Dual Diaphragm based Cantilever Operated Mechatronic Differential Pressure Sensor and Transmitter

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ABSTRACT

This paper reports the development of a differential pressure sensor with a geometrical structure accommodating dual diaphragms fixed with cantilever operated mechatronic pickup. Thin metallic spherical diaphragms of shallow shell configuration are employed to yield larger drift resulting in increased sensitivity. The cantilevers are excited electromechanically as to produce vibrations and the frequencies of vibrations are determined by picking up signals with orthogonally arranged opto-couplers linked to the cantilever strips. With each frequency determined a lookup table is referred to obtain the pressure acting on each diaphragm. Then, the average pressure acting on two diaphragms and the differential pressure are computed. They are transmitted digitally and also as analogue currents. With improved performance this pressure sensor would be very much useful for measurement of relatively heavy pneumatic pressure.

KEYWORDS

Cantilever based mechatronics, differential pressure sensor, diaphragm actuation, pressure transmitter

1. INTRODUCTION

Pneumatic pressure cells are widely being used in production plants and process industries [1-2]. They invariably use diaphragm based structures with attachment of appropriate pickups [3-5]. A spherical shallow shell diaphragm with optical pickup, inductive pickup and capacitive pickup was reported recently [6] targeting for improved dynamic performance. A diaphragm installed pressure cell attached with a cantilever for electromechanical conversion was also reported [7]. In this work we modify the cantilever installed mechatronic pickups with dual shallow spherical diaphragm structure for measurement of the differential pressure. The design for optimized geometrical structure for fixing the pickups occupying the minimal space for measurement of differential pressure is presented. The improved performances are analyzed and reported.

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2. SHALLOW SPHERICAL SHELL DIAPHRAGM FOR PRESSURE SENSING AND THEIR PARAMETERS

A thin metallic diaphragm having elastic properties undergoes changes in its surface when force is applied on it [8-10]. This change in deformation depends on the geometrical size and boundary conditions. A shallow spherical shell used in the development of a pressure cell [6] yields enhanced drift in its vertex compared to flat thin plate. As enhanced drifts ensure increase in sensitivity the structure yielding larger drift is always desirable for developing the pressure cell. In this project we use dual shallow shell spherical diaphragms for yielding optimal performance and differential pressure sensing.

2.1. Vertex Drift and Pressure Relations

Figure 1 shows simplified schematic of a single diaphragm based pressure cell. The shallow shell has the radius *ra* and height *f*. The height at vertex is maximum and zero at rim. At any radial distance *r* the height of the shell observed is denoted by *w*.

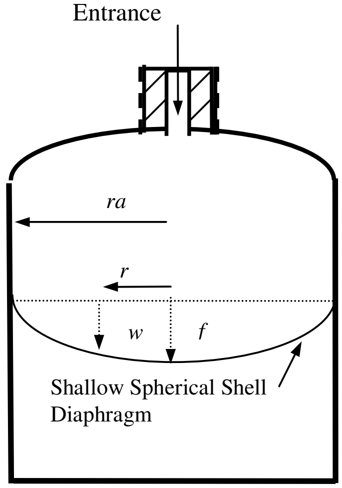

Figure. 1. Schematic of diaphragm based pressure cell

Depending upon the pressure acting on the diaphragm and deformation happening on the surface the magnitude of w and f would change [6]. The following relations show the dependancy of f and w on the applied pressure.

$$f = A - \frac{ra}{3.A} \quad (1)$$

where $$A = \left[\frac{\eta}{2} + \left(\frac{\alpha^3}{27} + \frac{\eta^2}{4} \right)^{1/2} \right]^{1/3} \quad (2)$$

and $$\alpha = \frac{56.h^2}{(1+\gamma).(23-9.\gamma)} \quad (3)$$

where h : plate thickness and γ : Poisson ratio.

$$\eta = \frac{7.p.ra^4 h^2}{8.D(1+\gamma).(23-9.\gamma)} \quad (4)$$

where D is flexural rigidity given by

$$D = \frac{E.h^3}{12.(1-\gamma^2)} \quad (5)$$

p is pressure acting on diaphragm and E : Young's modulus

The altitude of the diaphragm w at any radial distance r is related to f as

$$w(r) = f.\left[1-\left(\frac{r}{ra}\right)^2\right]^2 \quad (6)$$

When the pressure acting on the diaphragm changes, these heights f and w would change as per the above relations.

2.2. Cantilever Attachment with Diaphragm

A rigid metallic diaphragm having a thin metallic strip brazed at its center was excited mechanically and vibrations were produced [7]. The strip was loosely hinged at a pivoted support at a small distance from the diaphragm such that when the vertex of the diaphragm drifts due to applied pressure, the strip could smoothly slide through the hinge. The vibrations were produced by electromagnet excitation on the strip and an optocoupler at orthogonal direction was used to sense the signal produced due to vibration. As the frequency of vibration would be dependent on the length of the strip extending beyond the hinge it represents the pressure acting on the diaphragm.

2.2.1. Frequency Pressure Relationship

When the strip of length *l* extending beyond the pivoted hinge point is subjected subject to vibrations then the oscillations *y* seen at different distances *x* was obtained as

$$y(x) = k\left[Cos\ \frac{3.515}{l^2}\sqrt{\frac{E.I}{\gamma}}t\right] \quad (7)$$

where *E:* Modulus of rigidity, *I*: Moment of inertia and γ : mass of the strip per unit length. The factor *k* is a constant depending on the length, mass and other mechanical properties. Therefore, the vertex displacement depends on the pressure acting on the diaphragm which in turn would affect the frequency of vibration of the metallic strip. Ultimately, by measuring the frequency we can calibrate it to pressure acting on the diaphragm.

3. Dual Diaphragm Structure for Differential Pressure Sensing

Dual diaphragm structure helps enhancing the sensitivity and also helps in sensing the differential pressure. We now describe its optimized geometrical structure and the transducer circuits. Within the minimal space available all the elements of pressure sensor are accommodated.

3.1. Geometrical Structure

Figure 2 shows the geometrical schematic of the pressure cell sensing the differential pressure. There are two hollow cylinders holding the metallic diaphragms. In the vertices of the diaphragms thin metallic strips working as cantilevers are bonded. In order to avoid overlapping and mechanically interrupting each other the strips of the vertices have to be laterally displaced. Therefore the two hollow cylinders holding the diaphragms are laterally shifted and brazed at the rims making the joint. A circular disc contacting the rim of left cylinder (disc1) holds the opto-coupler kept orthogonal to the strip. This would pickup a signal proportional to vibration. A similar disc is fixed at the rim of right cylinder (disc2) also for picking up the vibration of the strip. Figure 3 gives the end view of the discs showing the location of opto-coupler and opening for the strip of the other.

Referring to Figure 2 there are two electromagnets employed for exciting the vibrations in the strips. Both strips are excited simultaneously by driving a pulse to the coils of electromagnets which would attract the strips and release them producing the vibrations. Connections to coils in the electromagnets and to opto-couplers are made through fine wires taken along the surfaces and extended to the connectors.

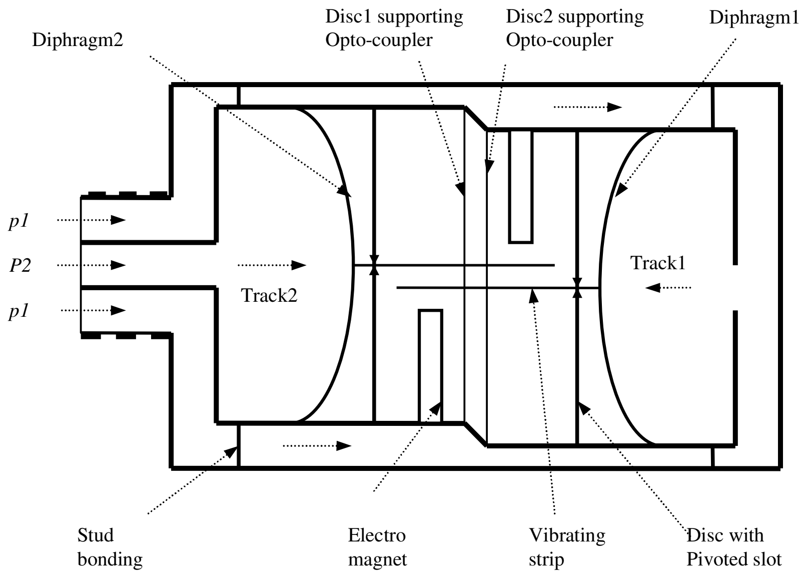

Figure 2. Structure of the differential pressure sensor

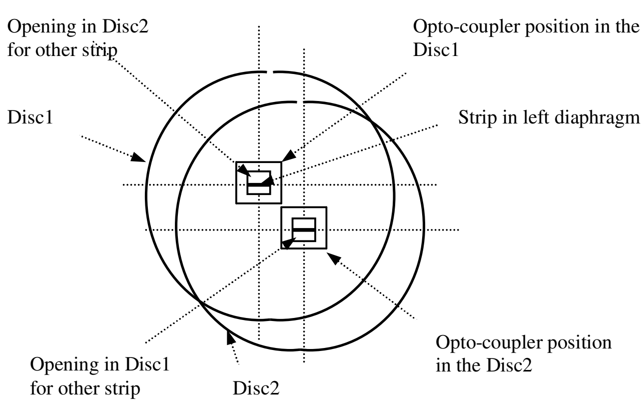

Figure 3. Position of opto-coupler and passage for the strip of other diaphragm

There are two sources of pressures denoted as *p1* and *p2* entering into two pneumatic tracks of the pressure cell. Source *p2* enters in the central track (track 2) and impede on the diaphragm 2 resulting in drift of its vertex. Source *p1* enters into the outer track (track 1) surrounding the cylinder holding diaphragms and impede on the diaphragm 1. This causes drift in its vertex in opposite direction of the drift of diaphragm 2. The drift in the vertex and hence the frequency of vibration of the strips depend on the respective pressure acting on the diaphragm.

3.2. Setup for Sensing Pressure and Circuits Involved

A microcontroller established with microprocessor 80286 is the used for driving the signals for exciting electromagnets and reading the sensed signals from opto-couplers and processing them. Figure 4 shows the simplified schematic and circuit diagram. The Clock frequency set is 20MHz. The microprocessor is interfaced with PIDs (Peripheral Interface Devices) having programmable I/O ports, EPROM, RAM, Timer, Keyboard and display devices as in standard format and procedures. The timer is programmed to produce a square wave signal of 1Hz which in turn is converted into a signal of 0.4s ON and 0.6s OFF periods by using a monostable multivibrator (MSMV1). The 0.4s ON signal drives a transistor to excite the electromagnet which in turn would attract the solenoid to hit the strip. The same signal drives both electromagnets simultaneously for setting the strips into vibrations. Both the opto-couplers produce signals as per the amplitude and frequency of vibrations. In every cycle the vibration is sensed for the period of 0.6s. In the following 0.4s period there are no vibrations since this time is reserved for the solenoid to hit the strip. In the 0.6s period the decaying sine wave is sampled periodically. The sampling signal is derived from 20MHz clock signal of the microprocessor. Its frequency is externally divided by a factor of 10000 and 2KHz signal is used as sampling signal (D-CLK). This sampling signal is applied to both the S/H (sample and Hold) circuits extended to opto-couplers. MSMV2 generates mono pulse for driving the S/H circuits. The flash ADCs (Analogue to Digital Converter) used here are built on advanced architecture [11] with high speed and reduced complexity and their outputs are extended to input ports available in the PIDs. The sampled data of opto-coupler is read into microprocessor and processed further.

During the period of sampling and holding the flash ADC would certainly complete its conversion and is ready for feeding to microprocessor. Therefore, the input and output of MSMV2 are given to an Ex-OR circuit to derive the interrupt signal (INTR) for the microprocessor. This would request the microprocessor to read the sample and process further.

From the sampled data gathered from the opto-couplers, the frequencies of vibration are estimated for both the cantilevers and the lookup table is referred to determine the pressure acting on each diaphragm. After then the average pressure and the differential pressure are computed. They are driven to the output ports externally. Therefore we have the average and differential pressure in binary form. They are converted into analogue form by driving to DACs (Digital to Analogue Converter). DAC produce the analogue output in current form and is ready for transmission to a remote location. Current transmission avoids losses in the cables taken to remote location. In order to meet the industry standards the current level is kept in the range of 4-20mA.

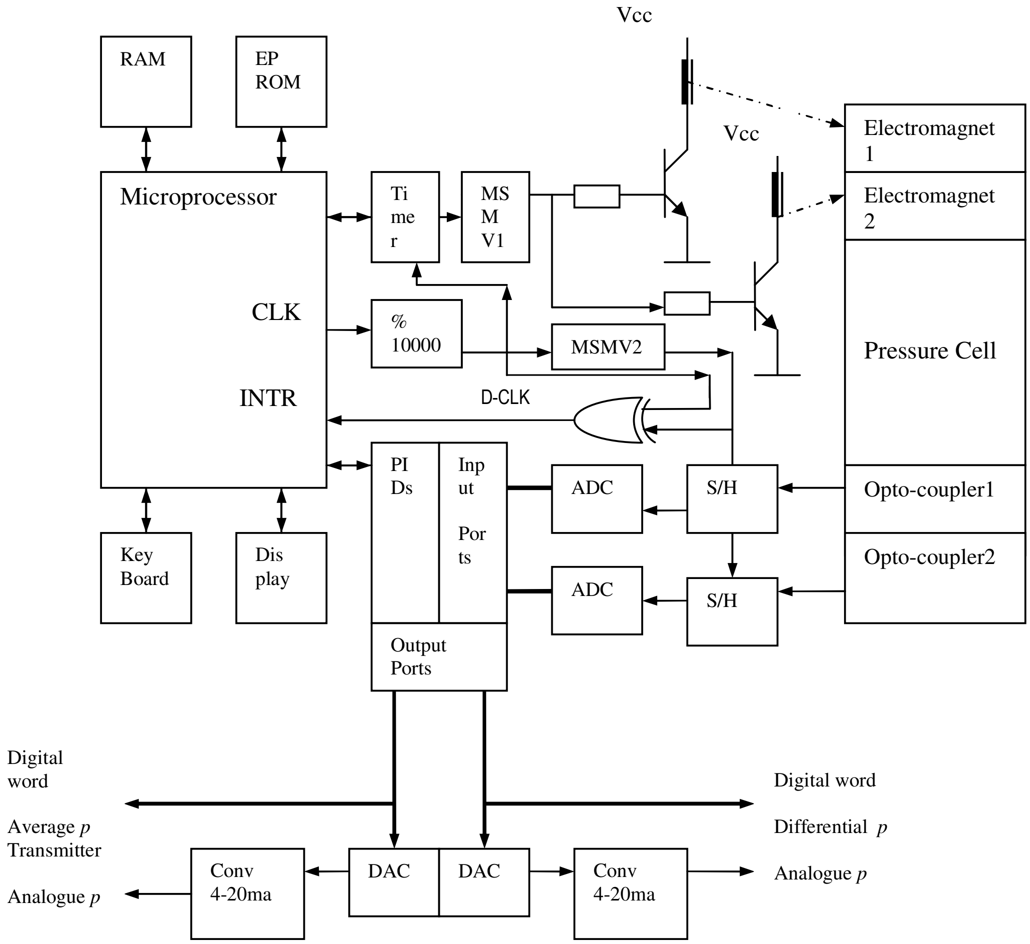

Figure. 4. Simplified schematic of the control schemes and circuits for pressure sensor and transmitter

3.2.1. Timing Diagram

The timing diagram would illustrate about the sequence of performed by the microcontroller in the pressure cell. Figure 5 shows essential timings. Figure 5.A shows the time slots for the electromagnet drive and for reading the opto-coupler samples to processor. Figure 5.B shows the time slots for the S/H derived for the frequency divided clock D-CLK in each sampling instant. It also shows the slot for interrupt signal to the microprocessor.

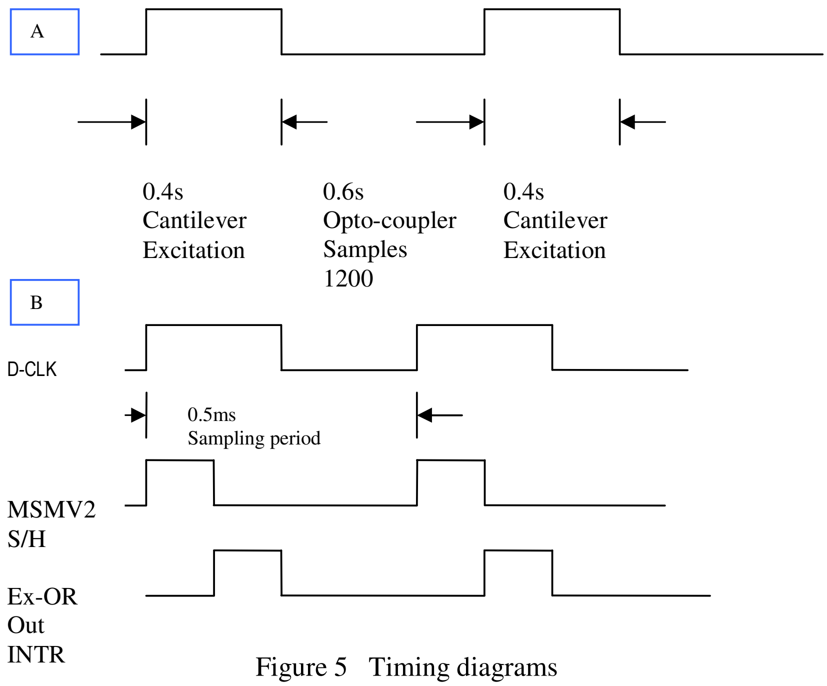

Figure 5 Timing diagrams
A. Time slots of 1Hz signal from MSMV1
B. Opto-coupler Sampling time slots

3.2.2. Software Overview

The sampled data are gathered and saved in RAM memory on interrupt basis and from which the instantaneous pressure is computed. During the OFF period of 0.6s of electromagnet excitation the sampled data are gathered. With the sampling frequency of 2KHz, there are 1200 samples available in each cycle. During the ON period of 0.4s where there is no vibration computation of pressure is carried on. Also display routine is called every second to display the computed information.

3.2.2.1. Features of Main program

In the main program the following operations are made. *i.* Computations of frequency of vibration and pressure data from the 1200 reserved locations of RAM memory where sampled data of opto-coupler are available; *ii*. Since two sets of samples are gathered from two opto-couplers there are two sets of data available for computing pressure acting on each diaphragm. After computing the dual pressures (*p1, p2*), the average pressure ((*p1+p2)/2*) is computed. The average pressure information would be useful in applications where single source pressure sensing is desired. Also, the differential pressure (*p1-p2*) is computed. This is main objective of this project and the differential pressure sensing has several applications. They are driven to respective output ports. *iii.* A display routine is called during the 0.6s period the average pressure and differential pressure on alternate basis.

Computation of the frequency of vibration of each strip is performed by using the 1200 discrete samples and calling an FFT algorithm. The fundamental frequency of oscillation is taken into consideration for using it as an input to lookup table. The lookup table relating the frequency of oscillation to the pressure acting on the diaphragm is made available in the EPROM provided in the microcontroller. Therefore, once the frequency is determined, the pressure acting on the diaphragm is quickly recovered by referring the lookup table.

Table 1 gives samples of information showing the relationship between the pressures, drift in vertex fixing the length of the strip and the frequency of vibration. The diaphragm used is a medium strength Al alloy of 2.5cm radius, 1.0mm thickness and 0.5cm of height for the spherical shell with Young's modulus 210GN/m^2 and Poisson ratio 0.3. This has a pressure range of 100 to 200 Pascals. The strip used is of thickness 0.5mm and length 4cm.

3.2.2.2 Interrupt Service Procedure

The interrupt occurs once in 0.5ms to feed the binary word from the ADC to the microprocessor for saving it in the reserved memory locations. Therefore, in the interrupt service procedure the following sequence of operations are performed. *i.* Read the sample from two ADCs one by one and save in the addresses pointed for each. *ii*. Increment the address pointers. If the upper limit of 1200 locations is reached then set the pointer to the starting address *iii.* Return to the main program.

Table 1. Pressure, length and frequency relations.

Pressure (Pascals)	**Length (Cm)**	**Frequency (Hz)**
100	2.50	250
120	2.65	236
150	2.91	214
200	3.50	191

4. EXPERIMENTATION

In order to assess the performance of the dual diaphragm pressure cell with cantilever pickup simulated experiment and practical experiment are performed. Simulated experiment is conducted by setting a known pressure and computing various parameters involved in equations (1) to (6) by a program written in C language. The drift in vertex is computed and for the change in length the frequency of vibration is estimated by using the FFT algorithm. After computing the frequency the pressure acting on the diaphragm is estimated using the lookup table information available in the EPROM. This computation provides the analytical results.

For conducting the practical experiment the microcontroller used in Figure 4 is extended with an I-to-P converter and the hardware scheme with this extension is shown in Figure 6. With a small program written for experimentation the set pressure data is sent to the output port. This is converted into analogue current by a DAC connected at the output port. The I-to-P Converter converts this into equivalent pneumatic pressure and applied to the pressure cell. The average pressure output given by the pressure cell in binary word is taken to an input port in the microcontroller and taken for display by calling the display routine. This makes us to know the response of the pressure cell for the applied pressure.

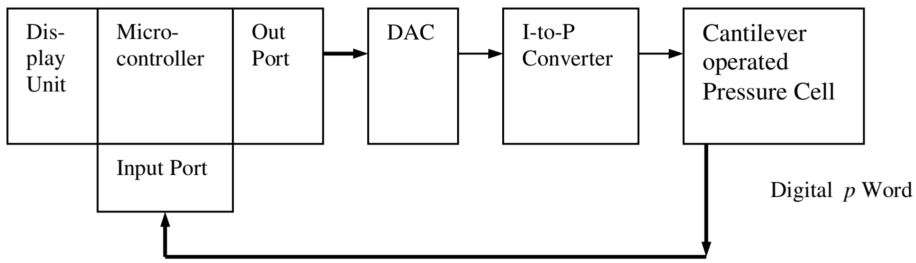

Figure 6. Hardware extension for experimentation

Figure 7 shows the results of analytical computation and practical experimentation. The analytical computation is made only once. This is because the computed pressure has to be the same as applied pressure used in various equations. Once the frequency is determined both the analytical computation and practical experimentation use the same lookup table loaded in the EPROM for computing the pressure. The lookup table has been prepared carefully by involving all geometrical and elastic characteristics of the diaphragm and also the geometrical and mechanical properties of the strip working as cantilever. Therefore, for the given frequency determined analytically or practically we get the same pressure. Nevertheless due to environmental conditions such as temperature the yield from diaphragm might vary in determining the frequency of vibration. Therefore in the case of practical experimentation 5 different trials at different times have been done and the median of the pressure is taken as the pressure sensed and plotted in Figure 7.

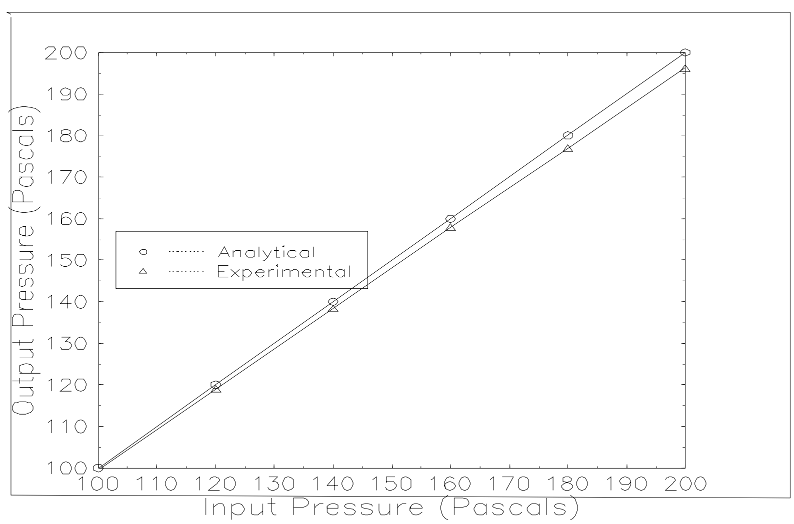

Figure 7. Experimental results

5. Discussions and Conclusion

For single source pressure measurement we need to apply the same pneumatic medium as input to both the pneumatic tracks in the chamber. Both pneumatic inputs acting on dual diaphragms would produce same strain effects on the diaphragms and would produce similar effects on the vibrating cantilevers. The frequencies of vibrations of both the cantilevers would be almost identical and produce identical pressure output produced from the frequency of vibration. We therefore take the average of the pressure output yielded from two cantilevers as the pressure sensed from the pressure cell.

The diaphragm based vibrating wire transducer also measures frequency and relates it to the pressure acting on the diaphragm. Vibrating wire transducer however is not durable owing to its weak fatigue characteristics leading to its mechanical breakdown and collapse. The procedure for replacing the wire with another one involves tedious tasks in alignment procedures involved. Therefore, cantilever based pickup is rugged and durable. The dual diaphragm structure enhances the sensitivity and also helps in picking up the differential pressure. The pressure transmitter is designed to transmit the average pressure and differential pressure computed by microprocessor in both digital form and analogue form. This enables us to make on the spot digital display of the sensed pressure and also allows us to take the pressure signal to any distance such as to control room or for interfacing to PC for further processing and analysis.

The diaphragm used in the cantilever operated pressure sensor is relatively thicker compared to the ones used in vibrating wire pressure sensor since this structure has to support relatively larger mass acting as load to the diaphragm than the thin vibrating wire. Nevertheless, for analytical dealing arriving at the vertex drift comes under the same thin plate theory with governing equations used for the vibrating wire pressure sensor. The lookup table in EPROM used for both the simulated experiment and the practical experiment need be changed whenever there is a change in geometry or change in the properties of materials used in making the diaphragm or the cantilever strip.

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