ELECTRICAL PRESSURE TRANSDUCERS– DESIGN AND APPLICATION OF

A DISSERTATION

submitted in partial fulfilment of the requirements for the award of the Degree of

MASTER OF ENGINEERING

in

ELECTRICAL ENGINEERING
(Measurements & Instrumentation)

by

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CERTIFICATE

CERTIFIED that the dissertation entitled "Electrical pressure transducers - design and application" which is being submitted by Shri B.R. SREENIVASA RAO in partial fulfilment for the award of the degree of Master of Engineering in Electrical Engineering (MEASUREMENTS AND INSTRUMENTATION) of the University of Roorkee is a record of the student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree of Diploma.

This is to further certify that he has worked for a period of 5½ months from February '77 to July '77 for preparing this dissertation at this University.

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SYNOPSIS

This dissertation deals with the design of various types of electrical pressure transducers (Resistive,capacitive inductive and piezo-electric) for above atmospheric pressures and the design of the associated electronic instrumentation system.

Three types of electrical pressure transducers (strain gauge, capacitive and LVDT types) have been designed and developed for measurement of very low wind pressures (range : 0 to 70 cms. of water). A measuring instrument has also been developed for use with the above transducers.

The special feature of strain gauge type is use of four active strain gauges in the arms of the bridge circuit in push-pull mode. These gauges are cemented to sense maximum bending stress. It is shown this method improves sensitivity.

Capacitive type is combined with strain gauge type by fixing two additional electrode plates one on each side of the same diaphragm on which the strain gauges are cemented.

The special features of LVDT type is development of miniature LVDT unit with null compensating arrangement.

All three types of transducers were experimentally tested and found that the response were linear. Performance ofLVDT type was found to be better than the strain gauge and capacitive type transducers.

CONTENTS

CHAPTER - 1

INTRODUCTION

A transducer is defined as a sensing device that converts physical phenomena and chemical composition into electric, pheumatic or hydraulic output signals for the purpose of measurement (1). In the present work electrical pressure transducers are understood to mean devices which convert input pressure into electrical output signals, their output/input and output/time relationships being predictable to a known degree of accuracy at specified operating conditions.

Electrical pressure transducers consist of mechanical sensing element and electrical transduction elements(2). This feature calls for expertise both in the mechanical and electrical fields for the design and development. Electrical measurements offer the advantages of simple indicating, record telemetering as well as information processing and also feeding to the computer.

For very low wind pressure measurement (in the order of 0 to 70 cms of water) in most cases manometers are used. Electrical signal in proportion to pressure is needed in many instances. Thus there is necessity for cheap, accurate and reliable pressure transducers in order to electrically measure pressure. In this work wind pressure measurement was kept in mind. The design methods given in this work can be applied to other fluids also with suitable modifications.

The working principles of most of the electrical pressure transducers are well known, but the design and fabrication presents enormous difficulties especially where precision and severe environmental conditions are involved. In the present work design and fabrication of commonly used electrical pressure transducers (resistive, inductive, capacitive and peizo-electric) are discussed in detail as per the following procedure:

(a) To present the design and fabrication details in a convenient form to enable the design of electrical pressure transducers most commonly used for various applications.

(b) To design and fabricate the following pressure transducers with the associated instrumentation for wind pressure measurement in the range 0 to 70 cms. of water :

   (i) Strain gauge type

   (ii) LVDT type

   (iii) Capacitive type

(c) To test and calibrate the above three types of transducers experimentally.

(d) To give some typical examples to show the various application possibilities.

This work is divided into five chapters. The second chapter deals with the design of pressure sensing elements (bourdon tubes, membranes, thin plates, capsules and bellows) and transduction elements (resistive, inductive, capacitive and piezo-electric including their sub-types). A number of design equations are developed and some fabrication details are also included. The measuring circuit details for selection and design is also discussed.

The third chapter deals with the design, fabrication and experimental testing of straingauge, LVDT, and capacitive pressure transducers developed for wind pressure measurement (range : 0 to 70 cms. of water). Details of the measuring instrument developed for the above purpose are also given. The special features of the transducer and the measuring instrument are explained. Results of the experimental test are discussed.

Considerations for various applications and some typical examples of applications are included in chapter four with a view of showing the various application possibilities.

Fifth and the last chapter contains the conclusions and scope for further work. It is concluded that the LVDT transducer performance was observed to be better than the strain gauge and capacitive transducers.

CHAPTER - 2

DESIGN AND FABRICATION

PRESSURE SENSING ELEMENTS

Pressure sensing elements are made of metals. Elastic stresses appearing as a result of element strains balance the external pressures. The most frequently used pressure sensing elements are (3) :

1. Bourdon Tubes
2. Membranes
3. Thin plates
4. Capsules
5. Bellows

Bourdon tubes are tubes of non-circular cross section coiled into a circle or spiral. The difference between the internal and external pressures cause a deflection of the closed end of the tube constituting a measure of that difference.

A membrane is a flat or corrugated sheet metal (usually a disc) fixed around the periphery. The deflection of the membrane is a measure of the difference of pressures acting upon both membrane sides. Its stiffness to bending forces is neglected.

Thin plate is similar to membrane but has thickness which modifies the properties as compared to membrane. Stiffness in bending is considered.

Two membranes joined along their edges constitute a capsule. Membranes and capsules are very sensitive elastic measuring elements used mainly for the measurement of low pressures.

Bellows are thin walled tubes with corrugation rings perpendicular to the generating line. Bellows deflection depends upon the difference between internal and external pressures. The range of application depends upon corrugation ring number, material and dimensions of the element.

Figure 2.1 (a)-(h) shows a selection of pressure sensing elements schematic diagram (2).

.1 General Features : Figure 2.2 shows the relationship of effective pressure p and the deflection f of a selected point of the element (3). In bourdon tubes this point is situated on the tube free end and in membranes, thinplates, capsules and bellows on the axis of symmetry.

Sensitivity of the element is defined as the ratio $s = \frac{df}{dp} = \tan \alpha$. Bourdon tubes and bellows have a recti-linear characteristic and therefore s = constant. Membrane and capsule characteristics are mostly curvi-linear with variable s.

The phenomena of hysterisis and elastic retardation occur in pressure sensing elements as in springs. In measuring elements elastic retardation results in a difference between the characteristic for rising pressure and that for the falling pressure and thus different deflection values correspond to a given value of pressure. The result of these phenomena will be the instrument indication error, called the error of hysterisis. To reduce it elastic measuring elements are subjected to a stabilisation process. Hysterisis index is given as

$\xi = \frac{f_h}{f_{max}} \times 100\%$ where f_h is the maximum value of hysterisis and f_{max} is the maximum deflection of the element. Pressure sensing elements show a hysterisis index of 0.3 to 2%.

The temperature effect on the pressure sensing element must be taken into account. The deflection of the element is a function of pressure acting upon the element, youngs modules of the material and coefficients depending upon the geometric shape and dimensions of the element. The effect of temperature is to vary the youngs modulus. It may be assumed that with in the range of practically occuring temperature variations youngs modulus varies according to the linear relationship (3)

$$E_T = E_o (1 + \gamma \Delta T)$$

where E_T — youngs modulus at temperature T^oC, E_o — youngs modulus at reference temperature (20^oC), γ — thermal co-efficient of youngs modulus variation, ΔT — temperature variation in relation to reference temperature.

Additional deflection Δf_T of the elastic element caused by variation of youngs modulus E in consequence of temperature variation results in thermal error of the instrument. Assuming at temperature T_o the deflection f_o is related by $f_o = \frac{f(p)}{E_o}$ while at temperature T, the deflection f_T is related by ~~thm~~ $f_T = \frac{f(p)}{E_T}$ we have

$$\frac{f_o}{f_T} = \frac{E_T}{E_o} \quad \ldots \quad \ldots \quad \ldots (2.1)$$

$$\therefore \quad f_T = f_o \left(\frac{E_o}{E_T} \right) \quad \ldots \quad \ldots \quad \ldots \quad (2.2)$$

substituting $E_T = E_o\ (1 + \gamma\ \Delta T)$ in eq. (2.2) we have

$$f_T = f_o \left(\frac{1}{1 + \gamma \Delta T} \right) \quad \ldots \quad \ldots \quad \ldots \quad (2.3)$$

$$\Delta f_T = f_T - f_o \quad \ldots \quad \ldots \quad \ldots \quad (2.4)$$

substituting the value of f_T from eq. (2.3) in eq.(2.4) we get

$$\Delta f_T = f_o \left(\frac{-\gamma \Delta T}{1 + \gamma \Delta T} \right) \quad \ldots \quad \ldots \quad \ldots \quad (2.5)$$

The relationship in eq.(2.5) is valid for recti-linear characteristic of an elastic element. For the curvi-linear characteristic, Δf_T is found as follows:

A curvi-linear characteristic may be expressed by the relation

$$f = c \left(\frac{p}{E} \right)^n \quad \ldots \quad \ldots \quad \ldots \quad (2.6)$$

c and n are constants. Similar to above procedure we have

$$f_T = f_o \left(\frac{E_o}{E_T} \right)^n \quad \ldots \quad \ldots \quad \ldots \quad (2.7)$$

and $$\Delta f_T = f_o \left[\frac{1}{(1 + \gamma \Delta T)^n} - 1 \right] \quad \ldots \quad \ldots \quad (2.8)$$

It is seen that in eq.(2.8) if n = 1, it reduces to eq.(2.5).

Bourdon Tube : A bourdon tube is coiled into a circle and has an oval or flat - sided cross-section as shown in Fig.2.3. Sometimes tubes of other cross-sections as shown in Fig.2.3, are also used. The tube is attached to a base which has a hole connecting the tube interior with the space where pressure is to be gauged. The free end of the tube is closed by one end piece whose deflections are utilised for transduction.

The calculation of bourdon tube consists in determining the tube dimensions, its cross-section, wall thickness, tube characteristic (i.e. the relationship between effective pressure and free end displacement) and the acting force. The principle of calculation of burdon tubes is given below:(Fig.2.4) (3).

The effective pressure p which causes the displacement of the free end is the difference between the pressure p_1 inside the tube and the ambient pressure p_2.

$$p = p_1 - p_2$$

After the tube is loaded by pressure p, the initial coiling angle Ψ_o decreases to Ψ (radian). The tube deflection is

$$\Delta\Psi = \Psi_o - \Psi$$

Displacement of the tube end may also be expressed by movement of point A.

The equation for the bourdon tube characteristic is approximate but satisfactory in practical applications.

Two cases are categorised as follows:

Thin wall tubes — ratio $\frac{t}{b} < 0.6$ to 0.7 and

Thick wall tubes — ratio $\frac{t}{b} > 0.6$ to 0.7

For thin wall tubes $\frac{\Delta\Psi}{\Psi_o} = p\,\frac{1-\nu^2}{E}\,\frac{R_o^2}{bt}\left(1-\frac{b^2}{a^2}\right)\frac{\alpha}{\beta+\chi^2}$ ... (2.9)

For thick wall tubes $\frac{\Delta \Psi}{\Psi_o} = p \frac{1-\nu^2}{E} \frac{R_o^2}{bt} \left(\frac{1-X}{\frac{t^2}{12\,b^2} + X} \right)$ ... (2.10)

where $x = \frac{R_o t}{a^2}$; x and X are constant parameters.

Values of α and β are given in table 2.1. The relationship between x and X is graphically represented in Fig. 2.5. The analytical expression relating x and X is

$$X = \frac{1}{c} \frac{\mathrm{Sinh}^2 c + \mathrm{Sin}^2 c}{\mathrm{Cosh}\ c\ \mathrm{Sinh}\ c + \mathrm{Cos}\ c\ \sin c} \quad \ldots \quad \ldots \quad (2.11)$$

where $c = \sqrt{\sqrt{\frac{3}{x}}}$

Equations (2.9) and (2.10) enable calculation of $\frac{\Delta \Psi}{\Psi_o}$.

The movement of point A of the free end of the tube in the radial and tangential directions is given by

$$f_r = \frac{\Delta \Psi}{\Psi_o} R_o (1 - \cos \Psi_o) \quad \ldots \quad \ldots \quad \ldots \quad (2.12)$$

$$f_t = \frac{\Delta \Psi}{\Psi_o} R_o (\Psi_o - \mathrm{Sin}\ \Psi_o) \quad \ldots \quad \ldots \quad \ldots \quad (2.13)$$

Resultant movement $f = \sqrt{f_r^2 + f_t^2}$ ... ... (2.14)

For $\Psi_o = 270^\circ$, a value most frequently encountered in practice is

$$f = 5.8\, R_o \frac{\Delta \Psi}{\Psi_o}$$

Maximum deflection occurs in the direction $A - A_1$. This angle ϕ is given by

$$\cos \phi = \frac{\Psi_o - \sin \Psi_o}{\sqrt{(\Psi_o - \sin \Psi_o)^2 + (1 - \cos \Psi_o)^2}} \quad \ldots \quad (2.15)$$

If the angle $\Psi_o = 270^\circ$, the angle $\phi = 10^\circ$.

The forces acting in radial and tangential directions at the free end of the tube are as follows :

For thin wall tubes :

$$p_r = pab\,(1 - \frac{b^2}{a^2})\, \frac{48\,S}{\xi + x^2}\, \frac{1 - \cos \Psi_o}{\Psi_o - \sin \Psi_o \cos \Psi_o} \quad \ldots \quad (2.16)$$

$$p_t = pab\,(1 - \frac{b^2}{a^2})\, \frac{48\,S}{\xi + x^2}\, \frac{\Psi_o - \sin \Psi_o}{3\,\Psi_o - 4 \sin \Psi_o + \sin \Psi_o \cos \Psi_o} \quad (2.17)$$

For thick wall tubes:

$$p_r = 8\, pab\,(1 - X)\, \frac{1 - \cos \Psi_o}{\Psi_o - \sin \Psi_o \cos \Psi_o} \quad \ldots \quad \ldots \quad (2.18)$$

$$p_t = 8\, pab\,(1 - X)\, \frac{\Psi_o - \sin \Psi_o}{3\,\Psi_o - 4 \sin \Psi_o + \sin \Psi_o \cos \Psi_o} \quad \ldots \quad (2.19)$$

where S and ξ are numerical coefficients given in table 2.1.

A bourdon tube characteristic is linear until the proportionality limit and the corresponding pressure p term are attained. The working range of the tube should be shorter than the proportionality range so that coeffecient $K = \frac{p\ term}{p\ max} > 1$ where p max is the maximum working pressure. The value of K is taken as K = 2 in the case of slow pressure variations, K = 2.5 at rapidly varying pressures and K = 3 for tubes working at temperatures exceeding + 50°C. Increasing the value of K reduces tube

Table - 2.1 : Numerical Values of Coeff[illegible]f Bourdon Tubes.

Tube Cross Section	$\frac{a}{b}$	1	1.5	2		8	9	10
ELLIPTICAL	α	0.750	0.636	0.566	06	0.400	0.395	0.39
Major axis = 2a Minor axis = 2b	β	0.083	0.062	0.053	12	0.042	0.042	0.04
	S	0.0982	0.0775	0.0662	50	0.0455	0.0451	0.044
	ξ	0.833	0.622	0.548	23	0.416	0.410	0.40
FLAT SIDED	α	0.637	0.549	0.548	72	0.360	0.350	0.34
Longer axis= 2a Short axis = 2b	β	0.096	0.110	0.115	21	0.119	0.119	0.11
	S	0.0833	0.0848	0.0815	02	0.0585	0.0571	0.06
	ξ	0.811	0.713	0.652	38	0.476	0.467	0.45

hysterisis. The proportionality limit of the tube rises when axis ratio $\frac{a}{b}$ of the cross-section is decreased, wall thickness t increased and coiling radius R_o reduced. The proportionality range can be considerably increased by heat treatment and stabilisation of the tube.

Bourdon tubes are generally used for measuring pressures not below 0.5 kg/cm^2. The upper limit of their measuring range depends upon the material and shape of the tube. Bourdon tubes are generally made of brass, phosphor bronze or steel.

2.1.3 Membrane : Flat membrane has small deflections and sharply curved characteristics. Corrugated membranes have larger deflections. The shape of the radial cross section of a membrane is called its profile and plays a decisive role in determining its characteristics. Introduction of the corrugation causes a reduction of stresses resulting from membrane tension. The possibility of obtaining any desired characteristic is a very important feature of corrugated membranes. Fig.2.6 shows the membrane characteristic (3,4).

Commonly used membrane profiles are shown in the Fig.2.7. Compound profiles are sometimes used inorder to get the desired characteristic, the profile shape in such cases is determined experimentally.

Membrane calculation consists in selecting the profile, sheet metal thickness, material and in establishing characteristic $f = f(P)$ while deflections are computed for the center point of the membrane.

Table - 2.1 : Numerical Values of Coefficients for the Calculation of Bourdon Tubes.

Tube Cross Section	$\frac{a}{b}$	1	1.5	2	3	4	5	6	7	8	9	10
ELLIPTICAL	α	0.750	0.636	0.566	0.493	0.452	0.430	0.416	0.406	0.400	0.395	0.3[illegible]
Major axis = 2a	β	0.083	0.062	0.053	0.045	0.044	0.043	0.042	0.042	0.042	0.042	0.0[illegible]
Minor axis = 2b	S	0.0982	0.0775	0.0662	0.0565	0.0515	0.0480	0.0465	0.0460	0.0455	0.0451	0.04[illegible]
	ξ	0.833	0.622	0.548	0.499	0.459	0.439	0.429	0.423	0.416	0.410	0.4[illegible]
FLAT SIDED	α	0.637	0.549	0.548	0.480	0.437	0.408	0.388	0.372	0.360	0.350	0.34[illegible]
Longer axis= 2a	β	0.096	0.110	0.115	0.121	0.121	0.121	0.121	0.121	0.119	0.119	0.11[illegible]
Short axis = 2b	S	0.0833	0.0848	0.0815	0.0743	0.0690	0.0652	0.0624	0.0602	0.0585	0.0571	0.05[illegible]
	ξ	0.811	0.713	0.652	0.591	0.552	0.524	0.504	0.488	0.476	0.467	0.4[illegible]

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Commonly used membrane profiles are shown in the Fig.2.7. Compound profiles are sometimes used inorder to get the desired characteristic, the profile shape in such cases is determined experimentally.

Membrane calculation consists in selecting the profile, sheet metal thickness, material and in establishing characteristic $f = f(P)$ while deflections are computed for the center point of the membrane.

Membrane characteristic calculated utilising the theoretical equations yield only approximate results because of the complicated nature of the problem. The deviation from theoretical claculation to experimental values will be with in 10% and generally serve for determining the shape of a prototype membrane. The final shape of the profile is established experimentally by modifying the profile and sheet metal thickness.

Table 2.2 gives the design equations for membranes. Membranes are made of phosphor bronze, beryllium copper, steel, german silver (3,4). They are generally shaped by hydraulic pressing. Membranes are stabilised to reduce hysterisis.

2.1.4 Thin Plate : The details of thin plates are similar to membranes except the modification of the characteristics due to consideration of stiffness to bending forms. The design equations for thin plates are given in Table 2.2 (4). Thin plates will not be having corrugations generally. A diameter/thickness ratio of 100 is probably the practical limit (4).

2.1.5 Capsule : The capsule consists of joining of two membranes along their edges by soldering, resistance welding, or curling and crimping. The deflection of the capsule is the sum of the deflection of the component membranes. Capsules are often joined into sets inorder to increase deflection.

Capsules intended for measuring the difference between pressures inside and out side the capsules are called differential or open capsules. Those intended for measuring absolute pressure have air removed from their interior, so that the reference pressure is close to zero, and are called closed capsules or aneoroids.

Table 2.2 : Design Relations for Membrane and Thin Plate

Flat circular diaphragms	Deflection at any point (m)	Centre deflection (m)	Maximum stress ($N\,m^{-2}$)	Lower natural frequency (Hert 2)
Membrane (Fig.2.8a)	$y = \frac{P}{4S}(a^2 - r^2)$ a = Radius (m) r = Radius of the point at which y is needed S = Membrane tension ($N\,m^{-1}$) P = Pressure ($N\,m^{-2}$)	$Z_{max} = \frac{a^2 P}{4S}$ Linear if $Z_{max} \leq 0.005a$	$\sigma_{max} \approx \frac{S}{t}$ Uniform over the membrane	$f_o = \frac{1.20}{\pi a}\sqrt{\left(\frac{S}{t}\right)}$ μ = Specific mass (Kgm^{-3})
Thin plate (Fig.2.8b)	$y = \frac{3}{16} P \frac{1-\nu^2}{Et^3}(a^2 - r^2)^2$ E = Youngs modulur (Nm^{-2}) ν = Poissons ratio (0.3 for steel)	$Z_{max} = \frac{3(1-\nu^2)\, a^2 P}{16\, Et^3}$ Linear if $Z_{max} \leq 0.5\, t$	$\sigma_{max} \approx \frac{3a^2 P}{4\, t^2}$ At circumference	$f_o = \frac{2.56\, t}{\pi a^2} \times \sqrt{\frac{E}{3\mu(1-\nu^2)}}$

Materials most commonly used in the manufacture of corrugated diaphragms and capsules are brass, phosphor - bronze, nickel - silver, berryllium copper, monel and stainless steel(3). In the fabrication of capsules electron-beam-welding is now quite common.

2.1.6 Bellows : Bellows are used where considerable deflections and rectilinear characteristics are required. Bellows sensitivity $S_b = \frac{f}{p}$ is constant with in the proportionality range (Fig.2.9). Bellows deflection caused by force F is given by (3)

$$f = F \frac{1-\nu^2}{Et} \frac{n}{A_o - \alpha A_1 + \alpha^2 A_2 + B_o \frac{t^2}{A_1^2}} \quad \ldots \quad \ldots \quad (2.20)$$

where f = deflection in mm, F = force in K_g, ν = poissons ratio, E = youngs modulus of the material in K_g/mm^2, t = wall thickness in mm, α = corrugation wave slape in radions n = no. of full waves, A_o, A_1, A_2, B_o are numerical coefficients graphically represented in Fig.2.10 as a function of constant parameters $m = \frac{R}{R_i}$ and $K = \frac{R_e}{R_i}$ where R_e = external radius in mm, R_i = internal radius in mm, R = corrugation radius.

Bellows are usually shaped hydraulically from a cup obtained by deep drawing. Bellows are sometimes provided with helical corrugation. In such cases rotation of bellows around its axis occurs as well as the deflection.

Bellows are usually made of brass, bronze or steel and are subjected to stabilisation (3).

2.2. RESISTIVE PRESSURE TRANSDUCERS

Variable resistance pressure transducers may be divided into two classes (4) :

(i) Transducers operating on large changes of resistance, employing mainly potentiometer circuits.

(ii) Transducers operating on small changes of resistance, employing mainly bridge circuits.

Potentiometer pressure transducers are most commonly used transducers in the first category and strain gauge transducers are most commonly used pressure transducers in the second category.

2.2.1 Potentiometer Type :

General considerations : The pressure sensing element (bellows, capsule etc.) is essentially a spring subjected to deflections during the application of pressure. The element must be designed to achieve the maximum possible force for a given deflection in order to overcome spring forces within the mechanism.

The elements performance deteriorates in terms of hysterisis, repeatability and linearity as the spring material approaches the elastic limit, and for this reason deflections should ideally be kept to the minimum (5).

To improve resolution the swept length must be as large as possible. The pressure sensor is generally manufactured from beryllium copper or stainless steel, can be an enclosed diaphragm or a capsule or a helical, spiral or c-shaped bourdon tube (5). Contact material and potentiometer wire are selected carefully for optimum wear resistance and resolution.

Temperature errors can be compensated by selection of materials of chosen coefficients of thermal expansion. Positive temperature coefficient of the resistors are used to electrically compensate the variations in the modulus of elasticity of the pressure sensor material. The fact that the temperature errors are essentially those of a mechanical nature ensures that precise temperature compensation can be achieved. Absolute accuracy of ± 0.35% including all errors due to non-linearity hysterisis and repeatability in the temperature band 0° to $40^{\circ}C$ is typical on transducers intended for general industrial use.

The basic design utilised in any pressure transducer is obviously directed at reducing the fundamental errors due to hysterisis, non-linearity and repeatability in the pressure sensor and mechanism.

Wiper-Wire radius : A small wiper diameter favours the early development of flats. A large wiper reduces the precision of the potentiometer. In fine-wire potentiometers of standard design a wiper-wire radius of 10 will normally give satisfactory results (4).

Noise: Thermal noise due to random motion of free electrons is normally small. Typical noise values for fixed carbon resistors are

0.05 μv per volt for 1000 ohm resistor

0.05 μv per volt for 1 M ohm resistor.

Wire wound resistors are free from this type of noise.

Contact noise generated in the wiper wire contact area is caused by variation of contact resistance. Contributors are contact area variation and pressure fluctuation especially in the presence of foreign particles on the track.

Noise due to the contact between dissimilar metals of wiper and track may be reduced to about 100 to 300 μv by suitable combinations of materials for wiper and wire potentiometers which are given in Table 2.3 (4):

Table 2.3 - Wiper and Wire Materials

Wiper material	Winding material
2 to 5% graphite in silver }	Nichrome
10% graphite in copper }	Constantan
40% nickel, 60% silver }	Manganin
Gold }	55% copper 45% nickel
Gold-silver }	(Constantan)

Finally there is vibrational noise, which is caused by jumping or bouncing movement of the wiper. The noise is due to temporary disengagement of wiper and track. For a given wiper-track combination there is a maximum wiper speed which must not be exceeded.

<u>Sensitivity</u> : The sensitivity of an unloaded potentiometer is given in volts for the full scale mechanical travel of the wiper. This voltage is ideally equal to the input voltage across the total potentiometer winding. The input voltage is

set by the wattage dissipated and inturn depends upon the thermal characteristics of materials used. In general the current density in the winding wire should not exceed 5 Amp mm^{-2} (4).

Linearity : The linearity is affected by minimum resolution, mechanical inaccuracies in the wiper movement, irregularities in winding pitch, variations in wire and former dimensions, noise etc. In addition to these with loaded potentiometers there is non-linearity due to the circuit. The linearity can be improved in two different ways (4):

(a) By a non-linear potentiometer of suitable shape to compensate the non-linearity,

(b) By introduction of variable resistance R' of suitable characteristic in series with the load R_L (Fig.2.11).

Fig.2.12(a) shows schematically the first method applied to a potentiometer circuit of given non-linearity.The required non-linear resistance function can be realised by a card-wound potentiometer of a variable winding height h as shown in the Fig. 2.12(b).

Fig.2.13 shows a practical arrangement of a potentiometer with a variable series resistance for linearisation.

Conductive Plastic Potentiometers : Improved performance up to a point where potentiometric resolution is virtually infinite with the related improvement in hysterisis and repeatability can be obtained by introduction of conductive plastic (5). The conductive plastic potentiometer provides a continuous high quality surface finish without the step contours, typical of wire wound potentiometer and this feature together with carefully developed contact technology, combines to produce contacting surfaces which maintain performance under operating conditions in excess of 60 x 10^6 cycles. The conductive track offers the facility of non-linearity correction. Correction techniques consist simply of increasing resistance in local sections of the potentiometer by removing the resistive film with a sharp hand tool or by controlled machining operation. The technique becomes extremely valuable in applications requiring output s non-linear with pressure.

Potentiometer pressure transducers are restricted to stationary industrial installations intended for monitoring and process control (6). The required long wiper travel of about 2.5 mm is obtained from capsules or bourdon tubes. Transducers of this type provide a large voltage swing but resolution is not better than 1%. In addition, progressive wear generates increasingly noisy output.

2.2.2 <u>Straingauge Type</u> :

(a) <u>General Design Considerations for Strainguages</u> :

<u>Strain gauge</u> : Strain gauge consists of a fine resistance wire of about 0.025 mm diameter which is arranged in the form of a grid. The grid is bonded to the structure under test as shown in the Fig.2.14. The bonding layer transmits the surface strain in the structure to the wire, thus producing a change of resistance in the wire, which is proportional to strain. Also since the strain gauge grid has a finite width, the gauge has a sensitivity to transverse strain which may amount to 0.5 to 2

percent of the longitudinal sensitivity (4). The gauge factor quoted by the manufacturer is normally obtained on test rod under tension and is thus related to uniaxial stress involving both longitudinal and transverse strain.

Sensitivity of the Strain gauge: When the strain gauge is exposed to strain with in the elastic limit, two mechanisms with cause a change of its resistance; its geometric form will vary and change of electrical resistivity will occur. The equation relating these effects is (7,8).

$$\frac{dR/R}{dL/L} = 1 + 2\nu + \frac{d\rho/\rho}{dL/L} \quad \ldots \quad \ldots \quad (2.2.1)$$

where ν = Poisson's ratio $= -\frac{dD/D}{dL/L}$

$\frac{dR}{R}$ = Fractional change of resistance

$\frac{dL}{L}$ = Fractional change of length

$\frac{d\rho}{\rho}$ = Fractional change of resistivity.

The term $(1 + 2\nu)$ denotes the geometric effect and the term $\frac{d\rho/\rho}{dL/L}$ denote physical effect as resistivity ρ is related to physical quantities by the equation

$$\frac{1}{\rho} = \frac{ne^2\tau}{m} \quad \ldots \quad \ldots \quad \ldots \quad (2.2.2)$$

where n = no. of electrons, e = charge of electrons

τ = relaxation time m = mass of electron.

The term $\frac{dR/R}{dL/L}$ is called gauge factor or sensitivity factor of the strain gauge. Its value for most commercial strain gauges is about 2 and for semiconductor strain gauges about 20 to 200 (9).

Current Capacity : The amount of current that may safely be used in a strain gauge is a function of the wire resistivity, the grid design, backing material, bonding cement, and heat sink to which they are attached. Gauges bonded to aluminium or steel parts can tolerate more current than those mounted on insulating materials. Paper gauges bonded to metals are limited to 0.025A while backelite types are rated as high as 0.05A. Currents of 0.005 to 0.006 A are recommended on poor conductors such as plastics (9).

Construction and bonding : The following factors must be considered in the construction of resistance strain gauges (4) :

(i) gauge wire material
(ii) shape of gauges and guage manufacture
(iii) gauge backing
(iv) cements
(v) connecting leads
(vi) protection of gauges.

From the manufacturing point of view it is desirable to employ materials which can be handled with ease as a fine wire. Materials for foil gauges must respond to the appropriate etching process. In both cases the gauge material must weld to suitable lead material without danger of electrolyte corrosion. Copper-Nickel alloys such as constantan, ferry and advance are most commonly used.

Flat grid type of construction is normally preferred to wrap around type. In the former type, the grid will be closer to the surface of the structure under strain compared to latter type. Etched foil gauges can be made of very small size.

The gauge backing must provide a strong bond between structure and grid. Its choise depends largely on the cement which must suit both the material of the structure and the gauge material. Table 4 gives summary of application techniques for bonded strain gauges (4):-

Table 2.4 : Summary of application techniques for bonded strain gauges.

gauge backing	Adhesive	gauge material	Remarks
Paper	Cellulose-acetone	Copper-nickel	Useful up to 60°C up to 100°C with increased drift.
Paper or epoxy type	Polyester or cold setting epoxy.	Copper-nickel	useful up to 80°C limitted life.
Phenolic or epoxy type	Heat setting phenolic or epoxy respectively	Copper-nickel	Useful up to 180°C up to 250°C for short periods

The choice of suitable lead material depends upon the resistivity, ability to produce reliable soldered or welded joints and upon corrosion resistance.

Strain gauges must be protected at normal temperatures from the moisture by suitable material. Arranged in rough order of permissible ambient temperatures, they are wax, bitumen, natural, synthetic and silicone rubber, thiocol polyester, epoxy and ceramic cements.

Semi-conductor Strain Gauges : The major advantages of semi-Conductor strain gauges as compared with metal gauges, are their vastly higher gauge factor and their small size. Their disadvantages are non-linearity and temperature instability both requiring sophisticated compensation technique (4,6,10,11).

The current carrying capacity and noise generation do not substantially differ from those of conventional gauges, but semi-conductor material is photo sensitive and gauges must be protected from strong fluctuating light.

As to future trends in strain gauge development generally, the field of semi-conductors is still wide open while conventional gauges have perhaps reached their level of perfection.

Silicon is used almost exclusively as a semi-conductor material, lead materials of semi-conductor gauges are gold, copper, silver or nickel.

By diffusing suitable impurities into selected areas of monolithic pieces of silicon strain sensitive cantilevers and diaphragms can be produced. These sensors may even be integrated with diffused electronic components providing signal modification.

<u>Thin Film Strain Gauges</u> : Thin film techniques have been applied to the manufacture of strain gauges applied directly to a measured surface such as the diaphragm. Such gauges can be made substantially smaller than other equivalent metal strain gauges. A thin insulation substrate is provided to the diaphragm upon which the thin film gauge patern is deposited and finished by a protective layer (4). Because of the close contact between the thin film sensor and the pressure sensitive diaphragm, creep is virtually eliminated and heat transfer is improved, thus permitting higher current densities, i.e. higher outputs than with cemented gauges. The use of thin film semi-conductor gauges has also been investigated with promising results.

~~The different types of strain gauge pressure transducers are given in the following:~~

Various types of strain gauge pressure transducers using strain gauges are discussed below (4):

2.2.2.(c) <u>Cantilever Type</u> : A number of pressure-summing elements in combination with strain gauged cantilevers is shown in the Fig.2.15 ( ). Ideally the cantilever stiffness should be high in comparison with the stiffness of the pressure-summing element in order to suppress the effects of instability and hysterisis inherent in the pressure-summing element. Differential pressure type can be derived from the basic types shown in Fig.2.15 by adding a second pressure chamber with pressure sensing element which is to oppose the movements of the first. In this arrangement the strain gauges need not be in contact with the pressure medium.

2.2.(d) <u>Diaphragm Type</u> : Strain gauges can be directly cemented to a pressure sensing diaphragm to one side or both sides of the diaphragm and wheat stone bridge connection is made. In a typical configuration a complete bridge circuit is formed by using two tensile gauges positioned in a radial direction near the circumference and two compressive gauges in a tangential direction near the centre of the diaphragm, thus taking the advantage of push-pull strains at these locations. Etched foil gauges are commercially available which are designed to cover the whole area of the diaphragm. The strain levels turn out to be disappointingly low if the strain-pressure relationship is to remain linear and the diaphragm stresses to be kept with in safe limits. At small deflections, say less than half the thickness of a thin clamped diaphragm as shown in the Fig.2.16 whose radius a and thickness t at pressure difference p between the two sides has its maximum radial stress near the edges and is given by (4)

$$= \frac{3}{4} p \left(\frac{a}{t}\right)^2 \qquad \ldots \qquad \ldots \qquad \ldots (2.2.3)$$

At higher loads the stress increases non-linearly. For the purpose of practical application table 2.5 is calculated using the equation (2.2.3).

Table 2.5: Pressure, Strain and Stress of Circular Steel Diaphragms with Linear Pressure-strain Relationship.

Ratio $\frac{a}{t}$	Maximum Pressure p Psi	Strain ε	Stress Psi
10	10^4	2.6×10^{-2}	80×10^4
100	1	2.6×10^{-4}	80×10^2
1000	10^{-4}	2.6×10^{-6}	80

Diaphragm aspect ratios of $\frac{a}{t} \approx 100$ are commonly used. In thicker diaphragms ($\frac{a}{t} \longrightarrow 10$) the sensitivity (strain versus pressure) declines and in thinner diaphragms ($\frac{a}{t} \longrightarrow 1000$) the measurable strain values and hence outputs are excessively small. Semi-conductor strain gauges offer a better solution if their shortcommings (non-linearity and thermal instability) are compensated. Advantages of diaphragm type pressure transducers are their simplicity, high natural frequency and therefore low sensitivity to acceleration.

The pressure-sensitive silicon diaphragms with diffused strain gauges also have the shortcommings; non-linearity and thermal instability. The concept of integrating diaphragm and strain gauges with temperature compensating and signal conditioning elements on one piece of single crystal silicon has recently been achieved.

Thin film strain sensor deposited on to a pressure-sensitive metal diaphragm is free from the problems arising from imperfectly bonded gauges. The gauges are in good thermal contact with the diaphragm and if made of suitable alloys, have low thermal instabilities.

2.2.2.(e) Tube (barrel) type : Figure 2.17 shows a cylindrical tube with one closed end. The fluid pressure p is applied to its inside. In a fairly long tube the end restraints can be neglected and we have at the inside of the tube (radius r_1) a tangential stress (4).

$$\sigma_i = p \frac{n^2 + 1}{n^2 - 1} \quad \ldots \quad \ldots \quad (2.2.4)$$

and at the outside of the tube (radius r_o) a smaller tangential stress

$$\sigma_o = \frac{2p}{n^2 - 1} \quad \ldots \quad \ldots \quad (2.2.5)$$

where n is the ratio of outer to inner radius $(\frac{r_o}{r_i})$. In combination with an axial stress of half the value, due to pressure on the ends of the tube the tangential strain in the outside of the tube is

$$\epsilon_o = \frac{\sigma_o}{E}(1 - \frac{1}{2}\nu) = \frac{P(2 - \nu)}{E(n^2 - 1)} \quad \ldots \quad \ldots \quad (2.2.6)$$

E and ν being young's modulus and poissons ratio of the material respectively. In tubes with thin wall (thickness $S = r_o - r_i$) we have

$$\epsilon_o = \frac{Pr_i}{SE}(1 - \tfrac{1}{2}\nu) \quad \ldots \quad \ldots \quad \ldots (2.2.7)$$

The strain ϵ_o obtainable on the outer surface of the barrel is thus inversly proportional to the wall thickness. In practice a wall thickness of 0.0075 inch is probably the smallest reasonable value which can be achieved with a ½" bore. Assuming a working strain of 10^{-3} the lowest pressure ranges possible will be approximately 1000 psi for steel tubes and 300 psi for duralumin tubes. At the other end of the range, instruments of this type have been made for pressures up to 20,000 psi and higher (12).

The arrangement of strain gauges consists of two well insulated and perfectly secured helical windings of strain-gauge wire around the barrel part of the tube, representing the two active arms of the bridge. Two identical compensating windings are bonded to the solid part at the inner end of the tube. Instead of helical windings strain gauges can be bonded to the outside of the tube with compensating gauges on the tail. Transducers of the barrel types are used for both static and dynamic measurements. This type of transducer is not suitable for the measurement of differential pressures due to inequality of inside and outside areas and therefore the differential calibration would exhibit different slopes depending on whether the higher pressure is applied to the inside or outside of the barrel.

A serious disadvantage of the barrel-type strain gauge transducer is its small overload margin. Tubes with elliptical cross sections have better over load ratios and lowest range of about 20 psi.

2.2.3 Bridgman Type : If a metal wire is subjected to pressure exerted from all directions, its resistance will change. This principle has been utilised in Bridgman type pressure transducers. The change of resistance at a pressure p can be shown to be (4,13)

$$\frac{\Delta R}{R} = \frac{p}{E}(1 - 2\nu) + \frac{\Delta \rho}{\rho} \quad \ldots \quad \ldots \quad (2.28)$$

The first term in eq. (2.2.8) represents the geometrical contribution and the second term the charge in resistivity due to pressure. The pressure sensitivity is (4,13)

$$Sp = \frac{\Delta R/R}{P} = \frac{1}{E}(1 - 2\nu) + \frac{1}{P}\left(\frac{\Delta \rho}{\rho}\right) \ldots \qquad \ldots \qquad (2.2.9)$$

values of Sp for a number of wire materials are listed in the Table 2.6.

Table 2.6 : Some Pressure Sensitive Resistance Materials

Material	Resistivity 10^{-6} ohm m	Youngs Modulus 10^{9} N m^{-2}	Bulk modulus K		Sp $10^{-12} m^2 N^{-1}$
Constantan	0.48	150	125	0.30	-7.0
Manganin	0.43	135	132	0.33	+23.5
Bismuth	1.17	23.5	30	0.37	+158

Bridgman type pressure transducers are suitable for very large pressures up to 20,000 Kg/cm^2 (350,000 psi).

Manganin is the most commonly used material since it combines high pressure sensitivity with high temperature stability. The very high pressure sensitivity of the semi-metal bismuth has been exploited in small sensors for the measurement of dynamic pressures. Even carbon compound resistors (eg: 100 ohm 0.1 watt) suspended by fine wires inside a cavity filled with grease, has been used to measure pressure with fair linearity and negligible hysterisis. However, the thermal noise equivalent to about 10 KNm^{-2} sets a lower limit to its useful pressure range. Carbon resistors have also been employed to measure pressure waves. The thermal stability of all carbon compound sensors is rather doubtful.

Bridgman type transducer is the only direct acting pressure transducer in existence. Its advantages over any mechanical gauge are simplicity and ruggedness (13).

2.2.4 Measuring Circuits : In case of potentiometer pressure transducer, the output can be made sufficiently higher so that an indicator can be directly connected without the use of amplifier. In case of strain gauge pressure transducers the strain gauges are connected in bridge formation and output signal is amplified. The consideration for selection of bridge circuit are magnitude of signal output needed, temperature compensation and linearity of output. Commercially available strain indicators or recorders can be used for indicating or recording.

Bridge Connection : Summary of properties of various bridge connection are given in Table 2.7 (14) to which reference may be made in order to select the suitable bridge circuit connection.

Bridge Supply : Besides d.c. energised bridge with chopper amplifier a.c. energised bridges with a.c. amplifiers are becomming common in recent years. The main reasons for superiority of a.c. over d.c. energisation is freedom from contact potentials and thermal voltage errors, simpler a.c. amplifiers as well as cheaper and more reliable than d.c. amplifiers. The disadvantages of a.c. bridges over d.c. bridges are more complexity, the a.c. resistance is different from its d.c. value, a.c. bridges require balancing of inphase and quadrature components (4).

Figure 2.18 shows a scheme for a.c. excited system. Excitation frequency is typically 1000 Hz providing frequency response up to about 100 Hz (9). Since the nominal frequency response is about 10% of the carrier frequency, problems requiring better response will necessitate higher carrier frequencies.

<u>Bridge Balancing</u> : There are two methods of balancing strain gauge bridge circuits (16) :

(1) Series balancing method (Fig.2.20(a))

(2) Parallel balancing method (Fig.2.20(b)).

Series balancing is less frequently used to obtain initial balance because of the difficulty in obtaining the small and precise variations in resistance required. The parallel balancing method is often used to obtain initial bridge balance because, by using a large value for R_{bal} very small changes in resistance between points ad and dc can be produced by moving the centre tap d'.

<u>Temperature Error</u> : Temperature variation causes the change in ΔR due to the following reasons :

(i) Specific resistance of the gauge element changes with temperature hence gauge factor changes with temperature.

(ii) A difference in coefficient of linear expansion of the gauge and the surface to which the gauge is bonded causes a change in grid length which produces the same ΔR as would be produced by stress induced change of gauge length.

Table 2.7: Summary of wheat stone bridge properties.

Bridge connection	Constant voltage drive	Constant current drive
1. One active strain gauge Fig. 2.19(a)	$E_o = E_1 \times \frac{\Delta Rg}{4Rg + 2\Delta Rg}$ E_o Versus Δ Rg is non-linear Temperature errors not self compensating.	$E_o = \frac{I\,Rg\,\Delta Rg}{4Rg + \Delta Rg}$ E_o versus Δ Rg is non-linear
2. Two active Strain guages opposite arms active. Fig.2.19(b)	$E_o = E_1 \frac{\Delta Rg}{2Rg + \Delta Rg}$ E_o versus Δ Rg is non-linear Temperature errors not self compensating.	$E_o = \frac{1}{2}\ I\ \Delta Rg$ E_o versus Δ Rg is linear
3. Two active strain gauges adjacent arms active Fig. 2.19(c)	$E_o = E_1 \times \frac{1}{2} \frac{\Delta R_g}{R_g}$ E_o Versus Δ Rg is linear Temperature errors not self compensating.	$E_o = \frac{1}{2}\ I\ \Delta Rg$ E_o Versus Δ Rg is linear
4. Two active strain gauges adjacent arms active Fig.2.19(d)	$E_o = E_1 \times \frac{2Rg\,\Delta Rg}{4Rg^2 - \Delta Rg^2}$ E_o versus Δ Rg is non-linear Temperature errors self compensating.	$E_o = \frac{1}{2}\ I\ \Delta Rg$ E_o Versus Δ Rg is linear
5. Four active strain gauges Fig. 2.19(e)	$E_o = E_1 \times \frac{\Delta Rg}{Rg}$ E_o versus Δ Rg is linear Temperature errors self compensating.	$E_o = I\ \Delta Rg$ E_o Versus Δ Rg is linear

The following are the most frequently used methods to compensate the temperature effects (13):

(i) Select the proper bridge circuit for self compensating the temperature error (Refer Table 2.7).

(ii) Dummy gauge system: The dummy gauge must be identical to the active gauge and mounted in identical manner so that the temperature effect is same in both gauges. A suitable bridge connection using active and dummy gauges enable cancellation of temperature errors. A variation of this method is also applicable to semi-conductor strain gauges; a p-type silicon gauge (positive gauge factor) is applied in one bridge arm of wheat stone bridge and n-type gauge (negative gauge factor) in the other arm. Both gauges are exposed to the same test sample and both gauges have positive temperature co-efficients, so that the stress sensitivity is increased while the influence of temperature variation is nearly cancelled.

(iii) Pulse Operation: If the temperature variation in a strain gauge is caused by the current passing through the strain gauge, the temperature of the gauges and thus the temperature error will increase with the square of the average current passing through the gauge. However, the higher the current which can be sent through the gauge, the higher will be the output signal from the gauge. A high output signal with a minimum of heating can be obtained by pulse operation. Strain gauges normally operated with potentials between 3.5 V and 14 V dc have been operated satisfactorily with pulses of different durations and amplitudes. Output signals up to 50 times greater than with dc operation have been obtained.

Circuit Considerations for Semi-conductor Strain Gauges: Since the operational resistance variation of semi-conductor strain gauge is large, the non-linearities of bridge circuits comprising these gauges cannot be ignored. With one active strain gauge of initial resistance R connected in a bridge circuit with three similar resistances the output-input voltage ratio is (4)

$$\frac{V_o}{V_i} = \frac{\Delta R}{R}\left(1 - \frac{\Delta R}{2R} + \cdots\cdots\right) \quad \ldots \quad \ldots \quad (2.2.10)$$

on the other hand the non-linear calibration curve of p-type silicon gauges follows the general pattern

$$\frac{\Delta R}{R} = \epsilon\left(C_1 + C_2\,\epsilon + \ldots\ldots\right) \quad \ldots \quad \ldots \quad (2.2.11)$$

Since the two non-linear terms in eq.(2.2.10) and (2.2.11) have opposite signs, compensation can be achieved by making the two ratio arms either smaller or larger than R, thus matching the bridge non-linearity to that of the strain gauge.

Two or four semi-conductor strain gauges operating in push-pull (compression-tension) fashion result in fairly good through not perfect linearity. For semi-conductor strain gauges constant current supply is desirable to get linear output (Table 2.7).

The accuracy of the transducer using semi-conductor strain gauges depends on the delicate balance of individually non-linear and temperature sensitive gauge and circuit characteristics. In this case bridge balancing can be obtained by using a second bridge in parallel with conventional balancing elements and giving an opposing output voltage which just cancels the zero-signal output of the strain-gauge bridge.

2.3 INDUCTIVE PRESSURE TRANSDUCERS

In majority of cases the change of inductance in an inductive pressure transducer is carried out in two stages; First the pressure is arranged to cause a deflection and then this deflection is used to change some parameter of a coil, thus changing its inductance (17). The coil inductance change is used to control electronic circuits to give a voltage output directly proportional to the applied pressure at the input of the transducer. For converting the applied pressure into displacement, any of the pressure sensing elements in Chapter 2.1 can be used with suitable fixtures. Normally ferromagnetic core is used in inductive pressure transducers to obtain the advantages (i) large values of inductance compared to air core (ii) less number of turns are needed to get the same magnitude of inductance as in the air (iii) lesser number of turns also help to reduce the self-capacitance of the coil (2).

The commonly used types of inductive pressure transducers are

(i) Airgap type

(ii) Plunger type

(iii) Transformer (LVDT) type.

In types (i) and (ii) variation of reluctance is utilised and in type (iii) variation of mutual inductance is utilised.

2.3.1. Airgap type : Fig.2.21 shows schematic representation of airgap type transducer. The variable reluctance transducers (airgap type and plunger type) may be considered as the fore funners of the modern LVDT (9). The basic design is given in the following (4) :

The inductance L of a coil of n turns with a ferro-magnetic core of length l (Cms) and cross section A (Cm^2) and a small airgap of g(Cms) is given by the equation

$$L = \frac{4 \pi n^2 \mu A}{l} \times 10^{-9} \text{ Henries} \quad \ldots \quad \ldots (2.3.1)$$

where μ is the effective permeability of the gapped core. The value of μ is

$$\mu = \frac{\mu s}{1 + (\frac{g}{l})\, \mu s} \quad \ldots \quad \ldots \quad \ldots (2.3.2)$$

where μs is the incremental permeability of a ring sample of the core material without airgap.

Combining equations (2.3.1) and (2.3.2) we get

$$L = \frac{4 \pi n^2 A}{10^{-9}} \times \frac{1}{g + \frac{l}{\mu s}} \quad \ldots \quad \ldots \quad (2.3.3)$$

If the airgap decreases by δg, the inductance correspondingly increases by δL

$$L + \delta L = \frac{4\pi n^2 A}{10^{-9}} \times \frac{1}{g - \delta g + \frac{l}{\mu s}} \ldots \quad \ldots \quad (2.3.4)$$

Dividing equation (2.3.4) by (2.3.3) we get

$$1 + \frac{\delta L}{L} = \frac{g + \frac{\ell}{\mu s}}{g - \delta g + \frac{\ell}{\mu s}}$$

$$\therefore \frac{\delta L}{L} = \frac{g + \frac{\ell}{\mu s}}{g - \delta g + \frac{\ell}{\mu s}} - 1 \quad \ldots \quad \ldots \quad (2.3.5)$$

Similarly for increase in airgap we have decrease in inductance and the expression for sensitivity is

$$\frac{\delta L}{L} = 1 - \frac{g + \frac{\ell}{\mu s}}{g + \delta g + \frac{\ell}{\mu s}} \quad \ldots \quad \ldots \quad (2.3.6)$$

Equations (2.3.5) and (2.3.6) enable calculation of sensitivity. Also it is seen by these equations that the change of coil inductance against airgap is non-linearity in the relationship between bridge output compares with pressure. Most transducers of this form would be a compromise between output level and linearity. But the worst case one would expect from this type of transducers is around 2% linearity (17).

The effect of coil resistance R_c is to cause copper loss. R_c can be calculated by using the equation

$$R_c = \frac{4\rho\, ns}{\pi\, d^2} \text{ ohm} \quad \ldots \quad \ldots \quad (2.3.7)$$

where n = no. of turns, s = Length of mean turn

d = diameter of the wire ρ = resistivity of wire material.

The equivalent circuit of the coil is shown in Fig.2.22 R_e represents eddy current loss resistance which comes in shunt with L . C represents the self capacitance of the coil winding. The magnitude of R_e is calculated by using the equation

$$R_e = \frac{2P}{t} \frac{\mathrm{Cosh}(\frac{t}{p}) - \mathrm{Cos}(\frac{t}{p})}{\mathrm{Sinh}(\frac{t}{p}) - \mathrm{Sin}(\frac{t}{p})} \omega L \quad \ldots \quad \ldots \quad (2.3.8)$$

where $P = \frac{1}{2\pi}\sqrt{(\frac{\rho i}{\mu f})} \times 10^{4.5}$ Cm = depth of penetration.

t = thickness of core laminations (Cms)

ρi = Specific resistance of the core material

μ = Permeability of core material

At low frequencies, i.e. $\frac{t}{p}$ values not greater than about 2 the equation (2.3.8) simplifies to

$$R_e \approx \frac{6}{(\frac{t}{p})^2} \omega L = \frac{12 \rho i\ An^2}{lt^2} \quad \ldots \quad \ldots \quad (2.3.9)$$

The effect of shunt capacitance C is to increase the sensitivity according to the approach of resonance conditions in such a circuit (4).

Some further advantages in terms of performance can be achieved by using push-pull arrangement, i.e. one coil inductance increases while the other decreases. The resultant output will be as shown in Fig.2.23. By this way linearity of response is improved. Fig.2.24 shows a practical schematic drawing of a pressure transducer using this idea. Here a single armature is used and a coil is mounted on either side(9).The pressure is applied to one side of the diaphragm via an appropriate port and if so desired one can apply a varying reference to the other side. The advantages of a system such as this are high output and better linearity. To obtain good linearity the fractional change of gap length must be kept small. This leads to low sensitivity and it is the designer's task to strike a compromise between the two conflicting requirements. As a rough guide the designer should aim at a fractional change of inductance of about 0.1 to 0.2. In such a transducer, assuming push-pull action, the non-linearity will be about 1 to 3 percent at full scale deflection. The hysterisis loss can be safely neglected if very low flux densities are used. Residual losses are also negligible in laminated cores compared with eddy current losses, but may be of some importance in ferrite cores at higher frequencies.

The ideal design of pressure transducers would be insensitive to any external effects, such as temperature, external magnetic fields, vibration or shock and compactness. If we consider the differential pressure transducer explained above we find that the magnetic circuit is extremely close coupled, so leading to high sensitivity and efficiency. The magnetic circuit itself form the shield and symmetry of the arrangement ensures self cancellation of temperature effects by proper matching.

2.3.2 <u>Plunger type</u> : In this type of transducer variation of reluctance in the leakage paths of a coil by movement of a plunger is utilised for transduction. The inductance of the coil depends upon the length of that part of the ferromagnetic core which has penetrated into the coil. Fig.2.25 shows the plunger type transducer with single coil arrangement and the corresponding distribution of magnetic field strength along the axis. Fig.2.26 shows push-pull coil arrangement and the corresponding distribution of magnetic field strength along the axis.

The fractional change of inductance in coil I (Fig.27) when the core is pushed into coil I can be shown to be

$$\frac{\delta L}{L} = \frac{\delta l_c}{l_c} \; \frac{1}{1 + \left(\frac{l}{l_c}\right)\left(\frac{r}{r_c}\right)^2\left(\frac{1}{\mu_m - 1}\right)} \quad \ldots \quad \ldots \quad (2.3.10)$$

where μ_m is the effective permeability of the ferromagnetic core in this arrangement (4). In a similar way coil II suffers an identical change of inductance of opposite sign. It is seen from the equation (2.3.10) that the maximum sensitivity is obtained by making the ratio $\frac{l}{l_c}$ and $\frac{r}{r_c}$ to approach unity and u_m should be as large as possible.

Performance of plunger type transducers are inferior to airgap type for most applications due to the following reasons (4) :

(a) Because of the large air path, i.e. the high reluctance of the magnetic path, the sensitivity to a given mechanical movement is lower than the airgap type.

(b) Long air path in plunger type needs large number of turns in order to raise the inductance value to that of air gap type. This increases the self capacitance of the coil which at higher frequencies may bring the inductance and capacitance combination to resonance. The cable length connected to the plunger type transducer must also be limitted in order to reduce the capacitive effect.

(c) Since the diameter of the plunger has to be quite small, in the majority of the transducers it is usually made of solid mild steel. This results in large losses.

(d) Because large portions of the magnetic path are in air it has an appreciable stray field and is therefore open to pick up from external fields.

(e) The shape of the coil or coil halves must be identical and should be geometrically stable for linearity and stability of the calibration curve. The air gap type, since it does not operate on the leakage flux distribution, is to a great extent independent of the shape of the coil.

Improved performance of plunger type inductance transducers can be obtained by using E-shaped laminated cores as shown in Fig.2.27. In this case the leakage flux is considerably reduced and thus pick up from external fields is small. This type is a compromise between a plunger and airgap type.

The main advantage of the plunger-type inductance transducer is its longer linear range compared with the more sensitive airgap type. At lower frequencies the plunger type can be used with advantage. However LVDT type also provides longer linear range and is of superior design.

2.3.3. <u>Transformer (LVDT) type</u> : These transducers consist of primary and secondary coils, the coupling of which is altered in proportion to the measurand. With one secondary coil, there will be large induced voltage in the secondary in the no-signal position. With two coils in secondary and connecting them in opposition zero (negligibly small) voltage can be obtained in the no-signal position. This arrangement forms the basic idea of the LVDT.

Fig.2.28(a) shows the LVDT coil and core arrangement and Fig.2.28(b) shows the ideal leakage flux distribution when the core is in null position. The leakage flux density can be calculated by using the equations(4)

$$B_{L_1} = \frac{2L_2 + b}{L_a} \; \frac{2 \pi \, np \, Ip}{10^7 \, r_1 \log_e(\frac{r_o}{r_1})} \quad \text{and} \quad \ldots \qquad \ldots (2.3.11)$$

$$B_{L_2} = - \frac{2L_1 + b}{L_a} \; \frac{2 \pi \, np \, Ip}{10^7 \, r_1 \log_e(\frac{r_o}{r_1})} \quad \ldots \qquad \ldots (2.3.12)$$

When the two secondaries are connected in opposition, the differential voltage e developed for the armature displacement x can be calculated using the equation

$$e = \frac{16 \pi^3 \, fIp \, np \, ns}{10^7 \log(\frac{r_o}{r_1})} \; \frac{2b}{3m} \left(1 - \frac{x^2}{2b^2}\right) \ldots \qquad \ldots (2.3.13)$$

where f = Frequency of the input supply

I_p = Primary current

n_p = Primary no. of turns

n_s = Secondary no. of turns

b = Length of primary

m = Length of secondary

r_o = Outer radius of the coil

r_i = Inner radius of the coil

The following relations are used for designing the LVDT (1,4,9):

(1) Length of primary (b) :

$$b = \frac{X_{max}}{\sqrt{2\epsilon}} \quad \dots \quad \dots \quad \dots (2.3.14)$$

where X_{max} = maximum displacement of the armature

ϵ = tolerated error of non-linearity in %.

(2) Length of secondary(m) :

$$m = b + X_{max} + \delta \quad \dots \quad \dots \quad (2.3.15)$$

where δ = a small fraction of armature diameter added to avoid emergence of the armature from the coils at maximum displacement.

(3) Length of armature (L_a) :

$$L_a = 3b + 2d \quad \dots \quad \dots \quad (2.3.16)$$

(4) Armature radius (r_i) may be chosen as a reasonable fraction of armature length, say $\frac{r_i}{L_a} = 0.05$

(5) Coil radius (r_o) :

$\frac{r_o}{r_i}$ ratio is selected generally between 2 and 8.

(6) Primary number of turns n_p is selected by considering available space for winding and supply frequency (self capacitance). Primary current I_p depends on primary voltage and coil impedance. Lower values of current is desirable.

(7) The number of secondary turns must be as large as possible when feeding into a high impedance or made to match the load impedance.

(8) Output voltage is calculated using equation (2.3.13). Sensitivity $\frac{e}{x}$ can then be claculated. At low frequencies say below 500 Hertz the computed and measured sensitivities are in good agreement when solid iron cores are used. At higher frequencies the sensitivity drops appreciably and at about 2000 Hertz it may be little more than half of the theoretical value. This is due to eddy current losses in the core and stator which is ignored while deriving equation (2.3.13). Therefore at higher frequencies cores made up of thin laminations or of magnetic materials of high permeability such as ferrites which have negligible eddy current losses are used. The rated sensitivity of an LVDT is usually stated interms of milli volts of output per 0.001 inch core displacement per volt of primary excitation.

Fig.2.29(a) shows the typical frequency versus output characteristic and Fig.2.29(b) shows the displacement versus output characteristic of LVDT.

<u>Phase Characteristics</u>: The phase angle of the output voltage with respect to input voltage has two values differing by 180°, depending on whether the core is on one side of null or the other. To calculate the phase angle of the primary current with respect to the input voltage, the following approximate relation is used:

$$\tan \phi = -\frac{2\pi f L_p}{R_p}$$

where L_p = primary inductance and R_p = primary resistance, the negative sign indicates that the current lags the voltage. The phase of the output voltage can be calculated if secondary resistance and inductance and the load impedance are known (1).

<u>Null voltage</u> : The null voltage is composed of three components: quadrature voltage, harmonics and noise. Minimum null results when the amplitudes of the two secondaries are equal (Magnitude balance). The difference in phase angle between the output voltages of the two secondaries should be zero (phase balance). However, non symmetrical windings, non uniform wiring and unsymmetrical magnetic circuits cause slight phase angle differences. Losses in the magnetic materials in the LVDT are the basic source of harmonics. The third harmonic is the major component of the harmonics present in the output. The null position of the harmonics is located at a different point from that of the fundamental (harmonic balance)(9).

For magnitude balance, the two secondaries must be having identical number of turns. A practical solution to correct the phase angle difference is to place a potentiometer and a variable capacitor across one of the windings and adjust it until the phase shift is zero. The effect of third harmonics can be eliminated by putting a low pass filter in the output circuit. By putting a capacitive load across the output the noise can be reduced (1). To sum up, the following design consideration should be taken into account for obtaining minimum null voltage(4) :

(1) The two coil halves and the core must be as symmetric as possible.

(2) Operate the LVDT at low level primary current and low loss and high saturation value magnetic material is to be used to reduce generation of harmonics.

(3) Proper matching of transducer and load is also advisable, for the residual voltage will increase at frequencies below as well as above the flat part of the frequency response curve of the LVDT.

(4) Residual voltages of the fundamental can be corrected by the addition of resistive and/or capacitive balance controls, but residuals due to harmonics cannot be reduced by these means. However as in the case of a.c. bridge techniques, they can be eliminated by using phase sensitive discrimination in the indicator circuit.

Temperature Characteristics : Change in resistance due to temperature alters the current and flux generated and results in change of sensitivity. At high frequencies, inductive reactance (which is unaffected by temperature) becomes the predominant part of the impedance, and resistance variations have less effect. Typically the change in sensitivity at low frequencies is about 10 to 12% for a temperature increase of 100°F. Due to temperature variation the phase angle shift also occurs which result in shift of null position. For every LVDT on optimum excitation frequency exists where losses and gains balance and produce no change in sensitivity due to thermal effects. Null shift has very little effect on the sensitivity. Manganin wire may be substituted for copper wire if the temperature effects are to be reduced, but the sensitivity drops to about $\frac{1}{5}$ th of copper coils due to higher resistivity of manganin. At higher frequencies when inductive reactance becomes dominent manganin may be used more efficiently (1,9,18).

<u>Construction of Cores and Coils</u> : The basic requirements for a good core material are high permeability and low losses to obtain high sensitivity and less space. The core material must also permit operation at reasonably high flux densities without excessive generation of harmonics. Secondary requirements are low cost, good availability and the ease with which a core can be shaped and assembled.

Inductive transducers mostly have long air path, there by the reluctance of the iron path becomes almost negligible in comparison with that of the air path. This also results in reduced core losses.

Ferrites are now widely used in transducer work even at relatively low carrier frequencies (4). They have high permeability, and their specific resistance is about 10^6 times higher than that of other ferromagnetic materials hence eddy current losses are negligible. Hysterisis losses are also small. The residual losses (capacitive losses due to stray) may become prominent at higher frequencies. For transducer work the most commonly used ferrite is Ferrox cube A (manganese-zinc ferrites). Maximum temperature is limitted by curie temperature.

The advantages of the LVDT are as follows(9) :

(1) Infinite resolution — the change of voltage is stepless.

(2) High sensitivity — as high as 1V/0.001 inch.

(3) Good linearity — 0.05% linearity is commercially available.

(4) Ruggedness — usually can tolerate a high degree of shock and vibration without degradation of performance.

(5) Low hysterisis — repeatability is excellent under all conditions.

2.3.4 Measuring Circuits : There are several basic circuits suitable for use with inductive transducer. The selection of the particular circuit depends on various factors such as consideration for amplication, null indication etc. Some of the basic circuits are briefly discussed below (4) :

(1) A.C. potentiometer circuit : Fig.2.30 shows the variable inductance coil whose inductance is L and resistance is R_s connected with a series resistance R. Z is the coil impedance. Output voltage across the transducer coil E_o is

$$E_o = \frac{Z}{R + Z} E_i \quad \ldots \quad \ldots \quad (2.3.17)$$

If Z changes to $Z + \delta Z$ then E_o changes to $E_o + \delta E_o$. Hence

$$E_o + \delta E_o = \frac{Z + \delta Z}{R + Z + \delta Z} E_i \quad \ldots \qquad \ldots (2.3.18)$$

Subtracting equation (2.3.17) by (2.3.18) and rearranging after simplification we get

$$\delta E_o = E_i \frac{R/Z}{R/Z + 1} \; \frac{\delta Z/Z}{R/Z + \frac{\delta Z}{Z} + 1} \quad \ldots \qquad \ldots (2.3.19)$$

Equation (2.3.19) shows the output voltage is non-linear. Also for high sensitivity $\frac{\delta E_o}{E_i}$, $\frac{R}{Z}$ must be small and for good linearity $\frac{R}{Z}$ must be large. In other words the effect of increase in R is to improve linearity and to decrease sensitivity and there fore proper value of R is to be carefully selected. Output voltage E_o is normally fed into high input impedance amplifier.

(2) Series circuit : Fig. 2.31 shows the circuit of inductance transducer in series with the meter. This circuit is useful if a current output is required to operate a current meter or galvanometer recorder without amplification. The effect of the shunting capacitor c is to compensate the non-linearity in inductance change for air gap changes.

(3) A.C. bridge circuits : Majority of inductance transducers are used with a.c. bridges. The basic configuration normally employed with inductance transducer is shown in the Fig. 2.32. The main advantage of a.c. bridge is push-pull

inductance transducer can be connected into adjacent arms of the bridge and any equal changes in the two coils are cancelled out in the output. This is an obvious advantage if the transducer is used at variable temperatures. If the resistive changes are ignored for a first approximation the output voltage $E_o = \frac{1}{2} E_i \frac{\delta L}{L}$. The indicator can be made to discriminate between a +ve and -ve signal by using phase-sensitive demodulator before feeding to the indicator. Carrier frequency must be about 10 times the signal frequency in order to cope with the highest signal frequency the transducer is designed to respond to.

A typical scheme commonly used for strain gauges, inductance transducers and LVDT's is shown in the block diagram of Fig.2.3.3. Typically carrier oscillator frequency is 5 KHz, and amplitude 0.1 to 5 Volts rms (7).

(4) <u>Oscillator Circuits</u> : The inductance change is utilised to cause proportionate frequency change of an oscillator by connecting the inductance transducer in the tank circuit of the oscillator. Normally single coil transducers are used. Therefore their calibration curve (inductance versus airgap) is non-linear but since the frequency is proportional to $\sqrt{\frac{1}{Lc}}$, the frequency versus airgap curve is of better linearity and may be satisfactory if moderate changes of inductance are required. Since the single coil transducer is not temperature compensated, push-pull arrangements in

which each transducer coil frequency modulates a high frequency oscillator and the beat frequency of both oscillators can thus be obtained featuring better linearity and temperature compensation.

2.4 CAPACITIVE PRESSURE TRANSDUCERS

In capacitive pressure transducers the deflection of the pressure sensing element is converted to change of capacitance. This change of capacitance is indicative of the magnitude of pressure acting on the pressure sensing element. The variable distance type of arrangement is used in most of the pressure transducer as this method is convenient to detect small displacements. The formulae for calculating capacitance and sensitivity are given in the following (4) :

(1) Two parallel plates of area A square cms. in air ($\epsilon \approx 1$) separated by a distance d cms. (Fig.2.34) will have capacitance c (pico-farads) given by

$$c = 0.0885 \frac{A}{d} \quad \ldots \quad \ldots \quad \ldots (2.4.1)$$

If the distance between the plates decreases by δd, then the capacitance increases by δc. Hence we have

$$c + \delta c = 0.0885 \frac{A}{d - \delta d} \quad \ldots \quad \ldots \quad (2.4.2)$$

Subtracting equation (2.4.1) by (2.4.2) and simplification gives

$$\delta c = 0.0885 \frac{A}{d} \times \frac{\delta d}{d - \delta d} \quad \ldots \quad \ldots \quad (2.4.3)$$

The fractional change of capacitance (sensitivity) is obtained by dividing equation (2.4.3) by equation (2.4.1).

$$\frac{\delta c}{c} = \frac{\delta d}{d - \delta d} \quad \ldots \quad \ldots \quad (2.4.4)$$

Equation (2.4.4) shows that the fractional change of capacitance is non-linear. To improve linearity d must be very large compared to δd, but this reduces sensitivity $(\frac{\delta c}{c})$. Hence a good compromise is to be made.

(2) Two parallel plates in air ($\epsilon = 1$) separated by distance d (cms) with a solid dielectric of thickness d_2(cms) and dielectric constant ϵ is inserted. The air gap thickness is d_1(cms) where $d_1 = d - d_2$ (Fig.2.35) :

The capacitance of the combination is

$$c = 0.0885 \frac{A}{(d_1 + \frac{d_2}{\epsilon})} \text{ P.F.} \quad \ldots \quad \ldots \quad (2.4.5)$$

If the airgap is decreased by δd_1, the capacitance will increase by δc. Hence

$$c + \delta c = \frac{0.0885\ A}{(d_1 - \delta d_1 + \frac{d_2}{\epsilon})} \quad \ldots \quad \ldots \quad (2.4.6)$$

Subtracting eq.(2.4.5) by (2.4.6) and simplifying

$$\delta c = \frac{0.0885\ A\ \delta d_1}{(d_1 + \frac{d_2}{\epsilon})(d_1 - \delta d_1 + \frac{d_2}{\epsilon})} \quad \ldots \quad \ldots \quad (2.4.7)$$

The fractional change in capacitance is given by

$$\frac{\delta c}{c} = \frac{\delta d_1}{d_1 - \delta d_1 + \frac{d_2}{\epsilon}} \quad \ldots \quad \ldots \quad (2.4.8)$$

In this case also for linearity $d_1 + \frac{d_2}{\epsilon}$ must be large compared to δd_1 but the same increase in $d_1 + \frac{d_2}{\epsilon}$ decreases sensitivity. Also sensitivity and non-linearity increases with increasing ϕ .

By connecting two variable capacitances in push-pull linearity can be improved.

The following types of capacitive pressure transducers are most commonly used (4):

(1) Membrane type

(2) Thin plate type.

2.4.1 Membrane type : Fig.2.3.6 shows the schematic diagram of this type of pressure transducer (4). When acted by pressure, the deflection profile will be spherical as shown in the Fig.2.3.6. For small deflection $(\frac{h}{a})^2 << 1$ the deflection y of a point at a distance r is given by

$$y = \frac{p}{4s}(a^2 - r^2) \quad \ldots \quad \ldots \quad \ldots (2.4.9)$$

The fractional change in capacitance is

$$\frac{\delta c}{c} = 0.125\,\frac{a^2 p}{sd} \quad \ldots \quad \ldots \quad \ldots (2.4.10)$$

For small deflections the sensitivity $\frac{\delta c}{c}$ of a capacitive pressure transducer with a membrane is directly proportional to the applied fluid pressure p and to the square of the diaphragm radius a and inversly propårtional to the tension s in the diaphragm and to the initial airgap d between undeflected membrane and the fixed electrode.

If we assume piston-like movement then the deflection will be uniform and the sensitivity can be shown to be

$$\frac{\delta c}{c} = 0.25 \frac{a^2 p}{sd} \quad \ldots \quad \ldots \quad \ldots (2.4.11)$$

Equation (2.4.11) shows that sensitivity calculation made on the assumption of piston type movement produces twice the actual value as calculated by equation (2.4.10), showing that the assumption is leading to erroneous value of sensitivity.

The above results are applicable only to static deflections since the cushioning effect of thin layer of air behind the diaphragm has been neglected. This air cushion increases the stiffness and thus reduces the sensitivity to dynamic pressures. Also the mass of the air layer which is in contact with the diaphragm may be of the same order as that of the diaphragm itself. Its effect on the dynamic sensitivity and frequency response is also ignored.

2.4.2 Thin plate type : Transducers using thin plate clamped around the edge is also commonly used. Fig. 2.37 shows the schematic diagram of clamped thin plate transducer. The deflection y at any radius r is (4)

$$y = \frac{3}{16} p \frac{(1 - \nu^2)}{Et^3} (a^2 - r^2)^2 \quad \ldots \quad \ldots (2.4.12)$$

where p = fluid pressure (K_g/cm^2)

a = radius of circular diaphragm (cm)

t = thickness of diaphragm (plate) (cm)

E = Young's modulus (K_g/cm^2)

ν = poissons ratio

The fractional change of capacitance is

$$\frac{\delta c}{c} = 0.0625 \frac{(1-\nu^2)\, a^4}{Ed\, t^3}\, p \quad \ldots \qquad \ldots \quad (2.4.13)$$

Equation (2.4.13) shows that the sensitivity of a transducer using thin clamped plate at small deflections is directly proportional to the fluid pressure p and to the fourth power of the thinplate radius a. It is also inversly proportional to the cube of the diaphragm thickness t, to a material ratio $\frac{E}{1-\nu^2}$ and to the initial airgap d between the undeflected diaphragm and the fixed electrode. If we compare this sensitivity to the fictitious sensitivity assuming piston like movement, the actual sensitivity is only $\frac{1}{3}$ of the fictitious sensitivity. The discrepancy is here even greater than in the case of membrane.

Constructional details for capacitive transducers : Since the electrodes, although insulated from each other, must be connected mechanically. Solid supports made out of insulation materials must be used. The insulation material must have sufficient mechanical strength and high form stability. Its thermal coefficient of expansion should be as low as possible. In some cases its thermal coefficient of expansion should match with that of other structural parts of the transducer so as to compensate the thermal effects. Ceramic insulation materials are generally a better choise than plastics or organic materials.

The metal parts, diaphragm, electrodes and supports also require a high degree of form stability. Low expansion and high temperature alloys of the nickel-iron type can be considered, though they are difficult to machine. The faces of the variable condenser plates inside the transducer cannot normally be cleaned in use. The airgap must therefore be protected from humidity and condensation as well as from corrosion and dust. Rhodium plating has proved useful and is a necessity for electrodes immersed in liquid. Metal and alloy combinations used in the design of the transducer must be chosen to avoid electrolytic corrosion, especially if the transducer cannot be effectively sealed against the atmosphere. The transducer housing must be made absolutely rigid to avoid any distortion when mounted on uneven surfaces, or the sensitive condenser unit inside the housing must be mechanically insulated from the housing.

Electrostatic screening of capacitance transducer leads is essential and should be screened up to the transducer housing. For this purpose a convenient length of cable is usually made an integral part of the transducer.

2.4.3. Measuring Circuits : The following basic circuits are commonly used in connection with capacitive transducers :

(1) A.C. bridge circuit
(2) Twin 'T' circuit
(3) Oscillator circuits.

(1) A.C. bridge circuit : Maxwell's capacitance bridge can be used. Fig.2.38 shows the basic bridge circuit. Output of the bridge for differential capacitor arrangement c_1 and c_2 will be linear (19). Balancing may be difficult if the magnitude of stray capacitances is large. Use of transformer ratio bridge simplifies screening and earthing problems and stray capacitance effect can be eliminated, thereby zero-stability of the circuit is greatly improved. The circuit is now widely used in capacitance transducer work and it is also useful in a.c. bridges for inductance and resistance transducers especially at higher carrier frequencies (4).

(2) Twin 'T' circuit : Fig. 2.39 shows the twin 'T' network. This circuit solves phase shift and grounding problem of Maxwells bridge. The twin 'T' network transforms capacitance changes due to pressure differentials into an output voltage (1,13,22). s is source c_1 and c_2 are the transducer capacitors. Capacitor c_1 is charged during one-half cycle of the applied ac through diode D_1, it discharges during the subsequent half cycle through the resistances R_1 and R_L to a common side or ground. Similarly, c_2 becomes charged and discharges 180 electrical degrees out of phase with c_1. The d.c. output voltage across R_L is a result of the difference of the average currents flowing through R_1 and R_2. When C_1, D_1 and R_1 are identical to C_2, D_2 and R_2 the average current through R_L is zero. This is the zero pressure condition for the transducer. A change in the position of the diaphragm will produce a net current through R_L proportional to

the change between C_1 and C_2. The sensitivity of the system reaches maximum if the time constants C_1R_1 and C_2R_2 are of the same order of magnitude as the period of the source voltage E_1. The circuit has further advantage that the source, the transducer capacitor, the balancing capacitor, and the output meter are all connected to ground.

(3) <u>Oscillator circuits</u> : The change in capacitance can be measured by connecting it in the tank circuit of the oscillator. Fig.2.40 shows a circuit diagram of astable multivibrator with the indicator connected as shown. The transducer may be connected in place of C_1 or C_2. The output voltage to the meter m can be shown to be (20)

$$V = V_o \frac{\Delta C/2C}{1 + \frac{\Delta C}{2C}} \qquad \text{when } R_1 = R_2 = R \text{ and } C_1 = C_2 = C$$

This shows the response is non-linear. Better linearity and sensitivity can be obtained by using monostable multivibrator.

A.C. bridge circuits amplitude modulates the signal. Other forms of modulation such as frequency and pulse modulation have also been used (21).

2.5. PIEZO-ELECTRIC PRESSURE TRANSDUCERS

Piezo-electric transducers are force sensitive-devices. They are essentially force measuring instruments of negligible deformation under load. Their mechanical stiffness is very high and has high natural frequency. They can be made very small in dimensions. The main draw backs of piezoelectric transducers are their lack of steady-state response and their high electrical output impedance, coupled with the need for low-noise cables of low capacitance value. The maximum working temperatures of most piezoelectric materials are in the neighbourhood of 200 to 250°C and above this value of temperature loss of insulation resistance sets a practical limit.

The equivalent circuit for piezo-electric crystal is shown in Fig.2.41(a). C_E and R_E represent the capacitance and shunt resistance (losses and leakage resistance) of the transducer element, C_L and R_L are the capacitance and resistance of the load (cathode follower) and C_C is the capacitance of the cable between transducer and load (4). For all practical purposes the resistances and the capacitances can be lumped into the total parallel resistance R and the total parallel capacitance C as shown in Fig.2.41(b). Typical values for R and C are $R = 2 \times 10^{10}$ ohms and $C = 5 \times 10^{-14}$ farad.

Piezo-electric pressure transducers measure dynamic pressures only. They donot respond to steady state pressures. Commercial applications comprise microphones, hydrophones, blast pressure gauges and engine indicators (1). Piezo-electric material used extensively are quartz (natural) and Leadzirconate titanate (synthetic). The most commonly used piezo-electric pressure transducer is pre-loaded crystal pile type. Details of the same ~~is~~ are given in the following (4):

2.5.1 Pre-loaded crystal type : The sensing element consists of a pair or a pile of pairs of quartz discs as shown schematically in the Fig.2.42. The optically flat faces of the quartz crystals are held between similarly flat metal faces of the load plate and the transducer body by way of a pre-loading spring of stiffness K_2, K_1 being the stiffness of the crystal pile. It has been shown that high natural frequencies are achieved only if residual air between the faces is removed by a high pre-load (say 50 - 100 K_g for disks of 6 to 10 mm diameter). Bending of the loading plate or the housing would have similar detrimental effects on the natural frequency and may also cause non-linearity of calibration.

The force p produced by the external pressure is split into the force in the crystal pile P_1 and a force in the preloading spring p_2 with a pile deflection δx we have

$$
\begin{aligned}
P &= P_1 + P_2 \qquad \ldots \qquad \ldots \qquad \ldots (2.5.1)\\
&= K_1\delta x + K_2\delta x\\
&= K_1\delta x\left(1 + \frac{K_2}{K_1}\right)\\
&= P_1\left(1 + \frac{K_2}{K_1}\right)
\end{aligned}
$$

$$
\therefore \frac{P_1}{P} = \frac{1}{1 + \frac{K_2}{K_1}} \qquad \ldots \qquad \ldots \qquad \ldots (2.5.2)
$$

Equation (2.5.2) gives sensitivity which increases with decreasing $\frac{K_2}{K_1}$ i.e. at a given pile stiffness it increases with the flexibility of the loading springs. Linearity is obtained only if $\frac{K_2}{K_1}$ remains constant over the pressure range, i.e. at high pre-loads when air cushioning is eliminated and bending stresses are swamped. The natural frequency will be about 30 to 50 KH_z. In the earlier designs the pre-load was obtained from a relatively stiff diaphragm which also served as gas seal (Fig.2.43(a)). The main disadvantages were temperature sensitivity, due to variable pre-load with temperature, and non-linearity even at high values of pre-loads. A better arrangement is shown in Fig.2.43(b) where pre-load is provided by a thin-walled tube under tension, the sealing being provided by a very thin diaphragm of flexible material.

Techniques and transducers for the measurement of airblast pressures and for under water pressure transients are usually classified. In these the transducers should be non-directional which could be achieved by a spherical sensing element, of small size compared to the wave length of the pressure wave. For practical purposes a small cylinder is the next best choise.

Piezo-electric pressure transducers can be designed for pressures ranging from about 0.5 psi to the order of 10,000 psi. Sensitivities of 0.15 PF/psi to 1 PF/psi has been obtained(1)

2.5.2 Measuring circuits : Conventional voltage amplifiers are normally unsuitable to use with piezo-electric transducers because of their relatively low input impedances. In the past electrometervalve input stages and cathode-follower circuits have been employed. They offer high input impedances, but voltage amplifiers are limited in their frequency response, particularly at the low-frequency end. Since the output voltage also depends on cable capacitance piezo-electric measuring systems using voltage amplifiers must be recalibrated when changing the transducer cable. Charge amplifiers are now in almost exclusive use with piezo-electric transducers (4).

The equivalent circuit of piezo-electric transducer with charge amplifier is shown in the Fig.2.4.4(a). Battery of voltage E, capacitors C_1 and ΔC_1 comprises the piezo-electric crystal equivalent circuit (23). The charge amplifier employs capacitance feedback. As the capacitance ΔC_1 varies, the charge also changes according to the equation.

$$\Delta q = \Delta C_1 E \qquad \ldots \qquad \ldots \qquad (2.5.3)$$

This charge flows into the feedback capacitor C_F through the inverting input terminal. The resultant change in charge C_F generates an output voltage

$$E_o = -\Delta C_1 \frac{E}{C_F} \qquad \ldots \qquad \ldots \qquad (2.5.4)$$

Since the operational amplifier requires a d.c. path in the feedback circuit it is necessary to insert resistance R_F. In the absence of this resistor the capacitors will build up a d.c. charge until the output voltage reaches saturation. This resistor limits the lower cut off frequency of the charge amplifier. For stabilisation purposes and sometimes for protection of the amplifier input stage, it is also desirable to insert the series resistor R_F. This resistor limits the upper response frequency as shown in the Fig. 2.4.4(b). From the equation (2.5.4) we see gain of the amplifier is

$$\frac{e_o}{\Delta C_1} = -\frac{E}{C_F}$$

and can be varied only by changes in C_F. It is usually desirable to use a small value of C_F consistent with the desired frequency response and a reasonable value of R_F. The output voltage is substantially independent of cable length.

Temperature variations affect charge sensitivity, of piezo-electric materials. All piezo-electric materials suffer from loss of insulation resistance when water vapour is allowed to condense on their faces. Piezo-electric materials having a volume-expander mode produce spurious signals if exposed to high intensity air-borne noise. Cable noise can be caused by the electrostrictive properties of teflon and pvc. Also changes may be generated by friction and electrostatic induction due to whipping and twisting the cable during calibration and measurement. Special low noise cables must be used (4).

CHAPTER 3

PRESSURE TRANSDUCERS DESIGNED, FABRICATED AND TESTED FOR VERY LOW RANGE WIND PRESSURE MEASUREMENT

Pressure transducers using the diaphragm as sensing element are the most convenient to design and fabricate. For transduction strain gauges, LVDT or capacitive element can be used. For higher pressure ranges, design of pressure transducer utilising the above sensing and transduction elements is more reliable as compared with design of the same for very low pressure ranges at which diaphragm deflections will be very small and corresponding signal level also will be small. In the following pages discussion of the above three types of pressure transducers designed and fabricated for measurement of very low wind pressures (range 0 to 70 cms. of water) is given.

3.1 STRAIN GAUGE TYPE

Strain gauge pressure transducers using bonded wire strain gauges have been designed for low pressure ranges of the order of 0 to 10 psi (17). In a typical transducer of this range four active strain gauges cemented on one side of the diaphragm such that the two strain gauges cemented at the center will sense the maximum radial stress and the other two cemented at the edges will sense the maximum bending stress. Fluid to be measured may be allowed to one side of the diaphragm so that it will not come in contact with the strain gauges, featuring the use of the transducer for liquids also.

We can show that by fixing four strain gauges two on each side of the diaphragm to sense maximum bending stresses, the sensitivity can be improved. As the strain gauges will have to come in contact with the measured fluid, this arrangement is satisfactory for air only. The details of the transducers designed and fabricated are given in the following :

3.1.1 Design and fabrication :

(a) Location of the strain gauge position on the diaphragm : The place at which the strain gauge is to be cemented is based on the consideration of the strain that the gauge is expected to sense. We can derive an expression relating the change of resistance ($\triangle R_g$) of the strain gauge and pressure (p) acting on the clamped diaphragm as follows:

Fig.3.1. shows the drawing of the transducer. When the diaphragm is subjected to uniform pressure p, the shape of the deflection curve is as shown in the Fig.2.8(b). The radial and tangential stresses (S_r and S_t respectively) at any point on the low pressure surface of the clamped diaphragm is given by the equations

$$S_r = \frac{3\ PR^2 \nu}{8\ t^2} \left(\frac{1}{\nu} + 1\right) - \left(\frac{3}{\nu} + 1\right)\left(\frac{r}{R}\right)^2 \qquad \ldots \qquad (3.1.1)$$

$$S_t = \frac{3\ PR^2 \nu}{8\ t^2} \left(\frac{1}{\nu} + 1\right) - \left(\frac{1}{\nu} + 3\right)\left(\frac{r}{R}\right)^2 \qquad \ldots \qquad (3.1.2)$$

where r is the radius of any point at which S_r and S_t are considered (7).

From equations (3.1.1) and (3.1.2) when $r = 0$, i.e. at the centre

$$S_r = S_t = \frac{3PR^2 \nu}{8\,t^2} \left[\frac{1}{\nu} + 1\right] \quad \ldots \quad \ldots \qquad (3.1.3)$$

and when $r = R$, i.e. at the edge, we have

$$S_r = -\frac{3}{4}\frac{PR^2}{t^2} \quad \ldots \quad \ldots \qquad (3.1.4)$$

$$S_t = -\frac{3}{4}\,\frac{PR^2 \nu}{t^2} \quad \ldots \quad \ldots \qquad (3.1.5)$$

Strains at any point on the diaphragm are given by

$$\text{Radial strain} = e_r = \frac{S_r - \nu S_t}{E} \quad \ldots \quad \ldots \qquad (3.1.6)$$

$$\text{Tangential strain} = e_t = \frac{S_t - \nu S_r}{E} \quad \ldots \qquad (3.1.7)$$

By substituting equation (3.1.3) in (3.1.6) we get strain at the centre of the diaphragm, which is

$$\frac{3}{8}\frac{PR^2}{t^2 E}\,(1 - \nu^2) \quad \ldots \quad \ldots \qquad (3.1.8)$$

and by substituting equation (3.1.4) and (3.1.5) in (3.1.6) and (3.1.7) we find that

$$\text{Radial strain at the edge} = \frac{3}{4}\frac{PR^2}{t^2 E}\,(\nu^2 - 1) \quad \ldots \qquad (3.1.9)$$

Tangential strain at the edge = 0

If the gauge factor of the strain gauge used is G.F. and its nominal resistance is R_g, the change in resistance ΔR_g in the gauge cemented at the centre

$$= G.F \times R_g \times \frac{3}{8}\frac{PR^2}{Et^2}\,(1 - \nu^2) \text{ ohms} \quad \ldots \qquad (3.1.10)$$

nd in gauges cemented at the edge

$$= G.F \times R_g \times \frac{3}{4} \frac{PR^2}{Et^2} (\nu^2 - 1) \text{ ohms} \quad \ldots \quad (3.1.11)$$

omparing equations (3.1.10) and (3.1.11) we find that the strain auge fixed at the edge undergoes twice the change of resistance ompared to the gauge fixed at the centre. Therefore it is better o fix the strain gauges at the edge to obtain higher sensitivi-y.

b) <u>Selection of number of strain gauges and bridge connection</u> :

The summary of the characteristics of the possible heat stone bridge connections using single, two or four active train gauges is given in the table 2.7. Referring to this table e find that the four active strain gauges in the arms of the heat stone bridge circuit as shown in the Fig.2.19(e). Possess he following advantages :

(i) Output voltage is maximum among all other bridge circuits in Table 2.7.

(ii) Output voltage is linear.

(iii) Errors due to temperature variations are self-compensating.

Hence this circuit is selected for which output oltage

$$E_o = E_{in} \times \frac{\Delta R_g}{R_g}$$

ubstituting the value of ΔR_g from equation (3.1.11) we have

$$E_o = \frac{3\ PR^2}{4\ t^2 E}(\nu^2 - 1) \times GF \times E_{in} \quad \ldots \qquad (3.1.12)$$

(c) Selection of bridge supply voltage and frequency : A.C. excitation was used. The advantages of a.c. excitation over d.c. excitation are

(i) elimination of thermo-electric potentials generated at the junctions of dissimilar metals in the transducer or its leads.

(ii) a.c. amplifiers are more stable compared to d.c. amplifiers and it is desirable to have a.c. excitation for using a.c. amplifiers directly to amplify the bridge output(9).

The frequency of the supply must be about 10 times the signal frequency for good dynamic response. Frequency selected was 600 Hz thereby giving the dynamic response of about 60 Hz.

The supply voltage should be selected on the consideration of current that can be safely used with the strain gauge wire, which is a function of the wire resistivity, the grid design, backing material, bonding cement, and heat sink to which they are attached. For paper gauges current is limitted to about 0.05 ampere. Gauge resistance is 120 ohms. Therefore we can use maximum of 6 volts. Considering these factor the bridge voltage selected was 3.5 volts.

(4) Bridge balancing : Due to slight differences in the resistances of the strain gauges the bridge will not be perfectly balanced. Hence balancing arrangement is necessary. Parallel

balancing method has been selected (Fig.2.20 (b)) as this method is convenient for balancing(16).

(e) <u>Selection of thickness(t) and radius (R) of the diaphragm:</u>

Referring to article 2.2.2(d) and Table 2, we can select R and t. Thickness of the diaphragm selected was 0.53 mm. $\frac{R}{t} \approx 100$. Hence R = 53 mm. The radius selected was 60.5 mm. According to Table 2, for linearity the centre deflection must be within 0.265 mm. This sets the upper limit of pressure range as 70 cms of water.

Fig.3.1. shows the details of transducer, housing, diaphragm, strain gauge positions and connections, and pressure leads details. The volume of the pressure chamber on either side of the diaphragm was selected as trial. The main considerations taken into account in the design of the transducer housing was leak proof joints and simple fixtures. Two pressure ports are provided for differential pressure leads. In the design of the transducer, air flow property was not considered. The summary of theoretical calculations are given in the Table 3.1.

(f) <u>Fabrication</u> : The two differential pressure chambers were made out of mild steel plate and ring. The diaphragm was made out of utensil stainless steel. Pressure port connectors are screwed on to the housing for differential pressure tube connection. Strain gauges were cemented at the positions shown in Fig.3.1. using cold setting cement supplied by the strain gauge manufacturers. A thin layer of wax was coated on the strain

Table 3.1. Theoretical Values

Pressure cms of water	Centre deflection mm	Bridge output mV	Remarks
0	0	0	Diaphragm thickness
14	0.0456	10.8	is 0.53 mm.
28	0.0902	21.6	Hence for linear
42	0.1358	32.4	output, centre
56	0.1824	43.2	deflection should
70	0.2280	54.0	be within $\frac{0.53}{2}$ =
84	0.2740	64.8	0.265 mm.

gauges for protection from moisture. The specification of the strain gauges used is as follows :

Paper base bonded wire strain gauge (Rohits)

Type : SA 12

Resistance : 120.2 ± 0.2 ohms

Gauge factor : 2.06

Gauge length : 12 mm

3.1.2. Measuring Instrument : The main consideration in constructing the measuring instrument was that it should be useful for measuring the outputs of strain gauge, LVDT, and capacitive transducers. The signal conditioning circuitry was desired to be of ICs in order to minimise the number of discrete components. The outputs of all the three types of transducer are essentially differential in nature. The output impedance of strain gauge type was 120 ohms, LVDT type about 100 ohms and that of capacitive type may be more than about 30 Kohm. Therefore we need high input impedance for the measuring instrument. Also adjustable gain was preferred to select the desired gain. Differential amplifier with single IC was not suitable due to its draw backs as follows (34) :

(i) Its input impedance is quite low

(ii) High values of differential gain require a large feedback resistor which causes excess d.c. output offset due to the opamp input offset current. If both high gain and high input resistance are required, the input resistor must be very large and the feed back resistor must be much larger than the input resistor. Since it is difficult to match high meg ohm resistors, the CMRR due to resistor mismatching will suffer. Considering the high input impedance (10^{10} ohms typically), variable gain with single resistor adjustment, differential to single ended output and common mode signal rejection, we find IC instrumentation amplifier is ideally suited for our purpose.

The measuring instrument fabricated consists of D.C. regulated power supplies for ICs and emitter follower, a.c. power supply for bridge and LVDT excitation, IC instrumentation amplifier with gain selector switch and various other connecting terminals on the front panel and the indicating meter. The block diagram of the system is shown in the Fig.3.2 and the complete circuit is shown in the Fig.3.3. The design of the various blocks are as follows :

(a) Regulated D.C. power supply : We need three regulated D.C. power supplies, two for ICS (± 12 V) and one for the emitter follower (12 V). The regulated power supply designed consists of a 220 V/12 V step down transformer, full wave silicon rectifiers, filters and regulators. Output voltage of 12 volts is maintained constant for input voltage variations from 190 V to 240 V. [redacted]

(b) <u>Oscillator</u> : IC wienbridge oscillator with emitter follower stage was used to supply 3.5 volts a.c. at 600 Hertz, as this gives good output waveform and needs minimum number of components. Figure shows the wienbridge oscillator (35). Amplitude stabilisation is obtained from back to back diodes D_1 and D_2 which are connected in parallel with the resistor R_3. R_3 is in the negative feed back path in series with the 10 K ohm distortion control resistor R_4. The component values calculated are as shown in the figure. The frequency of oscillation was adjusted to 600 Hertz using presets.

(c) <u>Instrumentation amplifier</u> : Fig.3.3 shows the IC instrumentation amplifier. The output voltage from A_1 is V_3 and the output voltage from A_2 is V_4.

$$V_3 = (1 + \frac{R_2}{R_1})V_1 - (\frac{R_2}{R_1})V_2 + V_{ic}$$

$$V_4 = (1 + \frac{R_3}{R_1})V_2 - (\frac{R_3}{R_1})V_1 + V_{ic}$$

where $V_{ic} = \frac{V_1 + V_2}{2}$.

V_o is the output of A_3. If A_3 stage is perfectly balanced i.e.

$$\frac{R_6}{R_4} = \frac{R_7}{R_5}$$

then $V_o = \frac{R_6}{R_4}(V_4 - V_3)$.

R_4 is the input impedance for the stage A_3. We have selected R_4 = 56 K ohms. For symmetry let us select all resistors of 56 K ohms (except R_1). The limittation for highest value of R_4 is d.c. offset voltage that can be tolerated. Using the numerical value we have

$$\text{Gain} = \frac{V_o}{V_2 - V_1} = 1 + \frac{112{,}000}{R_1}.$$

By variation of R_1 gain can be controlled. A range selector switch was provided to vary R_1 in steps giving gain of 1000,750, 125 and 20.

CMRR depends on theCMRR of A_3 and how perfectly $\frac{R_6}{R_4} = \frac{R_7}{R_5}$. A mismatch of R_1, R_2 or R_3 merely affects the differential gain ($A_d = \frac{V_o}{V_2 - V_1}$) and not the common mode gain ($A_c = \frac{V_o}{V_{1c}}$).

(d) <u>Indicator</u> : Multimeter was used as indicator by connecting the same to the respective terminals on the measuring unit.The range switches were set to read A.C. voltages from 0 to 10 volts full scale. For lower ranges, 0 to 2.5 volts A.C. range can be used.

3.1.3 <u>Experimental testing and calibration</u> : The experimental set up is shown in the Fig.3.4. 'U' tube manometer was used as standard pressure indicator. Water was used as the manometer fluid. One end of the manometer was open to the atmosphere and the other end to the transducer pressure port through a 'T' joint as shown in the Fig.3.4. The other end of the transducer was left open to atmosphere. The transducer leads were connected to the measuring instrument.

Air pressure was applied at the 'T' joint as shown in the figure by blowing air into the tube. Readings on the manometer and the pressure indicator were simultaneously noted and the same is given in the Table 3.2.

Table 3.2 : Experimental results of strain gauge transducer.

Manometer reading p cms of water	Pressure indicator reading E_o volts	$\frac{E_o}{Gain}$ mV	Remarks
0	0		At p = 4 and p = 8,
4	2.5	3.3	gain was set at 750.
8	4.5	6.0	at remaining readings
12	1.5	12.0	gain was set at 125.
22	2.8	19.0	
30	4.0	32.0	
38	5.0	40.0	

Fig.3.5(a) shows the graph of pressure versus indicator reading. It is seen that the response is fairly linear. Fig.3.5(b) shows theoretical and experimental values plotted for the purpose of checking the theoretical calculations. For ideal conditions, the two must coincide, but in the calculation of theoretical values, the end effects were not accounted. This could be the cause for deviation from measured and calculated values. It was observed that by pressing the transducer body at the edge by hand some output was ~~observed~~ available. The volt meter reading was not quickly going back to zero when pressure was made zero. The time delay is due to the plate not going back to the initial position quickly. Also often the initial was changing whenever pressure was applied and released. These descripencies may be due to the property of the plate material.

3.2. LVDT TYPE

An LVDT pressure transducer was designed and fabricated for measurement of wind pressure in the range 0 to 35 cms of water. Experimental testing and calibration was also carried out. Null voltage compensation was provided. The details of the same is discussed in this chapter.

3.2.1 Design and Fabrication:

(1) Mechanical design of the transducer : The diaphragm thickness selected was 0.254 mm and radius selected was 25.4 mm. Calculations (article 2.2.2 (d)) show that this diaphragm can give linear results up to about 35 cms of water maximum. Other components of the transducer was designed similar to the strain gauge type. Fig.3.6 shows the drawing of the transducer.

(2) Design of the LVDT: The overall length of the LVDT was selected as 1.5 cms to enable to insert the LVDT unit inside the pressure chamber. Referring to article 2.3.3 the other parameters designed are as follows:

(a) Length of primary : Assuming maximum deflection of core as 4 mm and tolerated error of non-linearity of 0.5% the length of primary (using equation 2.3.14) = 4 mm.

(b) Length of secondary : Ignoring δ in equation 2.3.15, the length of secondary = 8 mm.

(c) Length of the armature : By equation 2.3.16, length of the armature = 13 mm.

(d) Radius of armature : Assuming $\frac{r_1}{L_a} = 0.04$, we get the radius of armature $\approx$ 5 mm.

(e) Inner radius of coils $\approx$ 5 mm.

(f) Outer radius of the coil is selected as 2.5 cm.

(g) Primary number of turns selected = 1000 (40 S.W.G. enamelled copper wire)

(h) Primary coil resistance = 88.8 ohm (as measured by multimeter)

(i) Secondary number of turns = 1000 turns each secondary coil (40 S.W.G. enamelled copper wire)

(j) Secondary coil resistance = 88.8 ohm each secondary coil.

Calculation of sensitivity ($\frac{\text{output voltage}}{\text{pressure applied}}$) is not done since calculation of the diaphragm deflection due to applied pressure will not be accurate due to the end effects and material properties.

(3) Fabrication : Diaphragm was made out of EN 24 steel. The pressure chambers were turned out of mild steel rod. Other mechanical fittings were made similar to that of strain gauge transducer.

Coils were wound on a plastic bobbin. Suitable insulation was provided around the coils. The armature core was made out of Ferrite rod. Ferrite core was first supported on a brass stud of 1 cm long and this stud was fixed to the centre of the diaphragm. Quick fix was used for fixing. The coils were fixed inside the pressure chamber very carefully such that the core can freely move inside the coils. The core was located to null position by giving spacers. Connecting leads were taken out through a hole in the transducer body. All leaks were blocked by using wax after final tightening of the nuts.

3.2.2 Null Voltage Compensation : It was observed about 1 mv output was available from the transducer even when the pressure was not allowed in. This is due to null voltage of the LVDT. It was planned to compensate this initial voltage by using a compensating circuitry.

Fig.3.7 shows the circuit used for compensating the initial voltage. The principle used here is to inject compensating voltage from primary to output side. Potentiometers R_1 and R_2 are adjusted for almost zero null voltage.

The supply voltage was 3.6 volts at 600 Hertz.

3.2.3 Experimental Testing and Calibration : The experimental set up used for testing and calibration is same as the strain gauge type except the strain gauge type transducer was removed and LVDT transducer was replaced. Readings of manometer and indicator were noted similar to that of strain gauge type and is given in the following Table 3.3.

Table 3.3. Experimental results of LVDT transducer

Manometer reading P cms of water	Indicator reading E_0 volts.	Remarks
0	0	
4	1.0	
8	2.0	
10	2.4	Gain = 800
16	3.6	
21	5.0	
29	7.2	
37	9.0	

Continu......

Continued.....

Manometer reading P cms of water	Indicator reading E_o volts	Remarks
0	0	
12	0.4	
18	0.6	Gain = 125
24	0.8	
32	1.1	
38	1.4	
52	1.8	

Fig. 3.8 shows the graph of indicator reading versus manometer reading. It is seen the response is linear. By increasing gain sensitivity also increases which can be observed from the graph at gain 125 and at gain of 750. Linearity is maintained in both cases. The response is observed to be far better compared to the strain gauge type. Hysterisis was not observable in LVDT type, where as inconsistent hysterisis - type error was observable with strain gauge type. The improved performance of the LVDT type may be due to the superior material and fabrication as compared to strain gauge type which was not fabricated to the standard of the LVDT type. Readings in LVDT type were repeatable accurately. Null voltage compensation circuit also was working satisfactorily. The initial reading could be brought to almost 0 at all ranges by adjusting the null compensating potentiometers slowly in sequence such that each potentiometer is adjusted for minimum null-voltage. This LVDT type

ransducer was also tested in actual wind tunnel and the perfor- ance was quite satisfactory.

3.3 CAPACITIVE TYPE

Capacitive pressure transducer based on the principle f variable distance between the diaphragm and fixed electrodes orming differential capacitor has been designed and fabricated or measurement of wind pressure in the range 0 to 70 cms of ater. Details of the design, fabrication and experimental esting are discussed in the following.

esign and Fabrication : For small displacement of the diaphragm ariable distance type of capacitive transducer is most sensitive 19). In order to save time and material for fabrication it was lanned to use the same strain gauge type transducer also for apacitive type by fixing two electrode plates on either side f the diaphragm to form differential capacitor arrangement. lots were cut on the fixed electrode plates to make way for s train gauge connecting leads and also for air to exert pressure n the diaphragm. Bakelite spacer rings are provided between he diaphragm and electrode plates. The drawing of the capaci- ive transducer is shown in the Fig.3.8. The gap between the lates and the diaphragm was kept about 1 mm. This ensures that n the pressure range intended for the transducer, the diaphragm ill not touch the electrode plate. The calculated value of the apacitance was 85.8 pF and the actual measured values were 3 pF and 67 pF. At frequency of about 10 KHz, the reactance will be about 250 K ohm, hence it was planned to use the readily available 22 K ohm in each arm with 100 K ohm pot for balancing. The complete details are given in the Fig.3.9.

3.3.2 Experimental Testing and Calibration : By supplying 3.5 Volts A.C. excitation to the input terminals of the transducer and connecting the output to the measuring instrument and CRO, it was observed the balancing potentiometer was functioning satisfactorily. However a small voltage (a few m.v.) exists at the balance position. This shows the balancing is not perfect. The cause for this may be due to stray capacitances due to cables. By using shielded cables for connections better balancing can be expected.

The experimental set up used for testing the capacitive transducer is also same as that used for LVDT and strain gauge types as shown in Fig.3.4. Capacitive transducer was replaced in position of strain gauge transducer and connections for measuring unit were altered. Readings were noted for various pressures and at supply frequencies 10 KHz and 3 KHz. A separate oscillator was used to supply 3.5 volts A.C. at 3 KHz and 10 KHz. The results are tabulated as follows (Table 3.4) :

The results are plotted in Fig.3.10. It is seen that the response is fairly linear both at 10 KHz and 3 KHz. Errors such as mentioned in strain gauge type (Hysterisis, plote buckling etc.) were observable in this case also. This observation confirms that by using better diaphragm and better and fixtures, the performance can be improved.

Table 3.4. Experimental results of capacitive transducer

Manometer reading P, cms of water	Pressure indicator reading E_o, volts	Remarks
0	0	
8	0.4	
14	0.7	f = 10 KHz
24	1.7	Gain = 750
28	2.2	V = 3.5 Volts
40	3.2	
58	4.2	
72	5.2	
52	4.2	
40	3.2	
0	0	
2 0	0.5	f = 3 KHz
30	0.8	Gain = 125
36	1.0	V = 3.5 Volts.
44	1.5	
52	2.0	

4. APPLICATIONS

Selection of a pressure transducer depends on the intended application. There is no such thing as best transducer for universal use (6). For each application both the mechanical input and electrical output characteristics must be considered. The developments that have taken place have been confined and attributed to the use of improved materials (stainless steels, alloys and plastics), application of new production process (electron beam welding, clean room assembly areas etc.)(24) and the improvements in the associated equipments, signal processing and recording techniques. In the following pages general considerations for selection and a few typical examples of application are discussed.

4.1 General Considerations for Selection (25) :

Range : Pressure transducers are designed to measure pressures over specified ranges. The actual measuring range is determined by the setting of the associated signal - conditioning and read out equipment for a given transducer output corresponding to the upper limit of the pressure range of interest (25).

Absolute pressure (Fig.4.1(a)) transducer require an internal vacuum or partial vacuum, maintained by a seal which normally also provides a hermitic seal for the transduction element and isolates it from at mospheric contact. Gauge and differential pressure (Fig.4.1(b) & (c)) transducers except sealed reference types usually expose the transduction element to the ambient or to the reference pressure. Differential strain gauge pressure transducers. Inductive transducers usually have less frequency-response capability than the above three types and potentiometer types are normally not used where a large frequency range must be monitored.

Pressure transducer frequency response is dependent upon the natural frequency of the sensing element as dictated mainly by its stiffness. The frequency response is also inversely proportional to the dead volume of the transducer and the length of tubing from the point of measurement to the transducer pressure port.

Environmental temperature : Errors due to temperature variation can be minimised through selection of materials with matched temperature coefficients and also by use of compensating circuitry.

Piezo-electric pressure transducers can be used at temperatures from $-240^{o}C$ to $+200^{o}C$, and potentiometric pressure transducers have been developed to operate at temperatures between $-200^{o}C$ and $+180^{o}C$. Strain gauge pressure transducers can be used in the temperature range $-270^{o}C$ and $+120^{o}C$ with careful compensation in the circuitry. Capacitive and inductive transducers are usually used in environments at or near room temperature.

Other factors to be considered are environmental factors such as acceleration, vibration, atmospheric effects, nuclear radiation and measured fluids.

Typical Applications : Resistive pressure transducers comprise virtually all kinds of application except for sub-standards and pressure transducers can always be used for gauge pressure measurements by venting the reference port to the ambient atmosphere.

Accuracy : Pressure transducer accuracy is strongly related to signal conditioning, signal transmission and read out system capabilities. Inductive and strain gauge types can profide very close accuracies in conjunction with a low error transmission and read out system. Other types of pressure transducers can be designed to provide very close accuracy under certain conditions but can usually be designed to yield the degree of accuracy normally required for a large majority of pressure measurements.

Output : Potentiometer type pressure transducer can provide high output without signal conditioning. The output of strain gauge pressure transducers can be large enough to drive the commonly used millivolt recorders. Capacitive and inductive pressure transducers require some signal conditioning to yield usable outputs. Piezo-electric transducers are almost invariably used in conjunction with charge amplifier since their output impedance is very high. Digital output can be obtained from analog output of the transducer by use of an analog-to-digital converter which can be built into the same case with the transducer.

Frequency response : The ability to reproduce rapid pressure fluctuations in their output is most pronounced in piezo-electric and capacitive pressure transducers and to a lesser extent in strain gauge pressure transducers. Inductive transducers usually have less frequency-response capability than the above three types and potentiometer types are normally not used where a large frequency range must be monitored.

Pressure transducer frequency response is dependent upon the natural frequency of the sensing element as dictated mainly by its stiffness. The frequency response is also inversly proportional to the dead volume of the transducer and the length of tubing from the point of measurement to the transducer pressure port.

Environmental temperature : Errors due to temperature variation can be minimised through selection of materials with matched temperature coefficients and also by use of compensating circuitry.

Piezo-electric pressure transducers can be used at temperatures from - 240°C to + 200°C, and potentiometric pressure transducers have been developed to operate at temperatures between -200°C and + 180°C. Strain gauge pressure transducers can be used in the temperature range -270°C and + 120°C with careful compensation in the circuitry. Capacitive and inductive transducers are usually used in environments at or near room temperature.

Other factors to be considered are environmental factors such as acceleration, vibration, atmospheric effects, nuclear radiation and measured fluids.

4.2 Typical Applications : Resistive pressure transducers comprise virtually all kinds of application except for sub-standards and ultra-fast responding types (6). Potentiometer type pressure transducers are restricted to stationary industrial installations intended for monitoring and process control. Wire and foil bonded strain gauge types cover wide and diverse applications. Unbonded strain gauges exhibit inferior stability to thermal shock because of poor heat transfer from their freely suspended wires. Transducers of foil strain gauge type has been used for range say 1 psi and upto 10,000 psi and are available in rugged bodies of reasonable size. Semiconductor strain gauge transducers require elaborate compensation artifices in the associated circuits due to their inherent non-linearity and high thermal coefficient of both resistance and gauge factor. There are also a number of pressure transducers employing semiconductor strain gauges diffused into the selected areas of silicon diaphragms. The main attraction of these transducers lies in their small size which generally is obtained at the expense of performance.

Next to resistive types, inductive pressure transducers have probably the widest use. The earliest and still most common type operates by the push-pull variation of reluctance of two coils with variable air gaps on either side of the ferromagnetic diaphragm. The coils are connected in adjacent arms of an a.c. fed bridge circuit. Analog d.c. voltage output is obtained after phase sensitive demodulation and filtering. Transducers of this type cover differential pressure ranges from about ± 10 psi to ± 1000 psi. LVDT type has a moving plunger hence the sensitivity to vibration and acceleration is higher than that of variable reluctance types with diaphragm.

Capacitive transducers are used as engine indicators in internal combustion research where their fast response and their high temperature capability are an advantage.

In industrial applications of pressure transducers reliability is of prime importance. Transducers requiring frequent maintenance are generally not acceptable since in many cases they are installed at in accessible locations. Minimising the detrimental effects of hostile environments is a growing demand. In industry transducer size and weight matter, though perhaps less than in research work.

(ii) Bio-medical applications : Strain gauge pressure transducers are used for the measurement of blood pressure, lung air pressure etc.(28). For rapid changes of pressure like blood pressure piezo-electric transducers can be used. Typically the requirements to be satisfied of a transducer to measure blood pressure are (1) measurement of pressure independent of patient's movement (2) pressure reading independent of transducer position (3) comfort to the patient and a small size to be used (4) no continuous care necessary. These requirements exclude direct measurement methods, pressure cuff type transducers and use of LVDT. Piezo-electric transducer satisfies all the above requirements (29). Also with amplifiers and peaking detectors diastolic (operational range is from 50 mm Hg to 120 mm Hg) and systolic (operational range is from 70 mm Hg to 130 mm Hg) pressures can be continuously monitored. Extreme diastolic or systolic pressures considered to be dangerous are set such that these signals are utilised to trigger either visual or audible warning device.

A typical transducer developed for implantation with in the body consists of a single silicon crystal diaphragm with an integral piezo-resistive wheat stone bridge on one surface(30). The circular diaphragm which is alloyed at its edge to a metal mounting ring deflects linearly without hysterisis upto the point of fracture. Two sizes are available, one is 6.25 mm in diameter by 2.8 mm deep and the other is 2.1 mm in diameter by 2 mm deep. Through out the physiological pressure range the linearity is better than 0.1% and resolution is infinite down to a thermal noise level equivalent to 5 x 10^{-6} mm Hg. One type, having a sensitivity of 1 mv for 10 mm Hg showed a maximum output drift of less than 30 uv in 50 hours. Among the medical applications reported were the insertion of a transducer into a patient's bladder to detect pressure changes and its use externally for blood pressure measure ment through a cathetor.

(iii) Aero-space applications : Diaphragm gauges evolved mainly from the requirements of space research and numerous types are available. The size of the diaphragm is as low as 13 mm for resistance strain gauge element and 3 mm diameter for semi-conductor strain gauge element. Miniature capacitive pressure transducer including hybrid integrated circuit has been developed with overall dimensions of 1 mm diameter and 8 mm long for use in wind tunnels and biomedical applications for pressure measurement (31).

Capacitive type pressure transducers can be used as micromanometer (32). In a typical transducer the diaphragm was made of a thin sheet of Terylene (0.0005 or 0.001 inch thick) aluminised on one side, and this instrument can be used to measure pressure differences up to about 5 mm Hg with an accuracy of ± 2%. A change in pressure difference as small as 40 μ of Hg can be detected. Capicitive type differential pressure transducers can be used for measurement of rate of climb, pitch and yaw of an aircraft by relating these parameters to rapid changes of air pressure leaking from a capsule through an orifice (1).

Quartz crystal pressure transducers of miniature size can be used to measure dynamic pressures from full vacuum to 3000 psi or more with limited applications to 5000 psi in blast and explosion or combustion. One type designed for low pressure blast and high intensity sound pressure measurements has a nominal sensitivity of 5.0 c/psi and a resolution of 0.005 psi with a capacitance of 50 pF. When connected to a charge amplifier it can measure blast pressures below 1 psi with good signal-to-noise ratio (1).

Many aero-space type transducers can be used for Industrial applications as well. In many applications, all that is necessary for direct use in industrial situation is to change the packaging of the standard aero-space transducer (33).

5. CONCLUSIONS AND SCOPE FOR FURTHER WORK

5.1 CONCLUSION : The information provided in this work is sufficient to design and fabricate strain gauge, capacitive and LVDT types of pressure transducers for any desired range.

In the case of strain gauge transducer, the theoretical sensitivity was 0.75 mv/cm of water and the experimental value was about 1.0 mv/cm of water. The reason for higher sensitivity realised may be due to end effect. If the diaphragm is removed and fixed again, a change in sensitivity may be expected. This problem of the end effect is observed with capacitive transducers also since both transduction elements are housed in common unit.

Among the three transducers developed LVDT transducer is recommended for practical use. While testing it was observed that this transducer was practically free from errors of hysterisis, zero shift, repeatability etc. The plot of pressure versus output also was found to be linear. The response of strain gauge and capacitive transducers also was linear but hysterisis and zero shift were noticeable. The reason for better performance of LVDT type may be due to superior materials and fabrication techniques used in making it. With better diaphragm material and improved fabrication techniques, the performance of strain gauge and capacitive types can also be expected to improve.

By using shielded cables, null voltage in case of LVDT can be further reduced and in case of strain gauge and capacitive types better balancing can be achieved.

5.2 SCOPE FOR FURTHER WORK : The design and fabrication of pressure transducer depends upon the available materials and fabrication techniques. Transducers with improved performance can be developed by using better materials and fabrication techniques.

Wide scope for research and development exist in the field of pressure transducers using semiconductor, integrated and thin film strain gauges.

The response of strain gauge and capacitive transducers developed were found to be inferior to that of LVDT. This may be due to better materials and fabrication used in making LVDT type. Strain gauge and capacitive transducers response also can be improved with better materials and fabrication techniques.

Performance analysis was not made to evaluate the capability of the transducers developed. In the design of the transducers air flow property was not considered, whose effect would be to cause dynamic lag. This aspect may be studied. The sensitivity of LVDT and capacitive transducer is function of frequency of supply. Best supply frequency may be determined experimentally.

Proper sealing must be provided to eliminate the leaks to realise better performance.

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