plate and against the other is extremely small, of the order of 0.06 N/cm^2. During each pressure ramp the diaphragm moves from the tank-side end plate to the test-side end plate in a small pressure range in the neighborhood of the zero-crossing point. This small displacement of the diaphragm is detected by an optical displacement sensor that is an integral part of the pressure switch. The fabrication and operation of this sensor are described in the next section.

OPTICAL DISPLACEMENT SENSOR

An essential part of the pressure switch is an optical displacement sensor that was developed (ref. 4) for detecting small diaphragm deflections. The configuration of this sensor is shown in figure 3. It consists of two optical fibers held in a metal sensor plate as shown. The free end of one of these fibers, the input fiber, is connected to a light source; and the free end of the other, the output fiber, is connected to a light detector. The two fibers are mounted so that their axes are in the same plane and are at an angle, θ, to the perpendicular to the sensor face. The two fibers just touch at the sensor face, and the ends of the fibers are polished in the plane of the sensor face. Light emerging from the input fiber is refracted as shown, then reflected off the diaphragm. The amount of light captured by the output fiber is a function of the distance of the sensor face from the diaphragm. This configuration is very sensitive to displacements of the diaphragm because a light ray emerging from the input fiber is refracted so as to make a small angle with the diaphragm; the light ray is also accepted by the other fiber at a small angle.

The optical fibers were plastic and had a diameter of 1 millimeter surrounded by a protective sheath 2.2 millimeters in diameter. The indices of refraction of the fiber core and cladding were 1.490 and 1.392, respectively. The fibers were mounted in holes drilled in the brass plate and were held in place with opaque epoxy. The mounted fiber ends were then polished flush with the sensor face.

To determine the effect of the angle θ on the output of the displacement sensor, the following experiment was performed: A number of sensors were made with θ of 45°, 40°, 35°, and 30°; the extreme case of $\theta = 0^{\circ}$ was also constructed. A microscope illuminator was used as the light source. The light output from the receiving fiber was monitored with a phototransistor connected as shown in figure 4. The displacement sensors were calibrated by measuring the output of this circuit as a function of the distance of the sensor from a test surface that was nearly specular. Initially, the output was adjusted to be approximately 1 volt at the distance that yielded the maximum output. In this calibration the sensor was mounted on a linear motion table connected to a micrometer screw. The resultant output-versus-distance curves for the five angles θ are shown in figure 4.

As the sensor was moved away from the test surface, the output rose from zero to some maximum value (the left sides of the curves in fig. 4) and then dropped off again (the right sides). A portion of the left side and a portion of the right side of each output curve are approximately linear. The sensitivity of the sensor was defined to be the maximum slope of the output curve when the gain of the light detection circuit was set to yield 1 volt at the distance of maximum output. The maximum for the $\theta = 0^{\circ}$ curve occurred at a distance of approximately 2.5 fiber diameters, which is off scale in figure 4. The sensitivities of the five sensors were measured and found to be 6.2, 5.2, 3.9, 2.6, and 0.72 mV/μm for θ of 45°, 40°, 35°, 30°, and 0°, respectively.

If the angle θ is too large, no light will escape from the end of the transmitting fiber; but light will be internally reflected from the end of the fiber, pass through the wall of the fiber, and be absorbed by the opaque epoxy. For a ray passing along the axis of the particular plastic fibers used in this experiment, the critical angle θ for total internal reflection at the end is 42°. For the light source chosen, not all the light was axial, so the sensor did function for θ greater than 42°.

Since the sensor with $\theta = 45^{\circ}$ had the maximum sensitivity and had a reasonable light output, the pressure switches were fabricated with this value of θ. The normal operating range of the sensor in the pressure switch was with displacements from 0 to 0.1 millimeter.

DESCRIPTION OF MULTIPLE-PRESSURE MEASURING SYSTEM

A 16-channel pressure measuring system, somewhat similar to the PPM of reference 3 was built for evaluating the pressure switches in a realistic environment. As mentioned in the INTRODUCTION, this system is called the MPM system. It is shown schematically in figure 5. The major components are (1) the tank in which the pressure is ramped, (2) a pressure source, (3) valves and an orifice for controlling the tank pressure, (4) 16 pressure switches, (5) a pressure transducer, (6) a light source for the pressure switches, (7) an optical detector module for the pressure switches, (8) an electronic logic module, and (9) a minicomputer.

The tank was machined from a brass cylinder and had inside dimensions of 95 millimeters in height by 45 millimeters in diameter. Two solid brass cylinders were installed inside the tank as volume fillers, reducing the total tank volume to about 37 cubic centimeters. The smaller tank volume requires less gas for ramping the tank pressure.

The various items connected to the tank, as shown in figures 5 and 6, performed the following functions: A total of 16 pressure switches were connected to the tank, whose pressure was periodically ramped from nearly atmospheric pressure to some full-scale value. Each of these switches detected its corresponding zero-crossing point as the tank pressure was ramped. A precision pressure transducer, selected for low nonlinearity (less than 0.1 percent of full scale), was connected to the bottom of the tank. Its range matched the particular pressure ramping range of the tank. The pressure source was connected to the tank through a solenoid valve and an orifice. The orifice was sized to operate under choked-flow conditions so that a nearly linear pressure ramp resulted. The other solenoid valve connected to the tank provided a vent for the tank after each pressure ramp. Finally, a relief valve located at the top of the tank eliminated the possibility of the tank pressure exceeding the range of the pressure transducer.

Lines containing pressures to be measured were connected to 14 of the pressure switches, and the remaining two switches were connected to two precisely known calibration pressure sources. One of these was at a pressure near full scale, called the high calibration pressure, and the other was at a low pressure, called the low calibration pressure.

The input optical fibers from the 16 switches were connected to a single light source consisting of a 115-volt, 60-hertz, 300-watt, tungsten-filament, quartz-halogen slide projector lamp. The lamp was operated at only 22 volts for longer life.

The output optical fiber from each pressure switch was connected to one channel of a 16-channel optical detector circuit. The circuit produced a pulse for each channel when the corresponding pressure switch reached the zero-crossing pressure point. A phototransistor provided the optical-to-electrical signal conversion.

The electronic logic module produced appropriate digitized pressure transducer readings corresponding to each pressure channel for the minicomputer. The basic elements of this logic circuit were a tracking 12-bit analog-to-digital (A/D) converter and a 64-word, 12-bit random access memory (RAM). The A/D converter updated the digital representation of the amplified analog signal from the linear pressure transducer every 100 microseconds. The 12-bit digital word ranged from 0 to 4095 counts. When a pressure switch detected a zero-crossing point, the digitized transducer output at that instant of time was stored in an appropriate memory (RAM) location. During each pressure ramp, all 16 memory locations corresponding to the 16 pressure channels were updated with the current respective pressure reading. These readings were then transferred to the minicomputer.

OPERATION OF MULTIPLE-PRESSURE MEASURING SYSTEM

A typical operating cycle of the MPM system is shown in figure 7. It started when the vent valve closed and the source-pressure valve opened. The pressure ramp lasted 0.5 second, then the source-pressure valve closed and the vent valve opened for another 0.5 second, allowing the tank pressure to drop to nearly atmospheric pressure. This cycle was repeated at a 1-hertz rate.

The MPM system was operated over two pressure ranges. The lower range was from 0.7 to 10 N/cm^2 gage (1 to 15 psig), with the 0.5-second pressure ramp being produced by a source pressure of 79 N/cm^2 gage (115 psig) applied to a 0.38-millimeter orifice. The upper pressure range was from 2 to 69 N/cm^2 gage (3 to 100 psig), with the 0.5-second ramp being produced by a source pressure of 152 N/cm^2 gage (220 psig) applied to a 0.64-millimeter orifice.

The digital data entered into the minicomputer for a given pressure ramp consisted of a set of digital numbers (counts) proportional to the tank pressure corresponding to the zero-crossing point of each switch. The nonlinearities of the tank-pressure transducer and its amplifier were specified by the manufacturer to be less than 0.1 and 0.01 percent of full scale, respectively. The nonlinearity of the A/D converter was estimated to be less than 0.05 percent of full scale. Thus, the total nonlinearity of the conversion of the tank pressure to a digital number was less than 0.15 percent of full scale. Within this tolerance, the digital output of the A/D converter was proportional to tank pressure and independent of the pressure linearity (with time). For a given channel the test pressure was derived from the expression (fig. 7)

$$P_M = P_L + (P_H - P_L)\frac{C_M - C_L}{C_H - C_L} \tag{1}$$

where

P_M measured test pressure

P_L low calibration pressure

P_H high calibration pressure

C_M counts corresponding to test pressure

C_L counts for low calibration pressure

C_H counts for high calibration pressure

PRESSURE-SWITCH EVALUATION IN MULTIPLE-PRESSURE MEASURING SYSTEM

The procedure followed in determining pressure measurement accuracy over the two pressure ranges was as follows: All pressure switches on the tank (except the low- and high-calibration-pressure switches) were connected to a single manifold to which a known pressure was applied.

The low and high calibration pressures and the manifold pressure were provided by self-regulating, pneumatic, deadweight pressure testers that were accurate to within 0.025 percent of output pressure over the range 0.7 to 69 N/cm^2 gage (1 to 100 psig). The three pressure testers were checked against a pressure calibration system that had previously been compared with a 0.01-percent pressure standard. The pressure testers were found to be consistent with the calibration system and with each other to 3 parts in 10 000.

For the low-pressure range the low and high calibration pressures were set at 13.3 and 86.7 percent of full-scale pressure, respectively. For the high-pressure range, the low and high calibration pressures were set at 10 and 90 percent of full scale, respectively.

The minicomputer was programmed so that the counts corresponding to the zero-crossing points for all 16 channels were recorded for each pressure ramp. Channels 1 and 2 were the low- and high-calibration-pressure channels, respectively. Channels 3 to 16 were connected to the manifold. At each selected manifold pressure level the counts for 50 sequential pressure ramps were recorded. For each of the 50 pressure ramps, the test pressure was calculated by using equation (1) for channels 3 to 16. Table I shows the matrix format of 700 pressures (14 channels for 50 pressure ramps) that was generated at each test pressure. Also shown in table I are four quantities that were derived from this matrix. They are defined as follows:

(1) The "single-channel average" is the result of averaging the 50 measured pressures for a single measuring channel.

(2) The "worst single-channel average" is that single-channel average (out of 14) with the largest deviation from the manifold pressure.

(3) The "composite average" is the average of the 14 single-channel averages.

(4) The "worst single measurement" is that measured pressure (from the matrix of 700) with the largest deviation from the manifold pressure.

Measurements were made at 15 test pressures over the low-pressure range and at 12 test pressures over the high-pressure range. The results are summarized in tables II and III. In these two tables the deviations of three of the previously defined quantities (the composite average, the worst single-channel average, and the worst single measurement) from the corresponding manifold pressure are presented. All values in these tables are expressed as a percentage of full scale. In all the calculations the low calibration, high calibration, and manifold pressures were assumed to be the correct pressures. This appears to be a reasonable assumption since calibration of the pressure regulators showed them to be accurate to within 0.03 percent, which was, in general, much better than the measured values.

The measurement results show that largest errors tended to occur at the extreme ends of the pressure ranges and that the pressure switches yielded more accurate measurements over the higher pressure range. For the low-pressure range the worst single measurement was in error by 0.73 percent of full scale, and for the high-pressure range the worst single measurement was in error by 0.22 percent of full scale. The errors were not completely random, in that certain measuring channels (5, 7, 14, and 16) tended to yield higher pressure values and other measuring channels (3, 9, and 10) tended to yield lower pressure values. These differences were attributed to differences in the switches. Another observation is that the MPM system tended to yield pressure measurements that were lower than the correct value over the high range and higher than the correct value over the low range.

It was suspected that the procedure whereby the 14 pressure switches were connected to the common manifold and thus switched at approximately the same time was having an effect on the measured pressure. A rough "worst case" calculation showed that there was a significant change in tank volume when the diaphragms of all 14 switches moved at once. An estimate of the fractional change in tank volume is

$$\frac{\Delta V}{V} = \frac{(\text{Diaphragm area}) \times (\text{Maximum diaphragm travel}) \times (14)}{(\text{Tank volume})}$$

$$= \frac{(130\ \text{mm}^2) \times (0.1\ \text{mm}) \times (14)}{(3.7\times10^4\ \text{mm}^3)}$$

$$= 4.9\times10^{-3} \tag{2}$$

Since it can be shown that

$$\Delta p = -p\left(\frac{\Delta V}{V}\right) \tag{3}$$

the value for $\Delta V/V$ in equation (2) yields an estimate of the change in tank pressure at full scale to be 0.5 percent. This calculation suggests that there might be a significant perturbation in the otherwise nearly linear tank-pressure ramp when all switches are switching together. Also, from table III, the largest error (-0.096) in the composite average occurred at full-scale pressure. To determine the actual effect on pressure measurement, the following experiment was performed: One of the 14 pressure measuring channels (channel 4) was disconnected from the common manifold and connected to a separate pressure source set at full scale of the higher pressure range (69 N/cm^2 gage (100 psig)). The remaining 13 pressure switches were left connected to the common manifold. Pressure measurements were recorded and averaged for 20 pressure ramps at each of a series of manifold pressure levels approaching full scale. Channel 4 (the separated channel) was left at full-scale pressure. The result is shown in figure 8, which is a plot of the error in channel 4 as a function of manifold pressure (the pressure applied to the other 13 pressure measuring channels). As shown by the plot, the error in channel 4 increased from -0.02 to -0.11 as the manifold pressure approached that of channel 4. The conclusion reached from this experiment is that many pressure switches switching at the same time can cause small errors in the measured pressure.

ADDITIONAL EVALUATION OF PRESSURE SWITCHES

All the pressure-switch designs that were considered yielded switches with non-negligible delay times. Thus, it was important to minimize the delay time and to fabricate the switches in such a way that the delay times for all switches would be as nearly the same as possible for any given pressure. In addition to normal operation in the MPM system, other tests were performed to measure the switch delay time and the static switching pressure.

Dynamic Test of Pressure-Switch Delay Time

The purpose of this test was to observe the light output of a pressure switch as a function of time near the zero-crossing point during real operating conditions and to measure switch delay time. An oscilloscope was set up to trigger at the actual zero-crossing point so that the delay time could be measured. The technique was as follows: A pressure transducer similar to the one on the MPM system tank was connected to the common manifold on the test-pressure side of the pressure switches. With the desired pressure in both the tank and the manifold, the outputs of the two transducers were then adjusted to be equal. These two outputs were applied to a comparator circuit so that during MPM system operation the comparator output would undergo a level change at the zero-crossing point. This level change provided the trigger signal for the oscilloscope.

The delay time introduced by the tank transducer was considered to be small compared with those (>1 msec) measured for the switches for the following reasons: First, the tank transducer was a bonded strain-gage type whose diaphragm-sensor structure had a natural resonant frequency of 5 kilohertz. Second, the acoustic delays introduced by the short (~3 cm) lines from the switch to the tank and from the transducer to the tank were about the same, so these delay times essentially canceled one another.

However, to get reliable delay-time measurements, an additional procedure had to be employed. It was observed that, during continuous ramping, the apparent switch delay time increased significantly within the first minute of startup and increased further over a period of several hours. For example, a measured delay time of 1.2 milliseconds would increase to about 3.7 milliseconds after several minutes. This apparent increase in delay time was actually caused by a short-term and a long-term increase in the sensitivity of the tank transducer. These changes in output were probably caused by heating of the transducer due to the periodic compression of gas within the transducer during the pressure ramps. The change occurring during the first minute was probably due to local heating of the pressure-sensitive element within the transducer. After several hours of operation over the higher pressure range, the transducer became noticeably warmer to the touch than ambient. This heating of the transducer correlated with the longer term change. To reduce the effect of these thermal shifts to a minimum, oscilloscope traces were obtained by ramping the system only once for a given trace. There appeared to be negligible thermal shift for only one pressure ramp.

In the optical detector circuit a phototransistor converted the light from the pressure-switch fiber to an electrical analog signal. This signal was displayed on an oscilloscope. A typical oscilloscope trace is shown in figure 9 for a pressure ramp with a slope of 140 N/(cm^2)(sec) (200 psi/sec) at a pressure of 35 N/cm^2 gage (50 psig). The delay time was observed to increase with pressure, ranging from about 1 millisecond at 7 N/cm^2 gage (10 psig) to about 2 milliseconds at 69 N/cm^2 gage (100 psig).

Static Test of Switching Pressure

The following technique was used to observe pressure-switch behavior at low, static, positive, and negative differential pressures. The tank side of a pressure switch was connected to a device that could generate small positive and negative gage pressures. With this device, basically a piston in a cylinder, the pressure applied to a switch could be changed in a smooth and controllable fashion. The pressure, which was measured with a water U-tube manometer, was varied over the range ±0.17 N/cm^2 gage (±0.25 psig).

Because the diaphragms used in the pressure switches were not perfectly flat, a pressure switch could be in a "light on" state, a "light off" state, or somewhere in between at zero differential pressure. To be acceptable, a pressure switch had to change states with a differential pressure less than the arbitrarily set level of 0.06 N/cm^2 (0.08 psi). Most of the pressure switches that were constructed passed this test.

This technique also demonstrated that about half of the pressure switches exhibited hysteresis. That is, over some range of differential pressures, the switch could be in either the "light on" or "light off" state. Whether a pressure switch exhibited hysteresis had no apparent correlation with whether it yielded good measurements in the MPM system.

SOME IMPORTANT FACTORS AFFECTING PRESSURE-SWITCH PERFORMANCE

The surface condition of the brass end plates was found to be an important factor in pressure-switch operation. To minimize potential distortion of the diaphragm by the clamping process, the end plates were lapped flat after the gas fittings had been silver soldered. The procedure was to use 6-micrometer polishing grit against an iron lapping plate, which produced a matte finish. If the tank-side end plate was further polished to produce an optically smooth surface, longer delay times sometimes resulted. An explanation might be that when the diaphragm is pushed against the tank-side end plate and is then pulled away, a force due to partial vacuum resists the motion. A rough surface lessens this effect.

Another important factor affecting the delay time was the pattern of holes in the tank-side end plate. The holes allow the gas in the tank to reach the diaphragms. Figure 10(a) shows the hole pattern that was used. It consists of two circles 4.8 and 7.9 millimeters in diameter, with each circle containing six equally spaced 0.76-millimeter-diameter holes drilled through. The two sets of holes were rotated 30° with respect to one another. The delay time at midrange for the high-pressure range was typically 1.5 milliseconds. Various other hole patterns were tried, with the following results: Using only the inner circle of holes increased the delay time to about 9 milliseconds, and using only the outer circle of holes increased the delay time to about 2 milliseconds. Increasing the total number of holes above 12 did not significantly decrease the delay time. The conclusion reached, as might be expected, is that it is important to spread the hole pattern over the effective area of the diaphragm.

The hole pattern in the test-side end plate did not have a significant effect on the delay time. As shown in figure 10(b), only six holes were provided in this end plate. The two oval patterns in the center are the polished ends of the optical fibers.

CONCLUDING REMARKS

This report shows that pressure measurements based on the multiple-pressure measuring (MPM) system with the present pressure-switch design can be made to accuracies within 0.25 to 0.75 percent of full scale. The results with this system do indicate, however, that there is significant variation in pressure-switch performance (i.e., delay time). To increase measurement accuracy, pressure switches with more consistent delay times will have to be built. This might be achieved by a thermal annealing process on the diaphragm material that removes the effects of all previous mechanical forming used in making the material.

The measurement error introduced by many pressure switches switching at approximately the same time could be reduced in several ways. For example, diaphragm travel could be reduced to a minimum. Or the tank volume could be increased; however, this probably will reduce the tank-pressure ramp frequency.

There might be other applications for the pressure switch described in this report. For example, it might be used in an application that requires a sensitive pressure switch but also subjects the switch to large differential pressures.

National Aeronautics and Space Administration,
Lewis Research Center,
Cleveland, Ohio, May 13, 1977,
505-04.

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TABLE I. - MATRIX OF MEASURED PRESSURES GENERATED FOR EACH TEST PRESSURE

[14 Measuring channels for 50 pressure ramps = 700 pressure measurements. From this matrix the quantities described here were selected.]

Channel[a]	Ramp						Single-channel average[b]
	1	2	3		49	50	
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							

Composite average[c]

Worst single-channel average[d]

Worst single measurement[e]

[a]Channels 1 and 2 are the low- and high-calibration-pressure channels, respectively.

[b]The "single-channel average" is the result of averaging the 50 measured pressures for a single measuring channel.

[c]The "composite average" is the average of the 14 single-channel averages.

[d]The "worst single-channel average" is that single-channel average (out of 14) with the largest deviation from the manifold pressure.

[e]The "worst single measurement" is that measured pressure (from the matrix of 700) with the largest deviation from the manifold pressure.

TABLE II. - SUMMARY OF PRESSURES MEASURED WITH MULTIPLE-PRESSURE MEASURING SYSTEM FOR 0.7- TO 10-N/cm^2 gage (1- TO 15-psig) PRESSURE RANGE

[All values are expressed as a percentage of full-scale pressure. Refer to table I for definition of terms.]

Pressure, percent of full scale	Deviation of composite average from correct pressure	Deviation of worst single-channel average from correct pressure	Deviation of worst single measurement from correct pressure
6.7	0.33	0.60	0.73
13.3	.27	.53	.63
20.0	.21	.41	.53
26.7	.15	.40	.47
33.3	.12	.40	.40
40.0	.09	.33	
46.7	.09		
53.3	.08		
60.0	.07		
66.7	.06	.27	.33
73.3	.04		.33
80.0	.03		.60
86.7	.06		.33
93.3	-.04	.20	.27
100.0	-.14	-.27	-.33

TABLE III. - SUMMARY OF PRESSURES MEASURED WITH MULTIPLE-PRESSURE MEASURING SYSTEM FOR 2- TO 69-N/cm^2 gage (3- TO 100-psig) PRESSURE RANGE

[All values are expressed as a percentage of full-scale pressure. Refer to table I for definition of terms.]

Pressure, percent of full scale	Deviation of composite average from correct pressure	Deviation of worst single-channel average from correct pressure	Deviation of worst single measurement from correct pressure
3	-0.079	-0.11	-0.18
5	-.009	-.04	[a]±.09
10	-.003	-.04	-.12
20	-.012	-.03	-.12
30	-.037	-.07	-.13
40	-.026	-.04	-.11
50	-.016	-.03	-.11
60	-.014	-.03	-.13
70	-.023	-.04	-.14
80	-.054	-.07	-.14
90	-.002	[a]±.01	[a]±.09
100	-.096	-.11	-.22

[a]Some channels were above correct pressure, some were below.

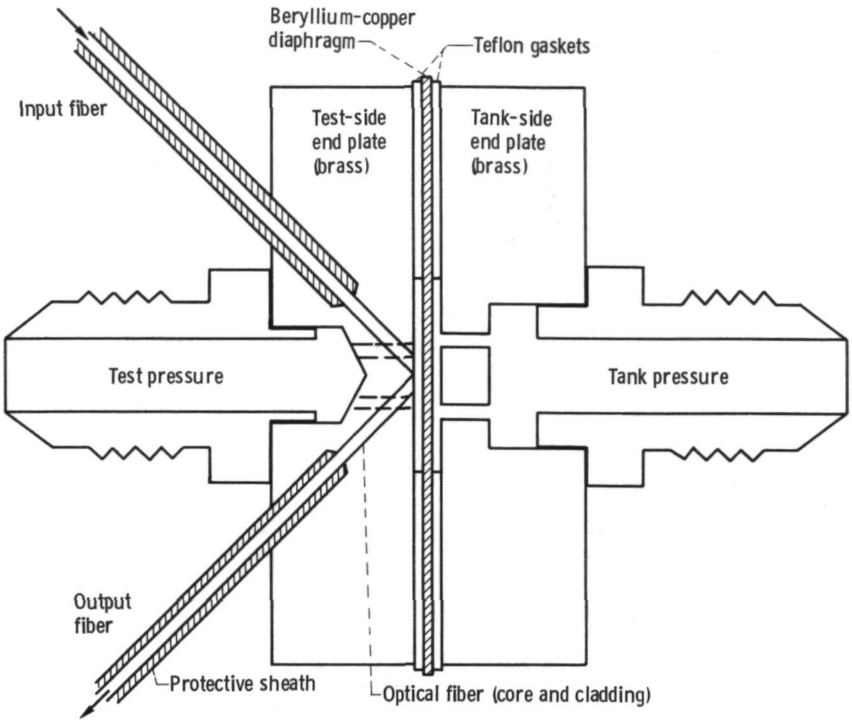


Figure 1. - Cross section of pressure switch.

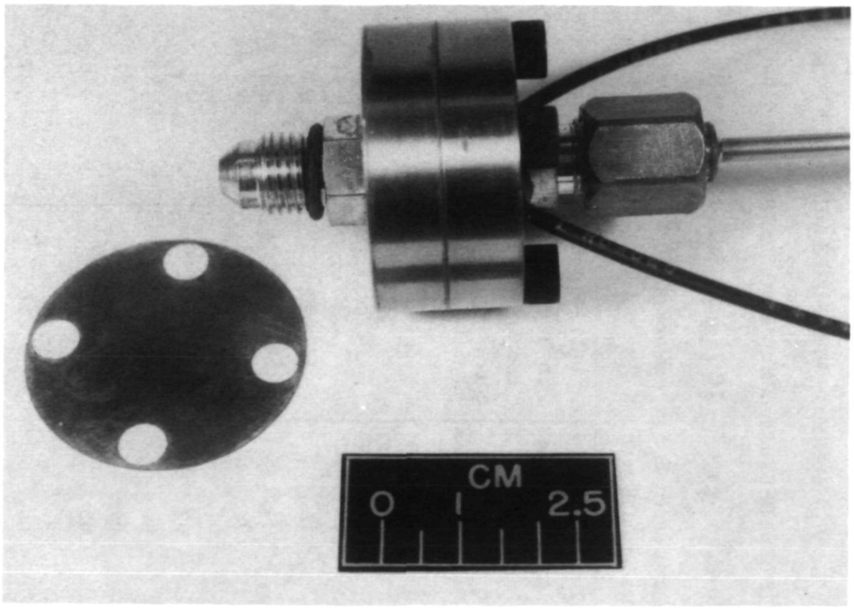


Figure 2. - Pressure switch. (Diaphragm is at left.)

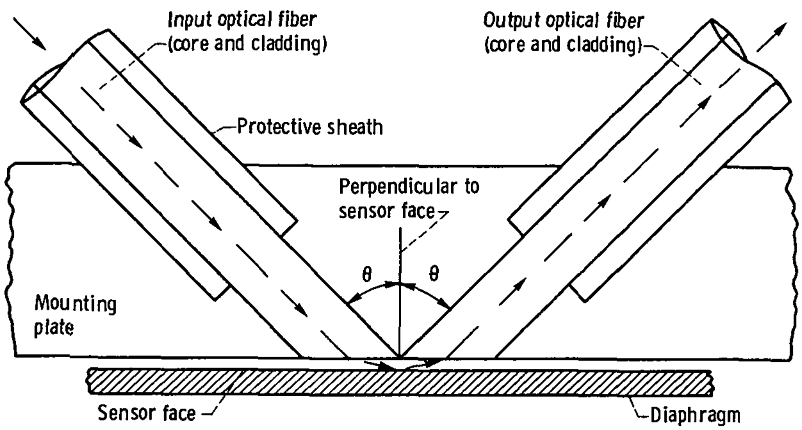


Figure 3. - Configuration of optical displacement sensor.

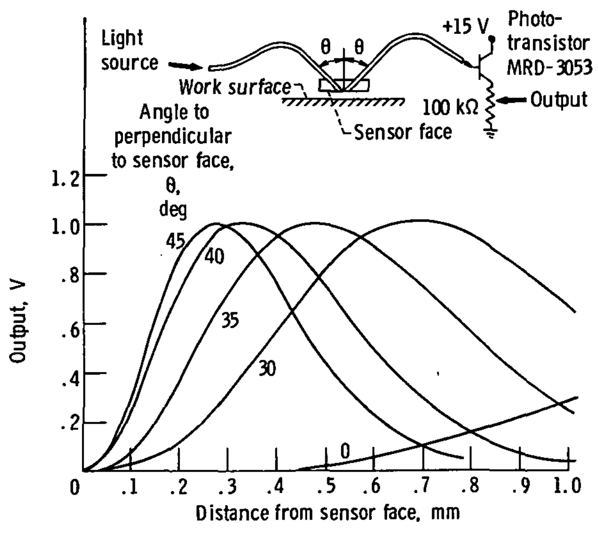


Figure 4. - Output as function of distance from sensor face for optical displacement sensor.

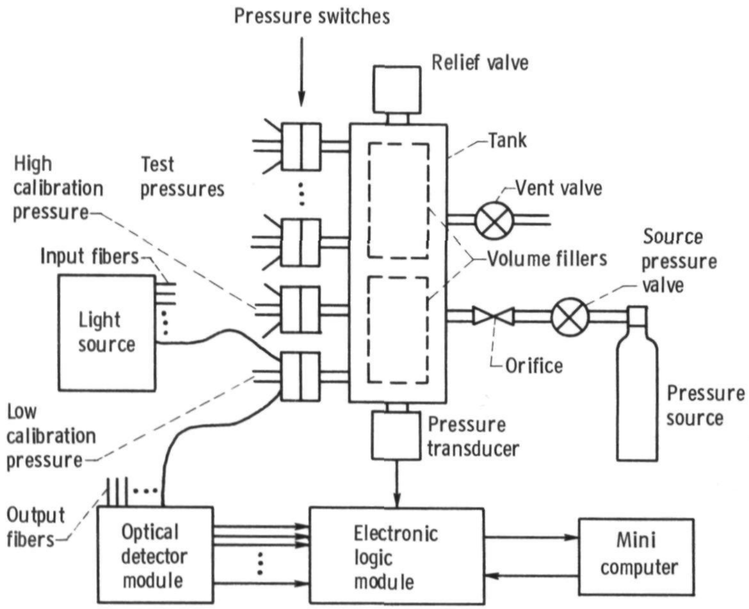


Figure 5. - Schematic diagram of multiple-pressure measuring system.

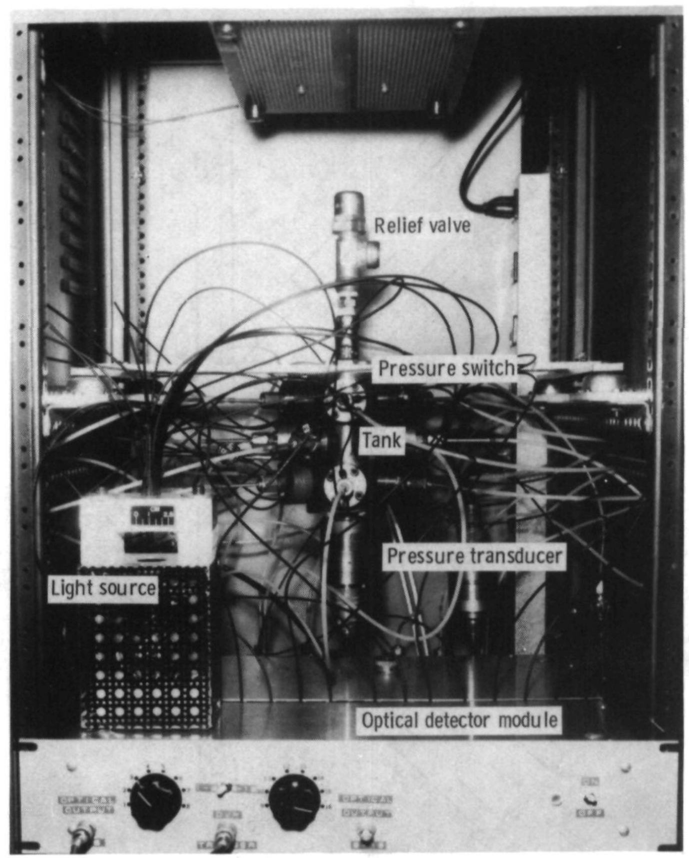


Figure 6. - Multiple-pressure measuring system.

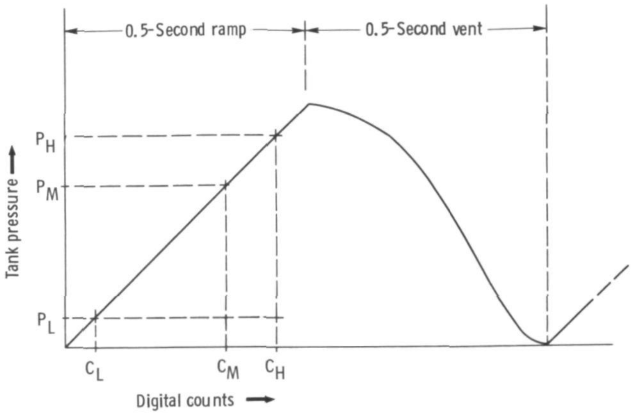


Figure 7. - Operating cycle of multiple-pressure measuring system.
$P_M = P_L + (P_H - P_L) \times \left(\frac{C_M - C_L}{C_H - C_L}\right)$.

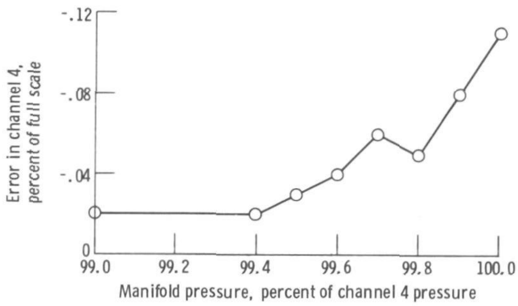


Figure 8. - Increase in error of channel 4 as manifold pressure approaches that of channel 4. Full-scale pressure, 69 N/cm^2 gage (100 psig); tank-pressure ramp, 140 $N/(cm^2)(sec)$ (200 psi/sec); test pressure applied to channel 4, 100 percent of full scale. (All 13 other pressure measuring channels were connected (test side) to manifold.)

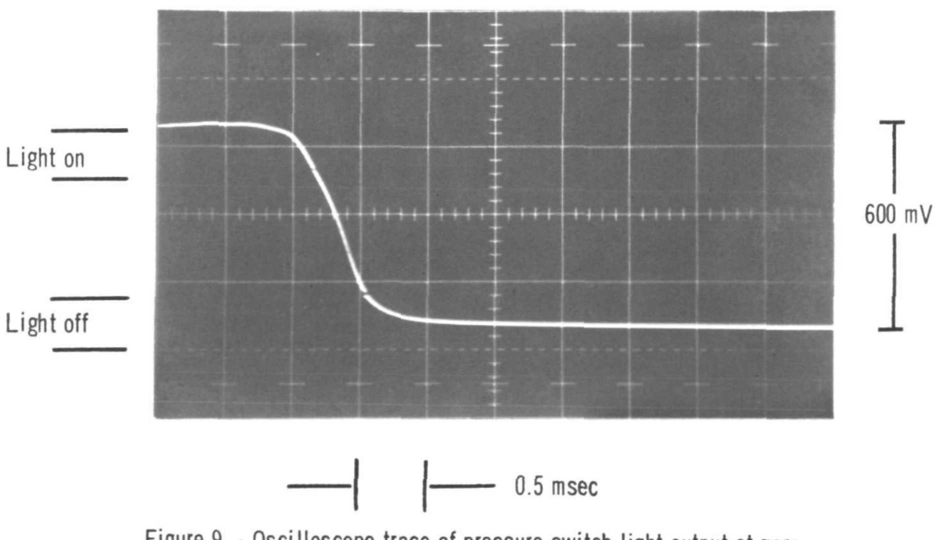
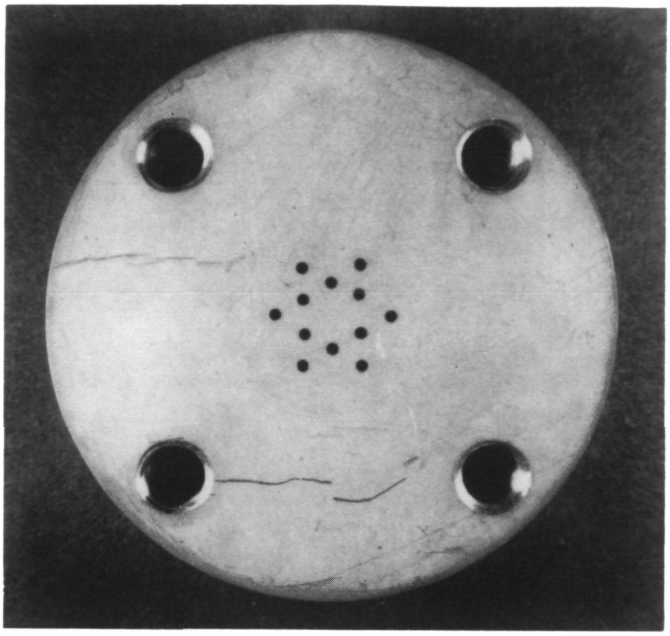
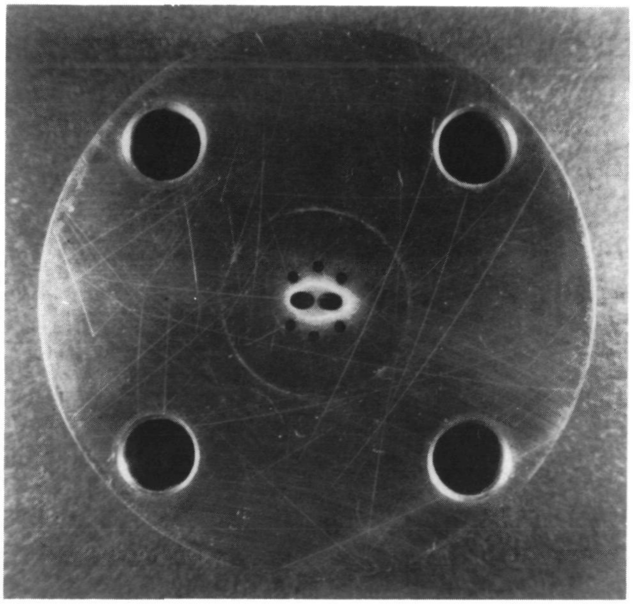


Figure 9. - Oscilloscope trace of pressure-switch light output at zero-crossing point.



(a) Tank-pressure side (12 ports).



(b) Test-pressure side (6 ports, 2 polished ends of optical fiber).

Figure 10. - Faces of pressure-switch end plates showing ports leading to diaphragm. (Four large holes are bolt holes.)

NASA-Langley, 1977 E-9139

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