THEORY, DESIGN, FABRICATION AND TESTING OF CAPACITIVE PRESSURE TRANSDUCER

Oleh

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ABSTRACT

Transducers are predominantly used as sensors, because with a few exceptions, their efficiency of conversion is very low and to achieve a higher efficiency of conversion, transducers need to use the electrical signals to the amplifier. The piezoelectric device (pressure sensing) is also a useful transducer (can be used in either direction). Transducer use of piezoelectric crystals is mainly confined to the conversion between pressure waves in a liquid or gas and electrical AC signals. The conversion of energy from an electrical form into stress can be achieved by the magnetically cored solenoids. **Pressure Transducer** operates to convert the physical variable pressure into an electrical output signal that is proportional to the pressure measurement. The output supply is in form of current or voltage signals. Standard signals allow combining transducers, controllers, computers or stored program controllers (SPC) of different manufacturers without incurring any problem. The standardization simplifies both works as the manufacturers and also as the designer or any company operating instruments and plants. **Capacitive Pressure Transducer** operates as a pressure sensing device which senses the changes of capacitance according to the changes of pressure applied to the transducer. The measurement of these changes (output) is defined in form of voltage signal using a special measurement circuit is build out of operational amplifiers, resistors, capacitors and switch. The measurement results and conclusion of the project conducted on the *capacitive pressure transducer* is presented in the last part of this report together with design of the pressure transducer and the measurement circuit.

ABSTRAK

Transduser digunakan sebagai penderia, kerana dengan beberapa pengecualian, kecekapan penukarannya adalah amat rendah dan untuk mencapai kecekapan penukaran yang lebih tinggi, transduser harus menggunakan isyarat elektrik pada amplifier. Peranti piezoelektrik (pengesan tekanan) juga merupakan tansduser yang penting (digunakan pada kedua-dua arah). Penggunaan kristal piezoelektrik dalam transduser ditumpukan terutamanya untuk penukaran antara gelombang tekanan dalam cecair atau gas dan isyarat elektrik AC. Penukaran tenaga dari bentuk elektrikal kepada tegasan boleh dicapai oleh solenoid yang berteras magnet. **Transduser Tekanan** beroperasi untuk menukarkan tekanan boleh ubah fizikal kepada suatu isyarat keluaran elektrik yang berkadaran kepada ukuran tekanan. Bekalan output adalah dalam bentuk isyarat arus atau voltan. Isyarat piawai membenarkan penggabungan transduser, pengawal, komputer atau pengawal aturcara terstor (SPC) dari pengilang berbeza tanpa menyebabkan sebarang masalah. Pempiawaian tersebut mempermudahkan kerja kedua-dua pengilang dan juga perekabentuk atau sebarang syarikat yang mengendalikan peralatan dan loji. **Transduser Tekanan Berkemuatan** beroperasi sebagai peranti pengesan tekanan yang mengesan perubahan kemuatan berdasarkan perubahan tekanan yang diaplikasikan pada transduser. Pengukuran perubahan ini (keluaran) ditakrifkan dalam bentuk isyarat voltan menggunakan suatu litar pengukuran khas yang dibina menggunakan penguat kendalian, resistor, kapasitor dan suis. Keputusan pengukuran dan kesimpulan projek yang telah dikendalikan ke atas transduser tekanan berkemuatan disertakan pada bahagian terakhir laporan ini bersama-sama dengan rekabentuk transduser tekanan dan litar pengukuran.

ACKNOWLEDGEMENT

I would like to take this opportunity to express my sincere gratitude to all those who have contributed in completing this project because this project would not have been a success without the help and attention of many parties.

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CHAPTER 1 : <u>INTRODUCTION</u>

*1.1 **Overview on Capacitive Pressure Transducers***

Capacitive pressure transducers are basically capacitive sensors that sense the changes of capacitance according to the pressure applied to the transducer. This type of pressure transducers are the very common type which are produced in many companies in the world. Every manufacturers of capacitive pressure transducer have their own range of sensing according to their design specification. The manufacturers of pressure transducers have to consider a few characteristics of the transducers because there are few ways of selecting pressure transducer which are:

Accuracy

This is the first consideration. Accuracy is generally expressed as a percentage of full scale. Accuracy consists of several errors: Hysteresis, Non-linearity and repeatability must be known and considered.

Pressure Media

This is the fluid that will be measured. Gas or liquid. Corrosive or non-corrosive. The transducer selected must have elastomers and a diaphragm compatible with the pressure media.

Frequency Response

This is the rate at which a transducer can respond to a change in pressure. Steady state pressure measurements are much simpler than transient pressure measurements. The frequency to be measured will have a large effect on the type of transducer selected.

Output

The data system and signal conditioning equipment will determine the output requirement. Outputs are low level or high level. Low level outputs are expressed in millivolts output full scale per excitation volt (mV/V). A transducer with an output of 3 mV/V will have a full scale output of 30 mV when the excitation voltage is 10 V. High level outputs are generally 1 to 10 Vdc. In this case, the transducer has built in signal conditioning with a DC amplifier to amplify the output to the high level.

Environment

What are the temperature, humidity, shock and vibration requirements for the test? All of these can have a large effect on the function of the transducer.

However, if there are more stringent requirements concerning zero-point constancy and long term stability, the physical limits of the piezo-resistive sensor technology will be reached. This is especially true of low differential pressure or absolute pressure measurement in metrology. In such application ***capacitive pressure transducers*** are the best choice. In these sensors, a diaphragm system forms an electric capacitor. When pressure is applied, the distance of the capacitor disks changes. The resulting change in capacitance makes the measuring voltage rise or fall proportional to the pressure. Sensors incorporating this classic measuring principals have unmatched characteristics and are among the best in measuring technology.

1.2 ***Objective of the project***

The objective of this project is concerned in studying the theory of capacitive pressure transducer. It also concern about designing a pressure transducer before fabricating and the testing is being done. The study of a capacitive pressure transducer involves the calculative ways of determining a small change in the capacitance value.

Then, it’s applied to a pressure transducer where if there is a pressure given to a transducer, the ways of finding the difference of capacitance on the pressured lead frames of the transducer.

1.3 Flow of the Report

This report will start with the reviews on the different pressure transducers in the second chapter. The motive of the review is to show types of pressure transducers which are available in the market. It also describes the characteristics of the transducers available. In the third chapter of this report, the theory and the design of the capacitive impedance measuring system are explained. This chapter involves the explanation on capacitors, capacitance, capacitive impedance and the design of the measurement circuit.

The theory, design and the fabrication method used on the capacitive transducer is elaborated in chapter four. In this chapter, the design made for the capacitive transducer is shown with all the characteristics and also the proper ways to handle a fabrication procedure of the transducer is explained. The fifth chapter of the report provides the results gained on the experiments done to the measurement circuit and also the transducer. This chapter provides the results in three different parts: testing of the measurement circuit done to identify whether the circuit is operating properly, measurement of the capacitance / resistor with a bridge connector and the measurement of the pressure transducer with the proposed measurement system.

In the end of the report, the conclusion is made based on the experimental results and also the studies made on the applications of the capacitive pressure transducer.

CHAPTER 2 : REVIEW OF DIFFERENT PRESSURE TRANSDUCERS

2.1 Basic Definitions

Pressure is a multidirectional uniform type of stress, force acting on a unit area; it is measured as force per unit area exerted at a given point. There are many types of pressure such as,

1) ***Absolute pressure*** which is measured relative to zero pressure.
2) ***Gage pressure*** is measures relative to ambient pressure.
3) ***Differential pressure*** is the pressure difference between two points of measurement, which is measured relative to a reference pressure or a range of reference pressures.
4) ***Partial pressure*** is the pressure exerted by one constituent of a mixture of gases not reacting chemically with each other.
5) ***Static pressure***, pressure of a fluid exerted normal to the surface along which the fluid flows.
6) ***Impact pressure*** is the pressure gained in a moving fluid exerted parallel to the direction of flow which is mainly caused due to the flow velocity.
7) ***Stagnation pressure*** (*Total pressure*) is the sum of the static pressure and the impact pressure.

Pressure is normally measured and expressed in units of force per unit of area, N/m^2 and in the special case the pressure the N/m^2 is called the *Pascal* (*Pa*) and the Pa is now the SI unit of pressure. The most commonly used unit of pressure is the *pound force per square inch* (*psi*), which has been in use in more specific forms denoting what pressure the expressed pressure is referenced to: *psia* (for *absolute*), *psig* (for *gage*), and *psid* (for *differential*) pressures.

2.2 Pressure Sensing and Referencing

Pressure is basically sensed by elastic mechanical element (such as plates shells, and tubes), which offer the force a surface (an area) to act upon. The element will deflect whenever this force is not balanced by an equal force acting on the opposition surface. The transduction element sees this deflection usually as either displacement of strain, depending on the type of transduction used. In most commonly used pressure-sensing elements, the displacement of a diaphragm is relatively small, whereas the displacement of bellows and multiturn Bourdon tubes is relatively large. This explains why certain types of pressure transducers tend to employ one or the other type of sensing element.

Transducers can be designed to measure differential, gage, or absolute pressure, although all pressure-sensing elements respond to a change in the differential pressure across them. It's all done depending on the reference pressure admitted to, or maintained at, the reference side of the element. The basic pressure reference is build with a diaphragm used to exemplify the sensing element. The reference side of an *absolute-pressure* sensing element is evacuated and sealed. *Gage pressure,* on the other hand, is measured when the reference side is vented to ambient pressure. A *differential-pressure* sensing element deflects with an increasing difference between two pressures, both of which may vary. When the measured pressure is always higher than the reference pressure, the transducer has a *unidirectional range* (normally in the range of 0 to 300 kPa differential). When the measured pressure can be either lower or higher than the reference pressure, the transducer has a *bidirectional range* (e.g., ± 200 kPa differential). In a special version of the *differential-pressure*, a fixed pressure greater than zero is maintained permanently on the reference side by sealing it in.

2.3 Different Types of Pressure Transducers

2.3.1 Capacitive Pressure Transducer

Capacitive pressure transducers convert a change in the position of the electro-conductive plates forming a capacitor, and a change in the properties of a dielectric between the plates into an electrical signal. The *Figure 2.1* below shows an example of a capacitive pressure transducer.

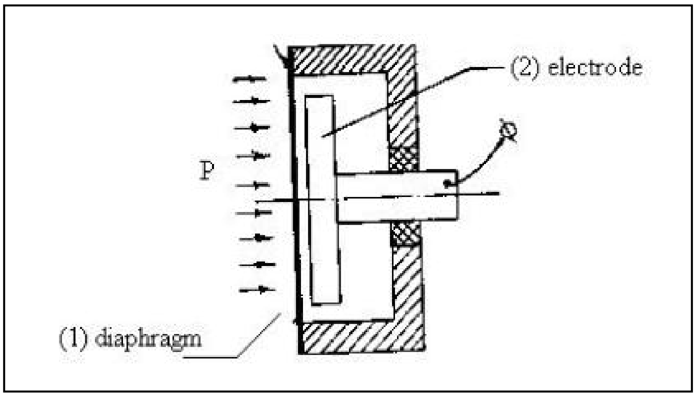


Figure 2.1 *Single Capacitor pressure-sensitive elements [Ref: 5]*

The electro-conductive diaphragm

1) affected by the pressure (P) moves towards a stationary electrode
2) positioned side along the diaphragm.

The diaphragm and electrode form a capacitor sensitive to pressure.

The capacitive pressure transducer has some disadvantages. There is a small change in the capacitance as a response to the mechanical signal. Accuracy is affected by wetting parts, capillary effects, some build up on electrodes, and an unpredictable change on the permittivity*[3] of the medium (for example forming gas fraction bubbles, fumes on the surface of liquid, and so on). The construction and the assembly must be precise.

The capacitive transduction principle is utilized in pressure transducers in either of the following two designs:

Single-stator: pressure is applied to a diaphragm which moves to and from a stationary electrode (*stator*).

Dual-stator: pressure is applied to a diaphragm supported between two stationary electrodes.

In *single-stator* designs, the diaphragm can be either the grounded or the ungrounded electrode. In the design shown in *Figure 2.2*, the diaphragm is integrally machined with its support member, moving towards the stator electrode on an insulating substrate. Full-scale diaphragm deflection is about 0.1mm, and a lead connects the stator to an external terminal (the case acts as the other terminal). The internal cavity of the absolute-pressure transducer shown is evacuated and then sealed. The diaphragm is of the (patented) "free-edge" type:

1) the free edge acts as a hinge when pressure (P_s) is applied to the diaphragm, reducing stress levels by a factor of about five over typical prestressed flat diaphragms
2) this reduces hysteresis and non-repeatability

Insulated stators, or, as used in other designs, insulated diaphragms, are now frequently made of quartz or ceramic with the electrode vacuum-deposited or sputtered onto the substrate.

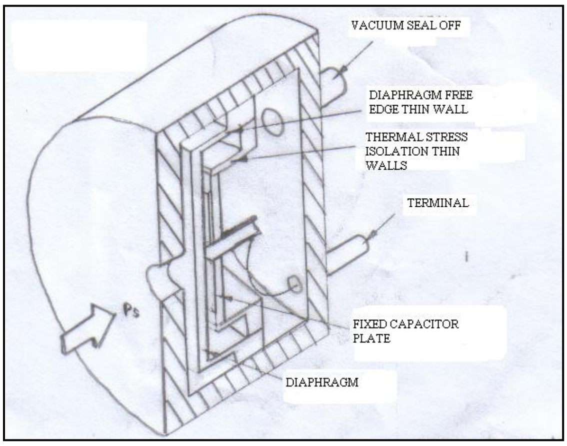


Figure 2.2 *Single-stator capacitive absolute–pressure transducer [Ref: 5]*

Dual-stator design, offers the advantage of a multiplication of the capacitance change, since, as the diaphragm deflects, its capacitance to one stator increases while it simultaneously decreases to the other stator. This effect is best utilized by connecting the two halves of the sensor as two arms in an ac bridge. In the transducer diagram shown in *Figure 2.3* below, the diaphragm is grounded by a welded seal to the case and two metallized electrodes on ceramic substrate have external lead connections. This design also uses two isolating diaphragms (isolating membranes) and a transfer fluid to isolate the sensing cavity from the measured fluid, as well as reducing shock and vibration effects and providing a fluid with a known and invariable dielectric constant between the capacitor electrodes. Use of appropriate metal alloys for the isolation diaphragms also enables the transducer to be used for corrosive measured fluids.

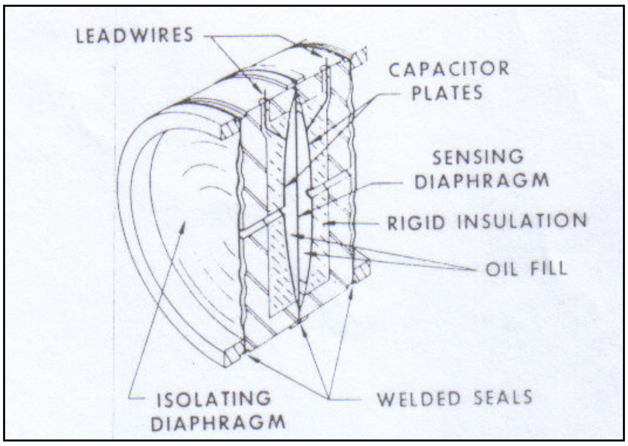


Figure 2.3 *Dual-stator capacitive differential-pressure transducer [Ref: 5]*

2.3.2 ***Inductive Pressure Transducers***

In an inductive pressure transducer, the self inductance of a single coil is varied by pressure-induced changes in displacement of a metallic diaphragm in close proximity to the coil, as shown in *Figure 2.4* below,

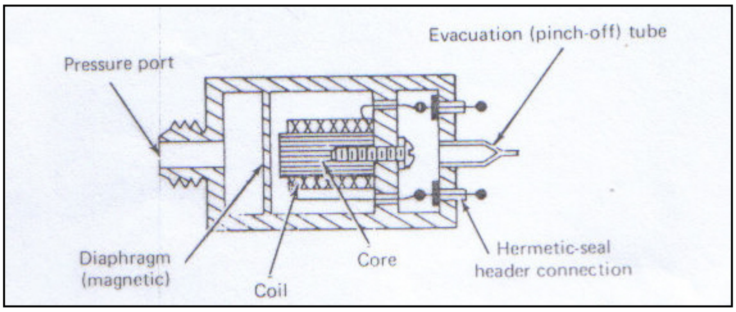


Figure 2.4 *Inductive pressure transducer [Ref: 5]*

Past designs used a diaphragm of magnetic material, and its motion to and from the ferric core around which the coil is wound, or actuation of a movable ferromagnetic core within a coil, to obtain the inductance changes. Some more recent designs use a metallic diaphragm and a coil excited by ac current at RF frequencies to use the changes in eddy currents in the diaphragm for obtaining the changes in self-inductance. A second (reference) coil is often included in the same housing; it remains unaffected by pressure variation and provides compensation for temperature changes. The table below shows the operating values of an inductive pressure transducer,

Dimension, mm	Diameter =13, L100
Measurement, MPa	0-20
Maximum operating temperature, °C	350
Pressure frequency, Hz	0-100
Main error, %	±1.5
Additional temperature error, %/100°C	<±1.2

Table 2.1 *Operating values of an Inductive Pressure Transducer*

2.3.3 ***Reluctive Pressure Transducer***

Reluctive pressure transducer includes two major types of reluctive transduction elements used in pressure transducers:

1) the differential transformer (usually the LVDT)
2) the two-coil inductance bridge

The former uses capsules, bellows, or Bourdon tubes as sensing elements and the latter uses diaphragm or Bourdon tubes as sensing elements.

Inductance-bridge reluctive pressure transducers use a magnetically permeable member to increase the inductance of one coil while decreasing the inductance in the second coil. The coils are connected in a bridge circuit so that the increase and decrease in inductance of the two coils are additive in the resulting bridge-output voltage change. When a diaphragm is used as in *Figure 2.5*, the diaphragm itself is the magnetically permeable inductance-changing member. When a Bourdon tube is used as the sensing element, it is usually a twisted Bourdon tube to whose tip a strip of magnetically permeable material (an armature) is attached. The armature is located between the two coils, and their inductances change simultaneously in position directions as the flux gaps of the two coils are changed by the armature's moving away from one coil and toward the other coil.

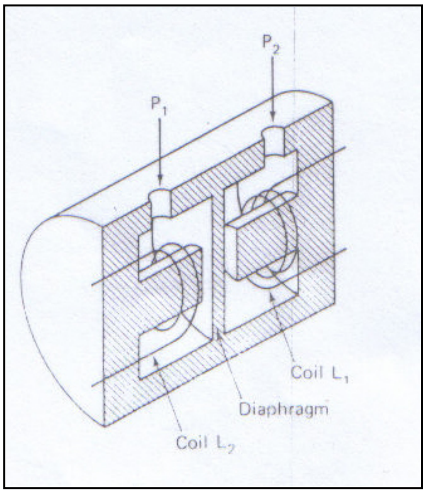
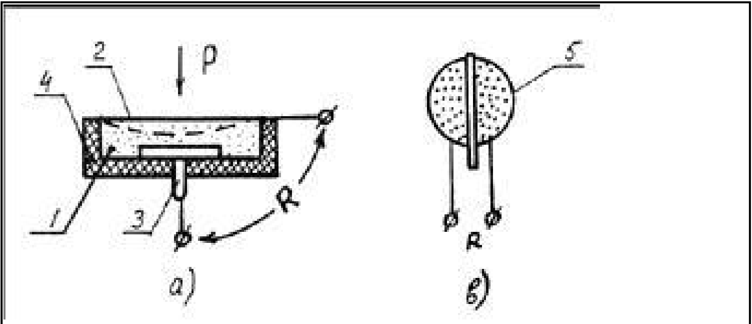


Figure 2.5 *Reluctance change by diaphragm deflection [Ref: 5]*

2.3.4 ***Resistive Pressure Transducers***

Resistive pressure transducers are the most common in the market. When pressure is applied to the diaphragm, it deflects proportional to the change in resistance. The change in resistance is measured by a strain gage. Because these pressure transducers are very sensitive to the deflection, their measurements are very precise. The resistive transducer has a very simple construction, most commonly of silicon. Silicon is a high-precision, high-strength, and high-reliability material. It is very functional where miniaturized precision mechanical devices must be fabricated in large quantities. High-temperature treatment, bulk imperfections, and depositions of different films on the surface of the single-crystal silicon cause a concentrate stress and cleavage on the material.

Silicon is best used at low temperatures because materials deposited on the surfaces have variations in TCE and develop a non-uniform deformation under heating. For those reasons we used LTCC (Low Temperature Co-fired Ceramic) tape to elaborate the pressure transducer. LTCC does not change its properties with the change in temperature and ideal for it can be sintered below 1000°C. It is very resistant to pressure and ideal for use with thick film technology. LTCC is piezoelectric, so it often is employed to convert mechanical signals into electrical signals. It is very practical for micro-technology and is low cost compared to silicon. Resistive pressure transducers contain materials sensitive to pressure, or particles whose contact resistance undergoes changes when pressure is applied to them. Manganin wire, mono-crystalline Tellurium, and Indium Antimonide reveal the change in resistance when they are exposed to pressure. *Figure 2.6* below show a resistive pressure transducer with conductive particles.



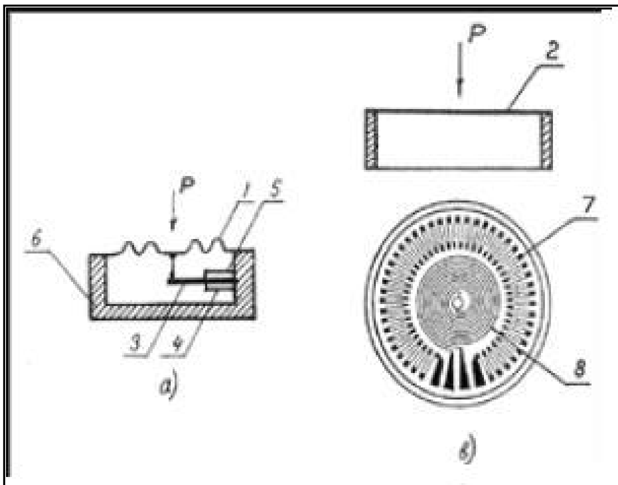
a) Resistive pressure transducers with conductive particles or manganin-wire wound-coil.

b) P= pressure, R= transducer's resistance, 1= conductive particles, 2= conductive diaphragm, 3= electrode, 4= case, 5= Manganin-wire wound coil.

Figure 2.6 *Resistive pressure transducers with conductive particles [Ref: 5]*

2.3.5 ***Strain-Gage Pressure Transducer***

The conversion of pressure changes into resistance changes, due to strain, in two or, much more commonly, four arms of a Wheatstone bridge have been used in pressure transducers for many years. Two basic types of strain-gage pressure transducers are used in practical measurements. In one of them, the deflection of the pressure sensitive spring element bends the beam with affixed strain gages. In the other type, the strain gages are affixed directly to the spring element and respond to the stress developed in the element's material. The gages are made of metal foil, vacuum-deposited or sputtered films and semiconductor material. *Figure 2.7* illustrates a strain-gage pressure transducer having separate diaphragm and sensing elements,



a) deposited gages

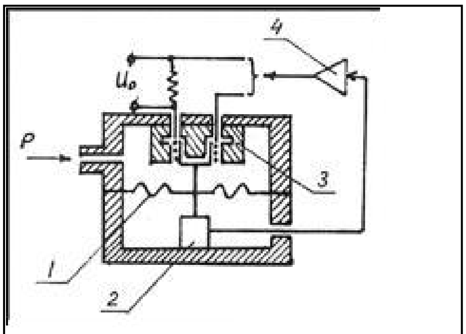
**b) P = pressure, 1 and 2 = pressure-sensitive diaphragm,
3 = cantilever, 4 and 5 = strain gages, 6 = case,
7 and 8 = deposited strain-gage patterns.**

Figure 2.7 *Strain-gage pressure transducer having separate diaphragm and sensing elements [Ref: 5]*

Unbonded wire strain gages were used in some of the earlier models. Bonded metal-foils gages are used in many current designs, typically mounted to a beam to which a bending force is applied by a pushrod attached to a diaphragm, but sometimes mounted to the back side of the diaphragm itself. Thin-film techniques have been applied to bonded-gage designs, with the gages sputtered or vacuum-deposited onto either beam or the back of the diaphragm. Diaphragms are used in the majority of designs; however, straight-tube sensing elements have proved very satisfactory in transducers that measure pressures in the higher ranges (10 MPa and up).

*2.3.6 **Servo-Type Pressure Transducers***

Servo-type pressure transducers generally provide very good accuracy, but at the cost of greater complexity. Servo-type pressure transducers have several modifications. The basic model contains a pressure-sensitive element, whose deflection under pressure provides an error signal that is fed into an amplifier. The amplified signal excites a force-restoring mechanism that balances the force developed in the spring element due to the applied pressure. The current or voltage feeding the restoring system at the state of balance is a measure of the pressure. Force-balancing is performed by a servomotor, the force coil of an electromagnetic system, or by a capacitive actuator. The displacement of the sensing element is detected by a transduction element (differential transformer, photoelectric cell, variable capacitor, etc.). *Figure 2.8* below illustrates a layout design of a servo-type pressure transducer,



P = pressure, Uo = output voltage
1 = pressure-sensitive element,
2 = displacement transduction element
3 = force-restoring mechanism,
4 = amplifier

Figure 2.8 *Servo-type pressure transducer [Ref: 5]*

2.3.7 ***Piezoelectric Pressure Transducers***

Piezoelectric pressure transducers are widely used for pressure measurements where a very high frequency response (up to 500 kHz in some of the designs) is required or where an equivalently short response time is required. In a piezoelectric pressure transducer, a pressure-sensing diaphragm transfers the pressure to a stack of disks made of piezoelectric ceramics or crystalline quartz. The electrical charges, picked up from the faces of the stack, are proportional to the pressure.

A typical piezoelectric pressure transducer using piezocrystals is shown in *Figure 2.9*. The pressure-sensing diaphragm acts against a stack of piezocrystals which produce the output signal. The crystals are mechanically preloaded. The design shown also includes a small seismic mass with an associated piezocrystals which senses acceleration and produces a signal that is used for compensating the pressure-generated signal for simultaneously experienced acceleration. The housing may contain an (optional) IC amplifier, a device very useful in providing a low-impedance output; the output impedance of the piezocrystal is very high.

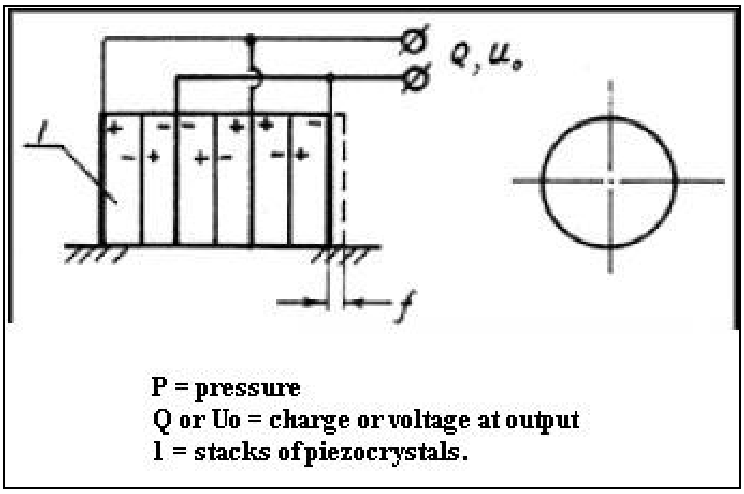
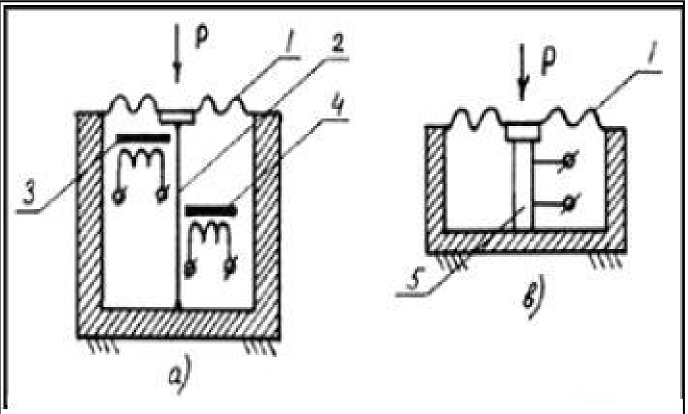


Figure 2.9 *Piezoelectric pressure transducer [Ref: 5]*

Piezoelectric pressure transducers exist in many general-purpose as well as specialized configurations; the latter includes designs that can replace a spark plug in an engine; those that fit into a small cavity in a fuel-injection line, also for automotive testing; and those that fit against a cartridge in a gum chamber, for ballistic measurements. Water-cooling adaptors are available for many configurations.

2.3.8 ***Vibrating-Element Pressure Transducers***

Pressure transducers using the change in the resonant frequency of a vibrating mechanical member, due to pressure changes, are capable of providing extremely close repeatability. Two basic designs are used in the construction of vibrating-element pressure transducers. A pressure-sensitive element (diaphragm or bellows) develops a force against a tensioned wire or quartz crystal whose natural mechanical frequency of vibration depends on the stress due to the force. As a result, the frequency is a function of pressure. The vibrations are maintained by a feedback loop with an amplifier in the loop. Electromagnetic and piezoelectric effects are utilized to pick up signals proportional to the deflection of the elements and to exert the driving forces on the vibrating member. *Figure 2.10* shows the diagram of vibrating-element pressure transducer,



a) quartz crystal
b) P = pressure, 1 = pressure-sensitive element,
2 = tensioned wire, 3 = pickup coil,
4 = driving magnetic system, 5 = quartz crystal.

Figure 2.10 *Vibrating-element pressure transducers with pressure sensitive element changing strain in vibrating wire [Ref: 5]*

They also produce a frequency output or frequency-modulated output (frequency deviation from a center frequency) which lends itself to digitization without conversion error (or direct display on a frequency counter). In some FM/FM telemetry systems, such transducer outputs were fed directly into the system as one of the sub-carrier channels. A significant number of vibrating-wire pressure transducers were built and used primarily in aerospace and oceanography. However, they were found to be difficult to produce. A vibrating-diaphragm transducer was designed and used experimentally, and vibrating-cylinder transducers were produced in several countries but suffered from high temperature sensitivity as well as producibility problems. These problems were finally overcome, and the vibrating-cylinder pressure transducer is now commercially available. Further development may bring similar results for other types of vibrating-element transducers.

CHAPTER 3 : THEORY & DESIGN OF CAPACITIVE IMPEDANCE MEASURING SYSTEM

3.1 Capacitors and Capacitance

A capacitor is a passive element which is designed to store energy in its electrical field. It is extensively used in electronics, communications, computers and power systems. A ***capacitor*** consists of two conducting plates separated by an insulator (or dielectric). The plates are mainly aluminum foil and the dielectric are usually air, ceramic, paper or mica in many practical applications.

When there is a voltage supply connected to the capacitor, the source deposits a positive charge q on one of the plates and a negative charge $-q$ on the other plate. The function of capacitor is to store the electrical charge. The word *capacitor* is derived from its elements capacity to store charge in an electric field. The stored charge, q, is directly proportional to the applied voltage v which can be shown in equation,

$$q = C\,v \qquad \mathbf{(3.1)}$$

where C, is the constant of proportionality which is also known as the *capacitance* of the capacitor. ***Capacitance*** is the ratio of the charge on one plate of a capacitor to the voltage difference between the two plates, which is measured in farads (F). Although the capacitance C of a capacitor is the ratio of the charge q per plate to the applied voltage v, it does not depend on q or v. It depends on the physical dimension of the capacitor as shown in the equation below,

$$C = \frac{\varepsilon A}{d} \qquad \mathbf{(3.2)}$$

where A is the surface area of each plate, d is the distance between the plates and ε is the permittivity of the dielectric material between the plates.

There are some important properties of a capacitor:

1) When the voltage across a capacitor is not changing with time (i.e., dc voltage), the current through the capacitor is zero. This proves that a capacitor is an open circuit to dc. But, there will be capacitor changes, if there is a battery connected across a capacitor.

2) The voltage on a capacitor cannot change abruptly, must be always continuous. Capacitor resists an abrupt change in the voltage across it. A discontinuous change in voltage requires an infinite current, which is physically impossible. The current through a capacitor can change in instantaneously.
3) An ideal capacitor does not dissipate energy. It takes power from the circuit when storing energy in its field and returns previously stored energy when delivering power to the circuit.
4) A real, nonideal capacitor has a parallel-model leakage resistance. The leakage resistance may be as high as 100MΩ and can be neglected for most practical applications.

3.2 Capacitive Impedance

Impedance is the total measure of opposition to electric current and is the complex (vector) sum of ("real") resistance and ("imaginary") reactance. Impedances (**Z**) are managed just like resistances (**R**) in series circuit analysis: series impedances add to form the total impedance. All the calculations are performed in complex (not scalar) form. It can be elaborated as the equation given below,

$$\mathbf{Z_{Total} = Z_1 + Z_2 + \ldots Z_n} \qquad \mathbf{(3.3)}$$

A resistive impedance will always have a phase angle of exactly 0° (Z_R = R Ω, 0°) but a purely capacitive impedance will always have a phase angle of exactly -90°(Z_C = X_C Ω,
-90°). When resistors and capacitors are mixed together in circuits, the total impedance will have a phase angle somewhere between 0° and -90°. A series AC circuits exhibit the same fundamental properties as a series DC circuits:

1) current is uniform throughout the circuit
2) voltage drops add to form the total voltage
3) impedances add to form the total impedance

Impedances (**Z**) are managed just like resistances (**R**) in parallel circuit analysis: parallel impedances diminish to form the total impedance, using the reciprocal formula.

All the calculations are performed in complex (not scalar) form. It can be elaborated as the equation given below,

$$\mathbf{Z_{Total} = 1 / (1/Z_1 + 1/Z_2 + \ldots 1/Z_n)} \qquad \mathbf{(3.4)}$$

When resistors and capacitors are mixed together in parallel circuits (just as in series circuits), the total impedance will have a phase angle somewhere between 0° and -90°. The circuit current will have a phase angle somewhere between 0° and +90°. Parallel AC circuits exhibit the same fundamental properties as parallel DC circuits:

1) voltage is uniform throughout the circuit
2) branch currents add to form the total current
3) impedances diminish (through the reciprocal formula) to form the total impedance

3.3 Capacitive Impedance Measurement System

Capacitive Impedance Measurement System is basically used to measure the changes of output voltage when there are changes to the capacitive impedance. It is designed to measure the output voltage when the designed Capacitive Pressure Transducer is fixed to the measurement circuit replacing the capacitors. The measurement system circuit is designed with several different processes which were brought together in one system that are used to measure the output of the transducer.

Figure 3.1 shows the design of the measurement circuit. The measurement circuit is built using the following processes:

1) Input source
2) Differentiator Amplifier
3) Quadrature Amplifier
4) Comparator
5) Switch (HCF4066B)
6) Output measurement device

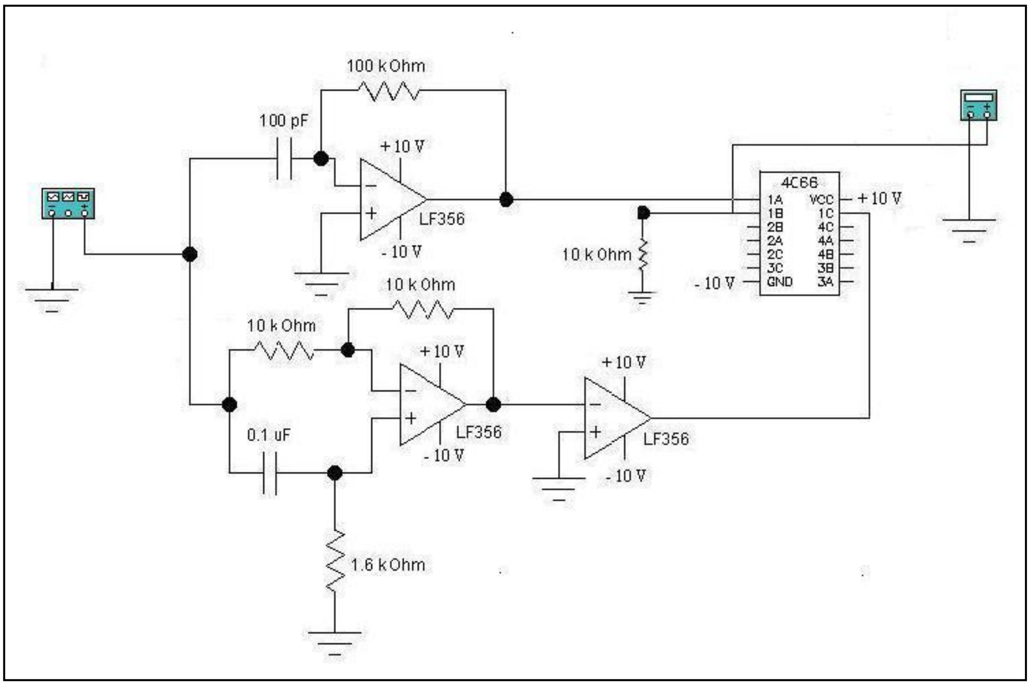


Figure 3.1 *Capacitive Impedance measurement circuit*

3.3.1 **Input Source**

The function of an *input source* is to supply voltage power to the operating circuit. The input voltage power is generated using an *audio generator* which supplies ac voltage in the form of sinusoidal input. The amplitude of the input voltage is set according to the requirement of the following processes circuit and it also has the frequency controller which indicates the frequency range of the input sinusoidal wave that determines the time duration of each cycle of the input wave.

The figure below shows an example of the *input source*,

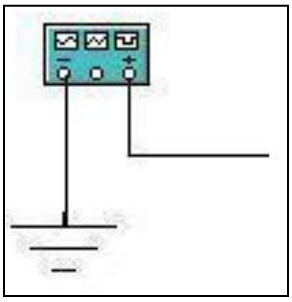


Figure 3.2 *Input Source*

3.3.2 ***Differentiator Amplifier***

Differentiator Amplifier is the result of interchanging the location of the capacitor and the resistor of an integrator circuit, which forms the mathematical function of differentiation. To see how the results comes about, let a time-varying function $v_i(t)$, and the virtual ground at the inverting input terminal of the *operational amplifier* (op-amp) causes $v_i(t)$ to appear in effect across the capacitor *C*. Thus the current through *C* will be $C(dvi/dt)$, and this current flow through the feedback resistor *R* providing at the op-amp output a voltage $v_o(t)$.

$$v_o(t) = -CR\frac{dvi(t)}{dt}$$

(3.5)

The frequency-domain transfer function of the differentiator circuit can be obtained as,

$$\frac{Vo(s)}{Vi(s)} = -sCR \qquad \textbf{(3.6)}$$

The frequency response of the differentiator can be thought of as that of an STC high-pass filter with the corner frequency at infinity. Finally, we should note that the very nature of a differentiator causes it to be a “noise magnifier.” This is due to spike introduced at the output every time there is a sharp change in $v_o(t)$; such a change could be “picked up” interference. For this reason and because they suffer from stability problems, differentiator circuits are generally avoided in practice. When the circuit in Figure 3.3 is used, it is usually connected with a small resistance in series with the capacitor, but this modification, unfortunately will turn the circuit into a non-ideal differentiator.

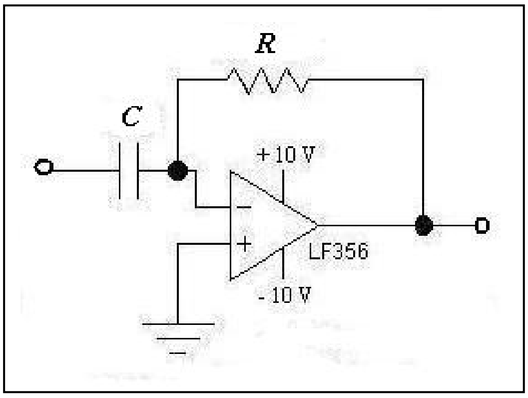


Figure 3.3 *Differentiator Amplifier*

3.3.3 ***Quadrature Amplifier***

Quadrature amplifiers find application in many areas, most notably in the design of instrumentation systems. As an example, consider the case of a transducer that produces between its two output terminals a relatively small signal, say 1 mV. However, between each of the two wires (leading from the transducer to the instrumentation system) and ground there may be large picked-up interference, say 1 V. The required amplifier, known as an **instrumentation amplifier,** must reject this large interference signal, which is common to the two wires (a common-mode signal), and amplify the small quadrated (or differential) signal.

Figure 3.4 shows a quadrature amplifier circuit which have been modified into a circuit function of a ***phase shifter*** to be used in this capacitive impedance measurement system. It is also known as a ***first-order all-pass filter***.

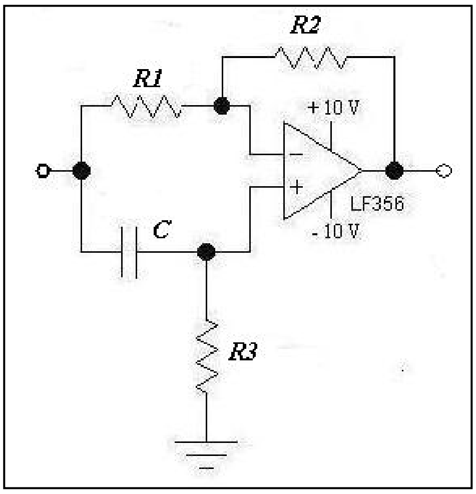


Figure 3.4 *Phase shifter (Quadrature Amplifier)*

The values of the *C* and R_3 is defined using an equation as below,

$$\boldsymbol{\omega CR = 1} \qquad \textbf{(3.7)}$$

where, $\boldsymbol{\omega = 2\pi f}$ ($\boldsymbol{f}$ is the input frequency used)

C = Capacitor value used (Farads)

R = Resistor value used (Ω)

*3.3.4 **Comparator***

The function of a *comparator* circuit is to convert the input wave form of the comparator (sinusoidal wave) into square wave form as the output of the comparator. A comparator circuit is designed with only one op-amp as in *Figure 3.5* and it is done by grounding the positive input of the op-amp. The negative input of the op-amp is directly connected with the input source (without any resistor or capacitor) and the output of the comparator produces a square wave output.

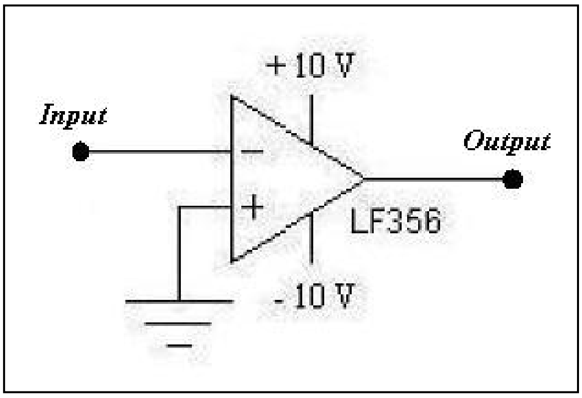


Figure 3.5 *Comparator circuit*

*3.3.5 **Switch (HCF4066B)***

The *switch (HCF4066B)* in this capacitive impedance measurement circuit is used as an important component, which is used to get the final output voltage of the measurement system. This switch is a monolithic integrated circuit, available in 14-lead dual in-line plastic or ceramic package and plastic micro-package. The *HCF4066B* consists of four independent bilateral switches. A single control signal is required per switch. Both the p and n device in a given switch are biased ON and OFF simultaneously by the control signal. *Figure 3.6* shows the switch diagram which is used in the capacitive impedance measuring system. The output signal from the ***differentiator amplifier*** is used as one of the input to the switch while the output from the ***comparator*** is used as the control input of the switch. This produces a semi-sinusoidal wave as the output of the switch.

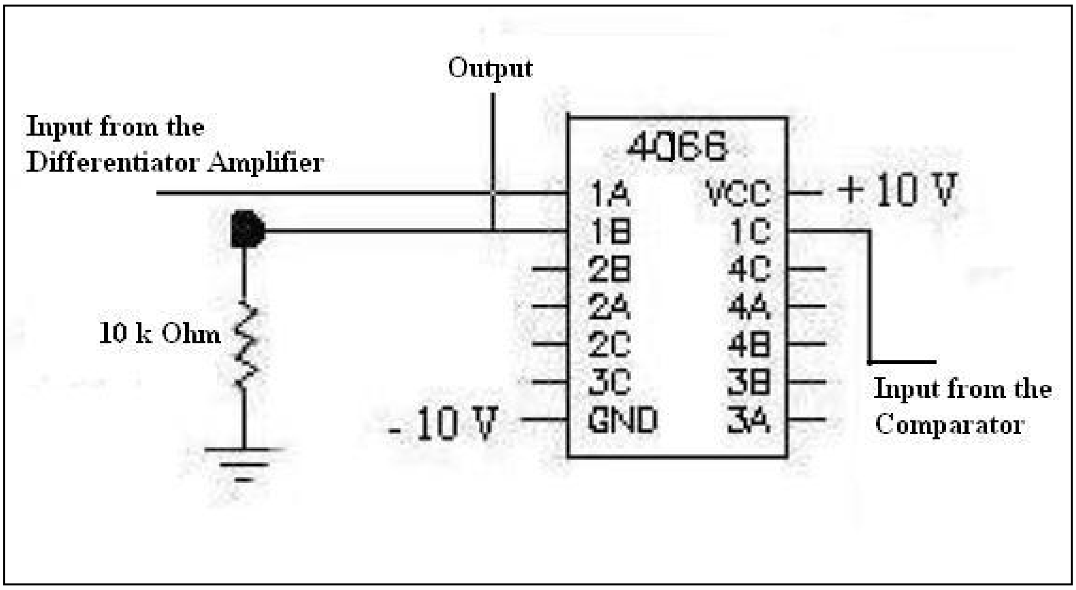


Figure 3.6 *Switch (HCF4066B)*

3.3.6 ***Output measurement device***

Output measurement device used in this capacitance impedance measurement circuit is an ***analog multimeter***. This multimeter operates to find the output voltage value when it is connected to the output of the switch. *Figure 3.7* below shows the diagram of a multimeter.

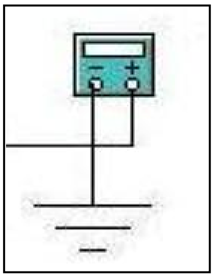


Figure 3.7 *Multimeter*

3.4 Theory of the capacitance measuring circuit

In a generalized inverter shown in *Figure 3.8,* output voltage, V_o may be given by the following expression.

$$Vo = -\frac{Z2}{Z1}(Vs) \qquad \textbf{(3.8)}$$

or

$$\frac{Vo}{Vs} = -\frac{Z2}{Z1} \qquad \textbf{(3.9)}$$

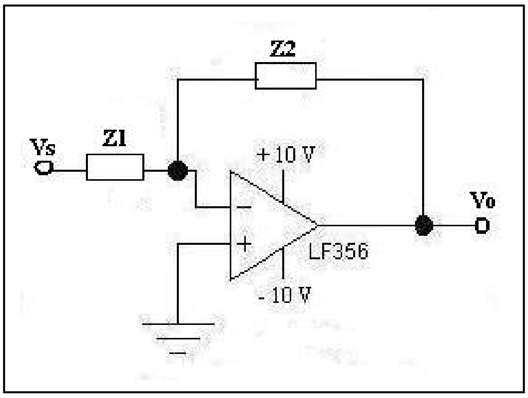


Figure 3.8 *Inverter circuit*

These may be represented in the phasor form as follows,

$$V_{inph} + j\,V_{quad} = -\,[\,M_1 \pm j\,M_2] \qquad \textbf{(3.10)}$$

Comparing real and imaginary parts, we get

$$V_{inph} = -\,M_1 \qquad \& \qquad V_{quad} = -j\,M_2 \qquad \textbf{(3.11)}$$

Equation **(3.11)** shows that if we can get inphase and quadrature components of the term $\frac{Vo}{Vs}$, we can determine M_1 and M_2 which is one or the other form of impedance.

Measurement of inphase and quadrature components can be made with the help of analog switch as follows,

1) Connect the output of the circuit to the input of one of the four analog switches.