SENSITIVITY ANALYSIS OF CAPACITIVE PICK-UPS

A DISSERTATION

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

MASTER OF ENGINEERING

in

ELECTRICAL ENGINEERING

(With Specialization in Measurement and Instrumentation)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled 'Sensitivity Analysis of Capacitive Pick-ups' in partial fulfilment of the requirement for the award of the Degree of Master of Engineering with specialization in Measurement And Instrumentation, submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out for a period of 32 months from 30th oct'1986 to 10th July'1989 under the supervision of Dr. S.C.Saxena, Professor, Department of Electrical Engineering, University of Roorkee, Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

Sanjay Agarwal.

Dated : 15th July'89 (SANJAY AGARWAL)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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It would not be out of place to express my heart-felt thanks to my friends who have rendered a lot of assistance to complete this work expecially to Mr. Radhey Shyam.

Finally I wish to express my thanks to all other who did their best directly or indirectly to co-ordinate me in successful completion of this work.

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A B S T R A C T

Pick-ups may be defined as device which transforms energy from one form to other. Capacitive transducers work on the principle of change in capacitance, caused by change in overlapping area, and change in distance between plates or change in dielectric constant. Capacitive pick-ups can be used for the measurement of length, thickness, level, displacement, humidity etc.

The sensitivity of a bridge measurement may be regarded as the accuracy with which balance is achieved. It is expressed in terms of the smallest response of the detector which can be observed with reliability. The capacitances are generally used in bridge circuits for detecting the changes in their values.

In this dissertation analysis has been carried out for the sensitivity analysis of different types of capacitive pick-ups. The influence of environmental parameter on capacitors has been studied and an instrumentation scheme has also been developed for continuous measurement ofcapacitance changes. The capacitance changes does not affect the sensitivity of the bridge. The sensitivity of the developed pick-up can be very accurately determined by using this bridge circuit.

CONTENTS

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CHAPTER-I

INTRODUCTION

1.1 INTRODUCTION

In order to measure non-electrical quantities a pick-up is used. It converts the physical quantity into a displacement. This displacement actuates an electric transducer, which acting as secondary transducer and gives an output that is electrical in nature. The electrical signal may be current, voltage or a frequency. These signals are generated by the change in basic electrical parameters like, resistance, capacitance and inductance (8).

A transducer, in general form, may be defined as a device which converts energy from one form to another. However, this definition has to be restricted, many a times especially in the field of electrical instrumentation on account of this, transducer may be defined as a device which converts a physical quantity or physical condition in-to an electrical signal. Another name for a transducer in pick-up or sensor.

The transducer may be thought of consisting two important parts (i) Sensing Element (ii) Transduction Element.

(i) Sensing Element : A detector or sensing element is that part of a transducer which responds to a physical phenomenon or a change in a physical phenomenon. It is also called as primary element.

(ii) <u>Transduction Element</u> : It transform the output of a sensing element to an electrical output. It is also called as secondary element.

The sensitiveness of the pick-ups is also important and it should be as high as possible so that a minimum variation can be detected.

1.2 ADVANTAGES

There are number of transducers which transform a variety of physical quantities and phenomena into electrical signals. The advantage of converting physical quantities into analogous electrical quantities are as follows -

(i) Amplification and attenuation of electrical signal can be carried out easily and that too with static electronic devices and circuits.

(ii) The mass-inertia effects are minimized when delaying with electrical or electronic signals, the inertia effects are due to electrons which have negligible mass.

(iii) The effects of friction are minimized.

(iv) The electrical or electronic systems can be controlled with a very small power level.

(v) The electrical output can be easily used, transmitted, and processed for the purpose of measurement.

(vi) Telemetry is used in almost all sophisticated measurement systems. This completely eliminates the data transmission through mechanical means and hence electrical and electronic principles have to be employed for these conditions.

In short, it can be stated that the reasons for transforming a physical phenomenon into electrical forms is that the electrical output can be easily used, transmitted and processed for the purpose of measurement and control. Modern digital computers make the use of these transducers absolutely essential. In data acquistion system which are now a micro processors and micro computers based have first element as transducers, sensor or pick-up.

1.3 ELECTRICAL PHENOMENA USED IN TRANSDUCER

The different electrical phenomena (8) exploited for transformation in transduction elements of transducer are as follows -

(1) Resistive change (2) Inductive change (3) Capacitive change (4) Electromagnetic change (5) Pizo electric change (6) Variation in ionization (7) Photo electric effect (8) Photo conductive effect (9) Photo voltaic effect (10) Potentiometric change (11) Thermo-electric effect (12) Electro kinematic effect.

Table 1.1 shows the classification, principle of transduction, and application of various type of transducers according to different principles involved in process of transformation.

Capacitive transducers are one of the most commonly used pick-up in the field of measurement, Control and telemetry. These have some distinct advantages and dis-advantages over the other category of the pick-ups. Following section highlights the important features and applications of capacitive pick-ups.

1.3.1 Important Features of Capacitive Pick-ups (8)

The important features of capacitive pick-ups are as follows :

(i) They require extremely small forces to operate them and hence are very useful for use in small systems.

(ii) They are extremely sensitive.

(iii) They have a good frequency response. This response is as high as 50 KHz and hence they are useful for dynamic studies.

(iv) They have a high input impedance and therefore the loading effects are minimum.

(v) A resolution of the order of 2.5×10^{-3} mm can be obtained with these transducers.

(vi) The capacitive transducers can be used for applications where stray magnetic fields render the inductive transducer useless.

(vii) The force requirements of capacitive transducers is very small and therefore they require small power to operate.

Table 1.1

Types of Electrical Transducers

Electrical parameter and class of transducer	Principle of operation	Typical Applications
1	2	3
	Passive transducers(externally powered)	
Resistance		
Potentiometer device	Positioning of the slider by an external force varies the resistance in a potentiometer or a bridge circuit.	Pressure, displacement.
Resistance strain gauge	Resistance of a wire or semiconductor is changed by elongation or compression due to externally applied stress.	Force, torque, displacement.
Pirani gauge or hot wire meter	Resistance of a heating element is varied by convection cooling of a stream of gas.	Gas flow, gas pressure.
Resistance thermometer	Resistance of pure metal wire with a large positive temperature co-efficient of resistance varies with temperature.	Temperature, radiant heat.
Thermistor	Resistance of certain metal oxides with negative temperature coefficient of resistance varies with temperature.	Temperature, flow.
Resistance hygrometer	Resistanfe of a conductive strip changes with moisture content.	Relative humidity.
Photoconductive cell	Resistance of the cell as a circuit element varies with incident light.	Photosensitive relay.

....2

1	2	3
<u>Capacitance</u> variable capacitance pressure gauge.	Distance between two parallel plates is varied by an externally applied force	Displacement, pressure.
Capacitor microphone	Sound pressure varies the capacitance between a fixed plate and a movable diaphargm.	Speech, music, noise.
Dielectric gauge	Variation in capacitance by changes in the dielectric.	Liquid level, thickness.
<u>Inductance</u> Magnetic circuit transducer	Self-inductance or mutual inductance of a.c. excited coil is varied by changes in the magnetic circuit.	Pressure, displacement.
Reluctance pick-up	Reluctance of the magnetic circuits is varied by changing the position of the iron core of a coil.	Pressure, displacement vibration, position.
Difrerential transformer	The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force.	Pressure, force, displacement, position.
Eddy current gauge	Inductance of a coil is varied by the proximity of an eddy current plate.	Displacement, thickness.
Magnetostriction gauge	Magnetic properties are varied by pressure and stress.	Force, pressure, sound.
<u>Voltage and Current</u>		
Hall effect pick-up	A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current.	Magnetic flux, current.

....3

1	2	3
Ionization chamber	Electron flow induced by ionization of gas due to radio-active radiation.	Particle counting, radiation.
Photoemissive cell	Electron emission due to incident radiation upon photoemissive surface.	Light and radiation.
Photomultiplier tube	Secondary electron emission due to incident radiation on photosensitive cathode.	Light and radiation, photosensitive relays.
Self-generating transducers (no external power)		
Thermocouple and thermopile	An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated.	Temperature, heat flow, radiation.
Moving coil generator	Motion of a coil in a magnetic field generates a voltage.	Velocity, vibration.
Piezoelectric pick-up	An emf is generated when an external force is applied to certain crystalline materials, such as quartz.	Sound, vibration, acceleration, pressure changes.
Photovoltaic	A voltage is generated in a semiconductor junction device when radiant energy stimulates the cell.	Light meter, solar cell.

1.3.2 Use of Capacitive Pick-ups (8)

There are many uses of capacitive pick-ups some of them are as follows :

(i) Capacitive transducers can be used for measurement of both linear and angular displacements. The capacitive transducers are highly sensitive and can be used for measurement of extremely small displacements down to the order of melecular dimensions i.e. 0.1×10^{-6} mm.

(ii) They can be used for measurement of large distances upto about 30 m as in aeroplane altimeters. The change in displacement method is generally preferable for either very small or very large displacements. The change in area method is used for measurement of displacements ranging from 10 mm to 100 mm.

(iii) Capacitive transducers can be used for measurement of force and pressure. The force and pressure to be measured are first converted to displacement which causes a change of capacitance.

(iv) Capacitive transducers can be used directly as pressure transducers in all those cases where the dielectric constant of a medium changes with pressure.

(v) Capacitive transducers are used for measurement of humidity in gases since the dielectric constant of gases changes with change in humidity thereby producing a change in capacitance e.g. in case of air, at 45°C. for dry air dielectric constant is 1.000247 and saturated air is 1.000593.

(vi) Capacitive transducers are commonly used in conjunction with mechanical modifiers for measurement of volume, density, liquid level, weight etc.

1.4 ORGANIZATION OF THE DISSERTATION

The work in this dissertation has been carried out around analysis of capacitive pick-ups. After introduction in Chapter-I, the detail of various types of capacitive pick-ups and their applications in different fields are discussed in Chapter-II. This chapter includes the principle of transduction of various types of capacitive pick-ups based on change in their geometry due to variation in plate area, displacement between the plates, and the change in dielectric medium. The comparative study is given for capacitive pick-ups with respect to resistive and inductive transducers.

Chapter-III deals with the sensitivity analysis of the capacitive pick-ups in various bridge configurations. Both current and voltage sensitivity have been calculated for different configurations. The methods are suggested for measuring the sensitivity of the pick-ups.

The influence of environmental parameters is discussed in Chapter-IV. Basically the effect of variation in temperature, pressure, humidity and vibration is studied.

Chapter-V deals with an instrumentation system which has been designed, developed and tested for continuously, measuring the change in capacitance with greater sensitivity. This bridge circuit can be used for determining the sensitivity of capacitive elements practically.

Conclusions and scope for future are presented in Chapter VI.

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CHAPTER-II

CAPACITIVE TRANSDUCERS

2.1 PRINCIPLE OF OPERATION (8)

The principle of operation of capacitive transducers is based upon the familiar equation for capacitance of a parallel plate capacitor.

$$C = \frac{\epsilon A}{d}$$

where,

C is the capacitance value of the capacitor,

A is overlapping area of plates in m^2,

d is the distance between two plates in m.; and

ϵ is permittivity (dielectric constant) in F/m.

The capacitive transducer work on the principle of change of capacitance which may be caused by :

(i) Change in overlapping area A,

(ii) Change in distance d between the plates, and

(iii) Change in dielectric constant.

These changes are caused by physical variables like displacement, force, pressure in most of the cases. The change in capacitance may be caused by change in dielectric constant as is the case in measurement of liquid or gas levels.

The capacitance may be measured with bridge circuits. The output impedance of a capacitive transducer is :

$$Z = \frac{1}{2\pi f C}$$

where

Z is the output impedance

f is the frequency

C is the capacitance

The capacitive transducers are commonly used for measurement of linear displacements. These transducers use the following effects :

(i) Change in capacitance due to change in overlapping area of plates.

(ii) Change in capacitance due to change in distance between the two plates.

2.2 TRANSDUCERS USING CHANGE IN AREA OF PLATES (8)

It is found that capacitance is directly proportional to the area A of the plates. Thus capacitances changes linearly with change in area of plates. Hence, this type of transducer is useful for measurement of moderate to large displacement say from 1 mm to several cm. The area changes linearly with displacement and also the capacitance as shown in the figure 2.1. The initial non-linearity is due to edge effects.

For a parallel plate capacitor, the capacitance equals to

$$\frac{\epsilon A}{d} = \frac{\epsilon l w}{d} \text{ Farad}$$

where,

l is the length of overlapping part of plates in m., and w is the width of overlapping part of plates in m..

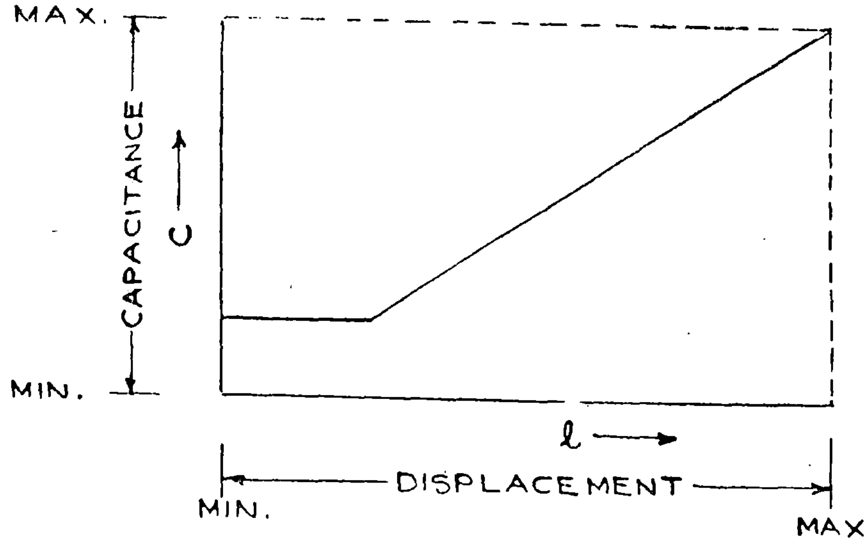


FIG. 2·1

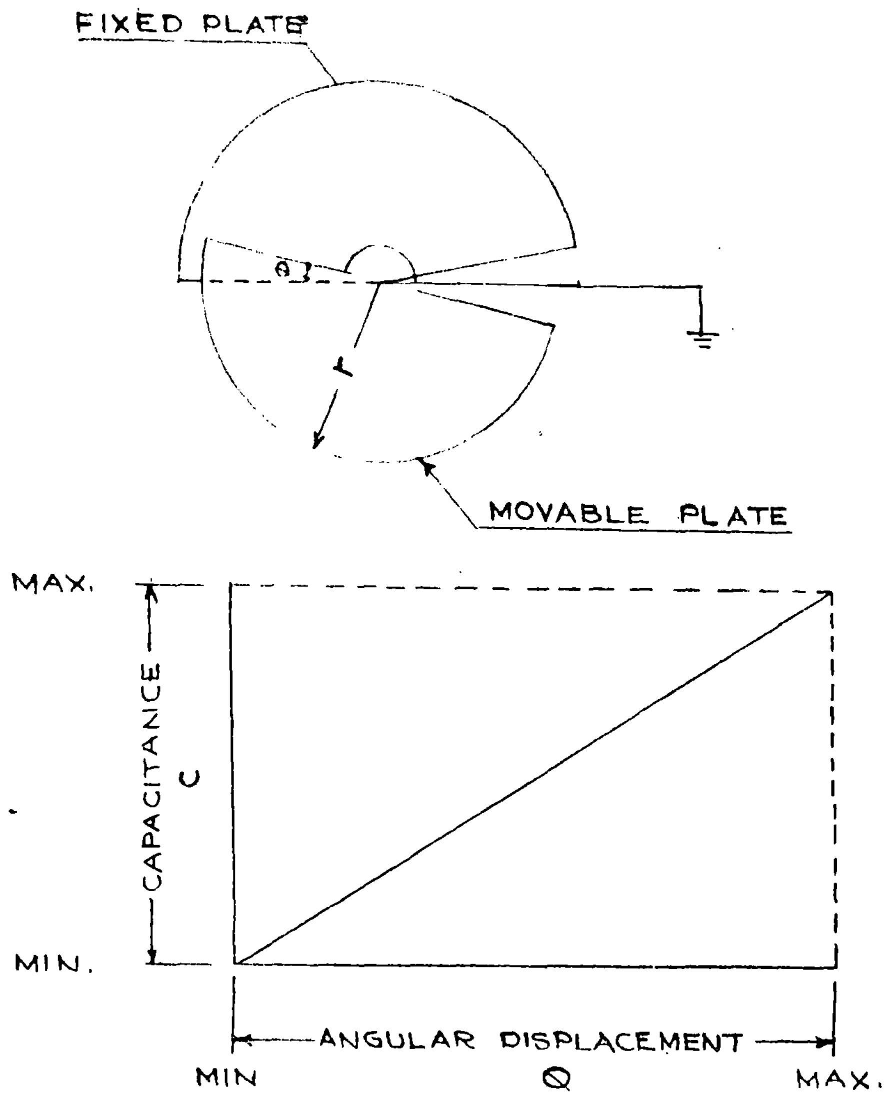


FIG. 2·2(a) & (b)

The sensitivity is defined as

$$S = \frac{\partial c}{\partial l} = \epsilon \frac{w}{d} \quad F/m$$

The sensitivity is constant and therefore there is linear relationship betwwen capacitance and displacement.

Sensitivity for a fractional change in capacitance

$$S' = \frac{\partial c}{c \partial l} = \frac{1}{l}$$

This type of a capacitive transducer is suitable for measurement of linear displacements ranging from 1 to 10 cm. The accuracy is as high as 0.005 %.

The principle of change of capacitance with change in area can be employed for measurement of angular displacement. Figure 2.2 shows a two-plate capacitor. One plate is fixed and the other is movable. The angular displacement to be measured is applied to movable plate. The angular displacement changes the effective area between the plates and thus changes the capacitance. The capacitance is maximum when the two plates completely overlap each other i.e. when $\theta = 180^{o}$.

$$C_{max} = \frac{\epsilon A}{d} = \frac{\pi \epsilon r^2}{2d}$$

Capacitance at angle θ is $C = \frac{\epsilon r^2}{2d} \theta$

θ = angular displacement in radian.

Sensitivity $S = \frac{\partial c}{\partial \theta} = \frac{\epsilon r^2}{2d}$

The capacitor configuration and its response are shown in fig. 2.2(a) and (b) respectively.

Above mentioned capacitive transducer can be used for a maximum angular displacement of 180^{o}.

2.3 TRANSDUCERS USING CHANGE IN DISTANCE BETWEEN PLATES(8)

Figure 2.3 shows the basic form of a capacitive transducer utilizing the effect of change of capacitance with change in distance between the two plates.

One is fixed plate and displacement to be measured is applied to the other plate which is movable. Since, the capacitance C, varies inversely as the distance d, between the plates the response of the transducer is not linear so it is used for the measurements of extremely small displacements. The sensitivity for this configuration is expressed as,

$$\text{Sensitivity } S = \frac{\partial c}{\partial d} = -\frac{\epsilon A}{d^2}$$

Sensitivity of this type of transducer is not linear but varies over the range of the transducer as shown in fig. 2.31. Thus transducer exhibits non-linear characteristics.

Variable Separation (4) : The variation of capacitance between the plates with the distance between them is hyperbolic and is only approximately linear over a small range of displacement but by inserting a piece of mica, thinner than the gap minimum distance, between the plates a linear characteristic can be approached.

$$S = \frac{c}{d} = \frac{\epsilon_0 \epsilon_r a}{d^2}$$

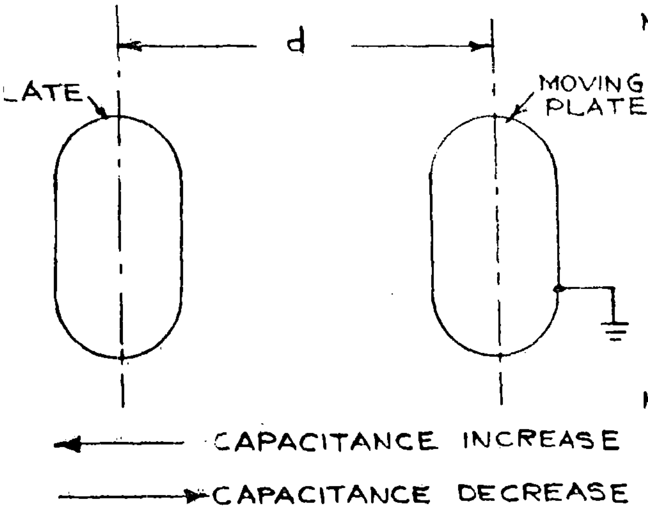


FIG. 2·3

CHANGE IN DISTANCE

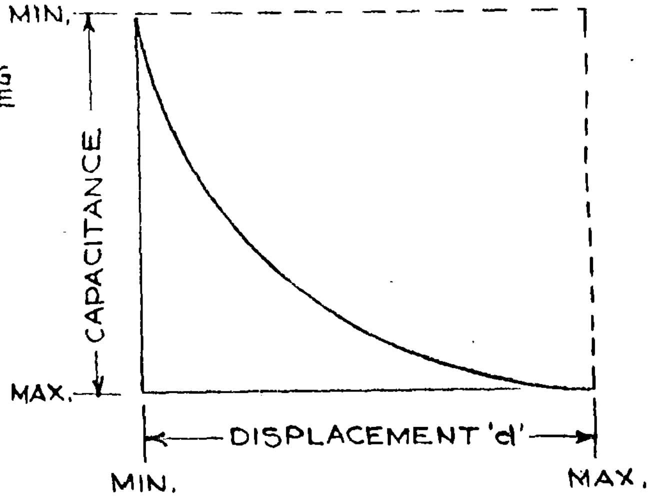


FIG. 2·3(1)

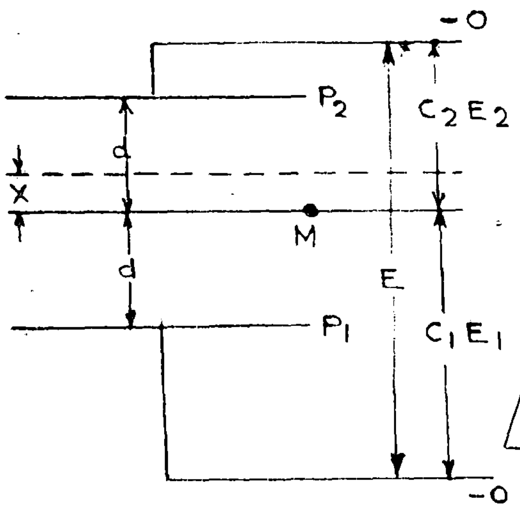


FIG. 2·3 (2)

VARIABLE SEPARATION

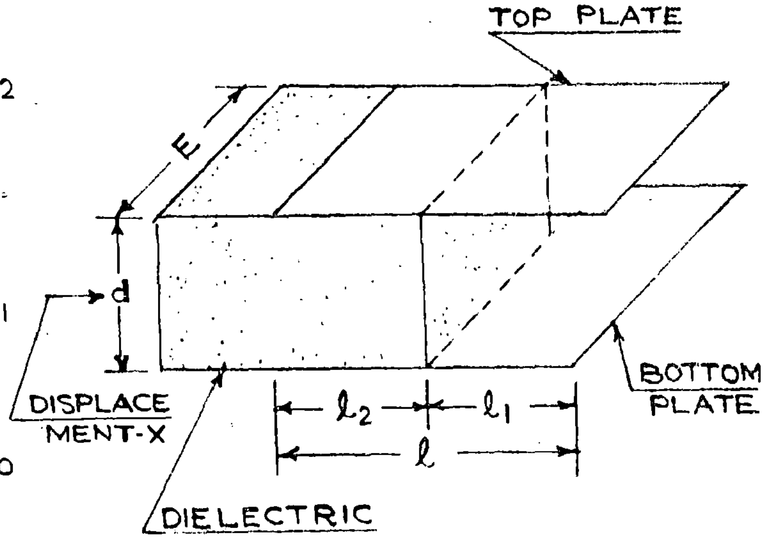


FIG. 2·4

CHANGE OF DIELECTRIC CONSTANT

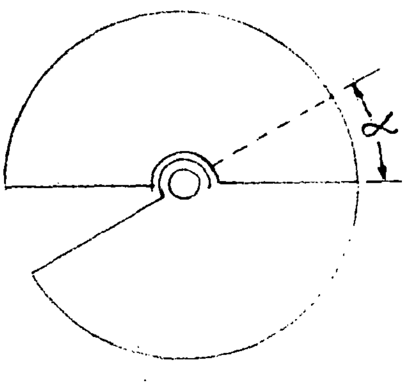


FIG. 2·52(a)

SINGLE

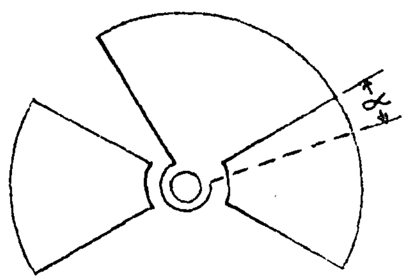


FIG. 2·52(b)

DIFFERENTIAL

CAPACITIVE TRANSDUCER FOR

360° ANGULAR DISPLACEMENT

The smaller the separation between the plates the greater the sensitivity but a practical limit is set by the voltage breakdown of the air in the gap at an electric field strength of 3 Kv/mm.

If the simple type of capacitor just described is modified so that it has two fixed plates a moveable plate which is mounted between the fixed plates so that the displacement increases the gap between it and one plate and decreases the gap between it and the other plate, the capacitance between the moveable plate and the two fixed plates also increases and decreases respectively.

P_1 and P_2 are the fixed plates and M the movable plate form the two capacitors C_1 and C_2. When M is midway between P_1 and P_2 and distance is d meter from them, the Capacitance C_1 and C_2 are equal. If now M is moved by distance x meter, then

$$C_1 = \frac{\epsilon_0 \epsilon_r a}{d + x} \qquad C_2 = \frac{\epsilon_0 \epsilon_r a}{d - x}$$

There are two ways of using these capacitance. Either the differences between them or the ratio of them is used.

(a) <u>Difference $C_1 - C_2$</u>

$$E_1 = \frac{EC_2}{C_1 + C_2} \qquad E_2 = \frac{EC_1}{C_1 + C_2}$$

$$E_1 = E\,\frac{\frac{\epsilon_0 \epsilon_r a}{d-x}}{\frac{\epsilon_0 \epsilon_r a}{d-x} + \frac{\epsilon_0 \epsilon_r a}{d+x}} \qquad = E\,\frac{\frac{\epsilon_0 \epsilon_r a}{d+x}}{\frac{\epsilon_0 \epsilon_r a}{d-x} + \frac{\epsilon_0 \epsilon_r a}{d+x}}$$

$$= E \frac{\frac{1}{d-x}}{\frac{1}{d-x} + \frac{1}{d+x}} \qquad = E \frac{d-x}{2d}$$

$$= E \frac{d+x}{2d}$$

$$E_1 - E_2 = E \frac{x}{d} = \Delta E$$

E versus x is a linear relationship

Sensitivity $S = \frac{\Delta E}{\Delta x} \propto \frac{1}{d}$

(b) Ratio C_1/C_2

$$\frac{C_1}{C_2} = N = \frac{\frac{\epsilon_0 \epsilon_r a}{d+x}}{\frac{\epsilon_0 \epsilon_r a}{d-x}} = \frac{d-x}{d+x}$$

The output varies in a non-linear manner with displacement although for very small displacement. When $d >> x$, $N \simeq 1 - \frac{x}{d}$. For $x = \frac{d}{5}$ deviation from linearity is about 20 %. The differential method has been used for displacements of 10^{-8} mm to 10 mm with an accuracy of 0.1 %.

2.4 TRANSDUCERS USING CHANGE IN DIELECTRIC CONSTANT(8)

The third principle used in capacitive transducers is the variation of capacitance due to change in dielectric constant. Fig. 2.4 shows a capacitive transducers for measurement of linear displacement working on the above mentioned principle. It has a dielectric of relative permittivity ϵ_r.

Initial capacitance of transducer $= C = \epsilon_0 \frac{wl_1}{d} + \frac{\epsilon_0 \epsilon_r wl_2}{d}$

$$= \epsilon_0 \frac{w}{d} [l_1 + \epsilon_r l_2]$$

Let the dielectric be moved through a distance x in the direction indicated. The capacitance changes from C to

$C + \Delta C$ is given as

$$C + \Delta C = \epsilon_0 \frac{w}{d}(l_1 - x) + \epsilon_0 \epsilon_r \frac{w}{d}(l_2 + x)$$
$$= \epsilon_0 \frac{w}{d}[l_1 - x + \epsilon_r (l_2 + x)]$$
$$= \epsilon_0 \frac{w}{d}[l_1 + \epsilon_r l_2 + x(\epsilon_r - 1)]$$
$$= C + \epsilon_0 \frac{wx}{d}(\epsilon_r - 1)$$

Change in capacitance $\Delta C = \epsilon_0 \frac{wx}{d}(\epsilon_r - 1)$

Hence the change in capacitance is proportional to displacement.

2.5 APPLICATIONS

2.5.1 Measurement of Length and Thickness (5)

The capacitance between two electrodes of cross-sectional area a m^2 and distance d meter apart is $C = 8.85 \epsilon \frac{a}{d}$ pf where ϵ is the dielectric contant of the medium between the plates.

If plates of radius r meter are used where r>>d, so that fringing effects can be neglected. The capacitance value is given by the relation

$$C = 27.8 \frac{\epsilon r^2}{d} \text{ pf}$$

This method is applicable for thickness measurement of thin insulating layers. Minimum thickness which can be measured is determined by the voltage at which break-down of the insulation occurs.

It will be noted that the value of capacitance depends upon the value of ϵ. If ϵ is constant the value of capacitance is inversely proportional to the distance between the plates, but keeping ϵ constant over a long period is difficult as the degree of humidity affects the value of ϵ .

2.5.2 Measurement of Angular Displacement (5)

The only type of capacitive transducer used for angular displacement is the variable area type and a single and a differential capacitive transducer as shown in fig. 2.52(a) and (b). The characteristic $C = f(\theta)$ can be modified by appropriate shaping of the movable plate. By using multiplate capacitors it is possible to increase the sensitivity.

The range of 360° can be obtained with an accuracy of $\pm$ 0.1 % and the law governing the relationship between the capacitance and the angular displacement depends on the shape of the plates.

2.5.3 Measurement of Angular Velocity (5)

A capacitive tachometer can be made by arranging for a capacitor to be charged from a source of direct voltage a portion of the revolution of the shaft and discharged through a meter for another portion of revolution (5). The average discharge current I is proportional to the rate of operation N.

$$I = C E N$$

where C is the value of the capacitor and E is the value of the charging voltage, N is the rate of operation.

Fig. 2.53(b) shows a slightly different version which provides an output current whose polarity depends on the direction of ration.

2.5.4 Measurement of Level (5)

Capacitive method uses variable area and can be used for conducting solids or liquids.

$$C = \frac{2\pi \epsilon h}{\ln(d_2/d_1)} F$$

where,

ϵ is absolute permittivity of the insulation

h is height of the liquid or solid in m.

d_1 is dia of metal rod in m.

d_2 is external dia. of insulator in m.

The container should be earthed to avoid any danger of electric shock and to prevent any errors due to external metal objects.

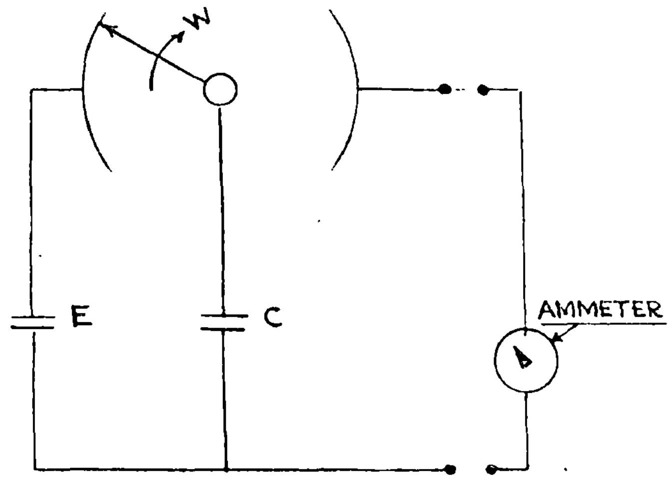
An auxiliary electrode P_1 is placed at a fixed distance above and electrically insulated from the reference electrode P_2. An alternating voltage is applied between the liquid and the electrode P_1. The electrode P_1 assume an alternating potential between zero and that of P_1 which varies with liquid level

$$E_o = E_a \frac{C_1}{C_1 + C_2} \text{ Volts}$$

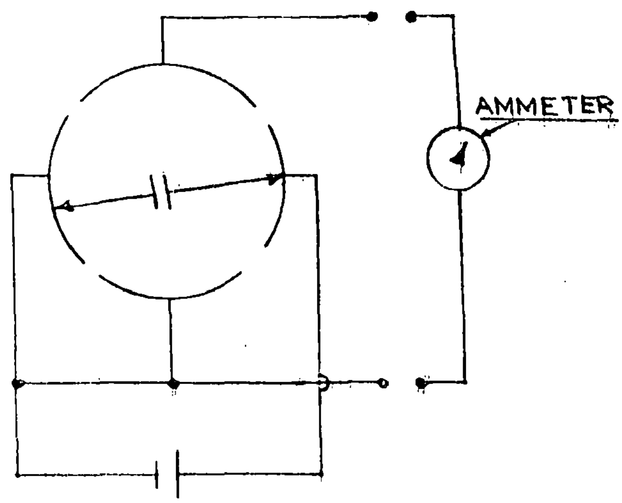
where,

E_a is the applied potential in V

C_1 is capacitance between P_1 and P_2 in F



CAPACITIVE TACHOMETER
FIG. 2·53 (a)



CAPACITIVE TACHOMETER
GIVING CHARGE OF OUTPUT VOLTAGE
POLARITY WITH CHANGE OF DIRECTION
FIG. 2·53 (b)

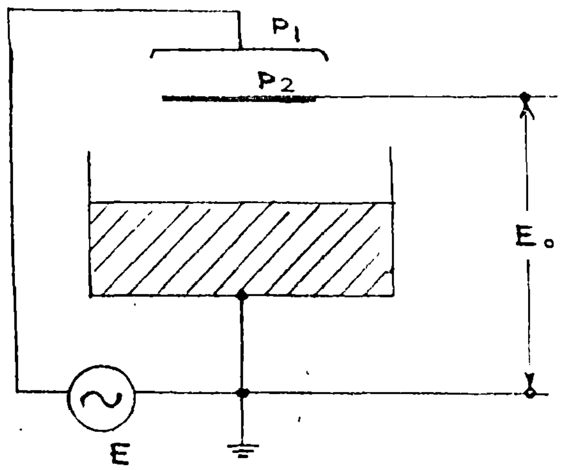


FIG. 2·54 (1)

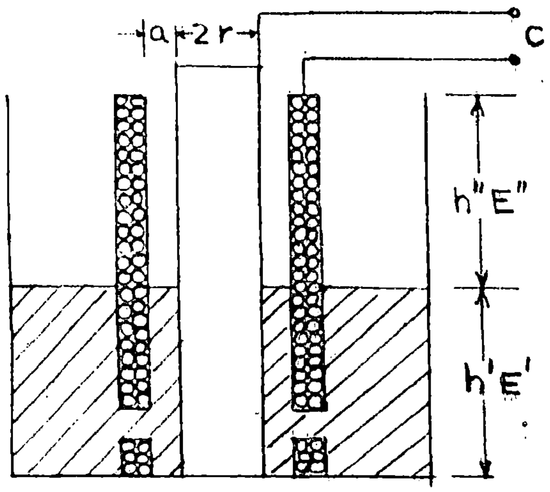


FIG. 2·54 (2)
MEASUREMENT OF LEVEL

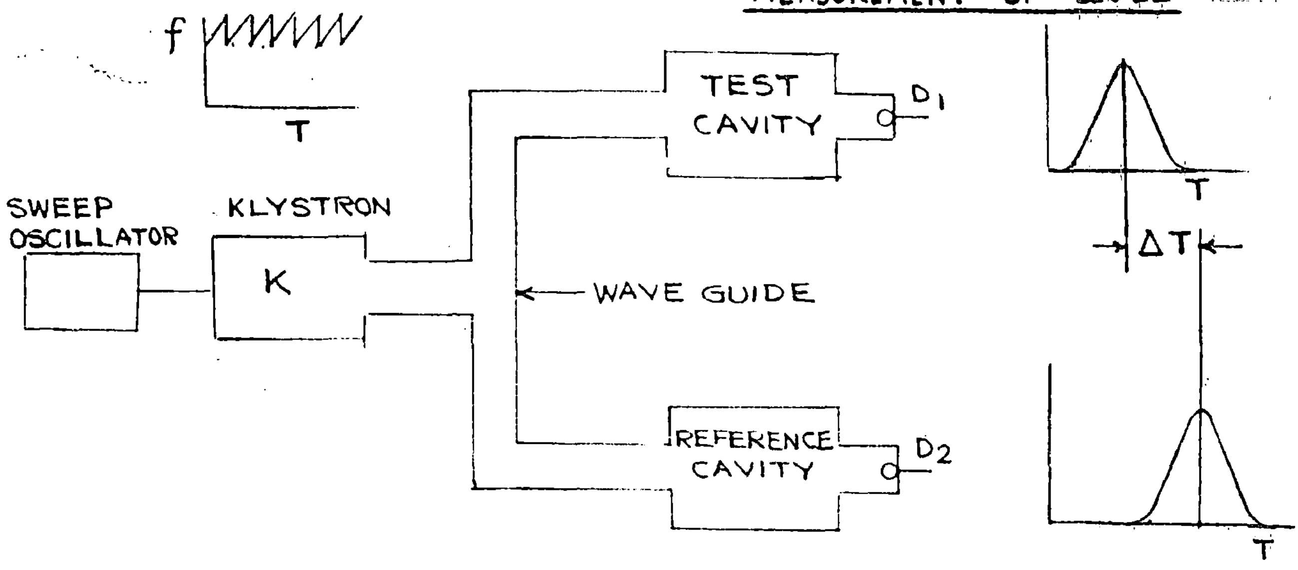


FIG. 2·55

C_2 is capacitance between P_2 and surface of the liquid in F. This is inversely proportional to the distance between the liquid surface and P_2

E_0 decreases with rise of liquid level and the relationship in non-linear.

By using a servo-system to move the two electrodes P_1 and P_2 up and down and keep the distance between P_2 and the liquid constant a more accurate system can be made. The minimum distance from the liquid for P_2 is 2.5 cm. The servo system is actually a conversion from level to displacement and then the level change is read by a displacement transducer. The range is 4.5 cm. with an accuracy of $1\frac{1}{2}$ % full scale. The linearity of the simple system is very poor but that of the servo system is that of the displacement transducer.

If the liquid is non-conducting, then it can be used as the dielectric in a capacitor. The electrodes are normally two concentric cylinders. Figure 2.54(2) At the lower end of the outer cylinder are holes which allow ingress to the liquid. If small enough, these holes provide mechanical damping of the surface variation.

The capacitance of a cylindrical capacitor is

$$C = \frac{\epsilon h}{2 \, l_n(r_2/r_1)}$$

where,

ϵ is absolute permittivity of the medium between the cylinders.

h is length of the cylinders in m.

r_1 and r_2 are the radii of the cylinder surfaces enclosing the liquid.

If the cylinder is partly filled with liquid, the capacitance C when $h \gg r_2$ and $r_2 \gg r_2 - r_1$ is

$$C \quad 2\pi \frac{\epsilon' h' + \epsilon'' h''}{l_n(r_2/r_1)}$$

To avoid errors due to external objects the outer cylinder should be earthed. In practice accuracies between ± 5 % and ± 10 % and linearities of 2 % to 3 % are obtainable.

Advantages : Can be used for solids or liquids.

Disadvantages : Material must be conducting.

2.5.5 Measurement of Humidity and Water Content (5)

Range	0 - 100 %
Accuracy	± 3 %
Linearity	Non-linear
Disadvantages	Equilibrium takes 10-100 S to be established. Capacitance varies by a factor of 100 between 0 and 100 % humidity.

Measurement of Water Content

Range	10 ppm to saturation
Accuracy	± 2 %
Linearity	Linear
Advantages	Can detect 1 ppm

The microwave refractometer consists of a cavity whose resonant frequency varies with the dielectric constant of the material in the cavity. If f_1 is the resonant frequency of the cavity when it is filled with a dry gas (dielectric constant ϵ_1) and f_2 the resonant frequency with the cavity filled with wet gas (dielectric constant ϵ_2).

$$\frac{\epsilon_2}{\epsilon_1} = \left(\frac{f_1}{f_2}\right)^2$$

A schematic diagram of the system used is shown in figure 2.55. Two resonant cavities are excited by a micro-wave source K (a Klystron).

The resonance in each cavity is indicated by the output from a crystal diode, D_1, D_2. A frequency modulator S shifts the Klystron frequency in a sawtooth manner as shown. If the two gases in the cavities have different dielectric constants, resonance will occur in one cavity followed a little later in time by resonance in the other cavity. The time interval, ΔT between the two resonances.

The proportion of one substance mixed with dissolved or absorbed in another can be determined by measuring the dielectric constant of the mixture, solution or other combination provided the variations cause the dielectric constant to vary by a sufficiently large amount. Since the dielectric constant of most insulating solids or fluids is less than 10 and that of water is 81, this is a reasonable means of measuring moisture content. The material is placed between the plates of a capacitor in one arm bridge while a similar capacitor with a dry sample of the same material is in an adjacent arm of the bridge.

However, the law concentration of water in gases even at saturation, causes only a very small change in the dielectric constant (for dry air at 45°C. r=1.000247 at saturation r = 1.000593). A transducer for measuring the small change consists of two concentric cylinders, between which the gas is blown, forming a cylindrical capacitor. The outer tube is thermally insulated and heated slightly to prevent condensation. This capacitor forms the frequency determining element in an oscillator operating at 2 MHz. A change in frequency is caused by the presence of water vapour in the gas, its magnitude depending on the quantity of water vapour.

The dynamic response depends on the velocity of the gas through the transducer, but 50 % of final response has been reached in 100 mS. The system can detect changes of 1 mg. of water vapour per litre of gas.will be proportional to the difference between the resonance frequencies.

In the practical form of transducer a null balance technique is used, in which a servo system alters the volume and hence the resonant frequency of the cavity until both cavities resonate at the same frequency. The gas temperature and pressure in both cavities are kept constant and the output is then directly calibrated in vapour pressure.

The response time is limited by the flow of gas through the cavities. The time constant is approximately 10 S.

An accuracy of $\pm$ 0.5 deg.C is possible for dew point measurement between $-40^{o}C$ and $+40^{o}C$.

2.5.6 Determination of Composition of Materials and Proportions of Mixture (5)

A method particularly suited for liquids and very often used for measurement of oil contamination and the salintly of water uses the change in dielectric. Constant of the solution with addition of contaminants. Provided the difference is large enough it can be used as a measure of the amount of added material.

A cell containing the specimen ofsolution, which can be a section of pipe through which the solution flows, has two plane electrodes placed in it. Any change in the concentration of the additive or any contamination produces a change in capacitance between the electrodes which is a measure of the amount of additive or contaminant. Range is 2 parts in 10^{6} to maximum saturation of solvent. Disadvantage is that it measures dissolved water in non-volatile liquid only.

2.5.7 Measurement of Temperatures (5)

The dielectric constant of some insulators and semiconductors varies with temperature and a capacitor made with such a material as dielectric changes its capacitance with temperature.

The dielectric material used in a transducer of this type has to be carefully chosen as some materials exhibit very large changes of dielectric constant with temperature but also exhibit large hysteresis effects. Other although having large dielectric constant changes increases their dielectric losses with temperature to such a degree that it is impractical to use them for transducer work.

Range of measurement is $-40^{\circ}C$ to $+160^{\circ}C$. Linearity is ± 1 %. The disadvantage is that the dielectric has to be carefully choosen.

2.6 COMPARISON WITH RESISTIVE AND INDUCTIVE TYPE TRANSDUCERS

2.6.1 Resistive Transducers (8)

The measurement of change in resistance are preferred to those employing other variables. This is because both alternating as well as direct currents and voltages are suitable for resistance measurement.

The resistance of metal conductor is expressed by

$$R = \rho \frac{L}{A}$$

where,

R is the resistance in Ω

L is the length of conductor in m.

A is cross-sectional area of conductor in m^2,

ρ is the resistivity of conductor material in Ω-m.

There are number of ways in which resistance can be changed by a physical phenomenon. The translational and rotational potentiometers which work on the basis of change in the value of resistance with change in length of the conductor can be used for measurement of translational or rotary displacements. Strain gauges work on the principle that the resistance of a conductor or a semi-conductor changes when strained. This property can be used for measurement of displacement, force and pressure. The resistivity of material changes with change of temperature thus causing a change in resistance. The property may be used for measurement of temperature. Thus electrical resistance transducers have a wide field of application.

<u>Potentiometers</u> : Consider a translational potentiometer as shown in fig. 2.6.

Let ei = input voltage, V; R_p = total resistance of potentiometer, r

xt = total length of translational pot, m.

xi = displacement of the slider from its O position, m

eo = output voltage, V

$$eo = \left(\frac{\text{resistance at output terminals}}{\text{resistance at the input terminal}}\right) \times \text{input voltage}$$

$$= \left[\frac{R_p/xt \times xi}{R_p}\right] \times ei = \frac{xi}{xt}\, ei$$

Under ideal condn. eo varies linearly with displacement.

$$\text{Sensitivity } S = \frac{\text{output}}{\text{input}} = \frac{eo}{xi} = \frac{ei}{xt}$$

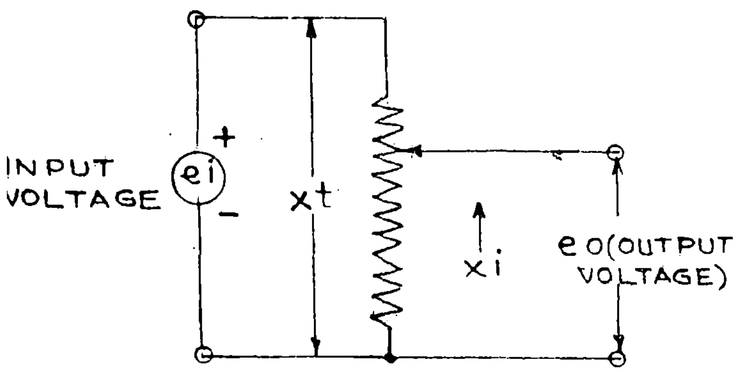


FIG. 2.6
POTENTIOMETER

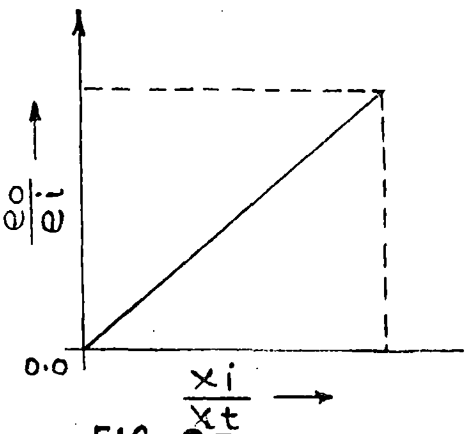


FIG. 2.7

Under ideal condn. sensitivity is constant. Output has linear relationship with input as shown in fig. 2.7.

Effect of Temp. Resistance of metal conductor changes with change in temperature by changing the resistivity of material.

$$\text{Let } R = \rho \frac{L}{A}$$

$$\Rightarrow \frac{\partial R}{\partial \rho} = \frac{L}{A}$$

$$\Rightarrow \text{Sensitivity } S = \frac{\partial R}{\partial \rho} = \frac{L}{A}$$

This implies that sensitivity S is inversely proportional to Area (A) while in capacitive pick-ups

$$C = \epsilon \frac{A}{d}$$

$S = \frac{\partial C}{\partial \epsilon} = \frac{A}{d}$, Sensitivity is directly proportional to Area (A).

Sensitivity : In order to get a high sensitivity the output voltage eo should be high which in turn requires a high input voltage ei. Due to limitations of power dissipation, ($ei_{max} = \sqrt{PR_p}$ volts) the input voltage is limited by the resistance of the potentiometer. In order to keep the power dissipation at a low level, the input voltage should be small and resistance of the potentiometer should be high. Thus for a high sensitivity, the input voltage should be large and this calls for a high value of resistance R_p.

Typical values of sensitivity are of the order of 200 mv/degree for a rotational potentiometer and 200 mv/mm. for translational potentiometer. The short stroke devices have generally a high values of sensitivity.

Advantages of Resistive Transducers over Capacitive Transducer

(i) They are simple to operate and are very useful for applications where the requirements are not particularly severe.

(ii) They are very useful for measurement of large amplitudes of displacement.

(iii) Their electrical efficiency is very high and they provide sufficient output to permit control operations without further amplification.

Disadvantages of Resistive Transducers Comparative to Capacitive Transducer

(i) They require large force to operate.

(ii) They are less sensitive.

(iii) Frequency response is not good.

(iv) Require large power to operate.

2.6.2 Inductive Transducers (8)

The variable inductance type transducers work upon one of the following three principles -

(i) Variation of self-inductance

(ii) Variation of mutual-inductance

(iii) Production of eddy current.

$$L = \frac{N^2}{R}$$

where,

N is the no. of turns, R is the reluctance of the magnetic curcuit, L is the self-inductance of a coil.

Normally the change in self-inductance ΔL or ΔM which is change in mutual inductance for Inductive transducers is adequate for detection for subsequent stages of instrumentation system. However, if the succeeding stages of instrumentation respond to ΔL or ΔM, rather than to $L+\Delta L$ or $M+\Delta M$ the sensitivity and accuracy will be much higher. The transducers can be designed to provide two outputs one of which is an increase of inductance and other is a decrease in inductance. In response to a physical signal, the inductance of one part increases from L to $L+\Delta L$ while that of other part decreases from L to $L-\Delta L$. The change is measured as the difference of the two resulting in an output of $2\Delta L$ instead ΔL when only a single winding used. This increases the sensitivity and also eliminates errors.

Inductive transducer can be used for the measurement of displacement etc.

Advantages and Disadvantages of Inductive Transducers over Capactive Transducers

Advantages :

(i) Resolution is good as fine as 1×10^{-3} mm.

(ii) Output is linear for displacements upto 5 mm

(iii) Inductive transducers can be used for measurement of weight.

Disadvantages :

(i) Capacitive transducers can be used for applications where stray magnetic fields render the inductive transducers useless.

(ii) The dynamic response is limited.

*****

CHAPTER-III

SENSITIVITY ANALYSIS

3.1 INTRODUCTION

Sensitivity analysis is useful in finding the accuracy of a bridge higher the sensitivity better is the bridge. Knowing the sensitivity -

(i) Select a galvanometer with which given unbalance maybe observed in a specified bridge arrangement.

(ii) Determine the minimum unbalance which can be observed with a given galvanometer in the specified bridge arrangement.

(iii) Determine the deflection to be expected for a given unbalance.

In case of capacitive pick-ups we can see that sensitivity is constant using change in area of plates but it is not constant using change in distance between plates in this case it varies over the range of the transducer. The capacitive transducers are highly sensitive and can be used for measurement of extremely small displacements down to the order of molecular dimensions i.e. 0.1×10^{-6} mm. This is on account of the fact that small capacitances changes produced on account of small displacements can be measured. In practice it is possible to detect capacitance change of the order of 1 aF = 10^{-18}F and that too with a good degree of accuracy. On the other hand they can be used for measurement of large distances upto about 30 m as in aeroplane altimeters. The change in displacement method is generally preferable for either very small or very large displacements. The change in area method is used for measurement of displacement, ranging from 10 mm to 100 mm and this is the advantage that by knowing the sensitivity we can find out the range for which it is applicable without less of sensitivity and accuracy.

The sensitivity of a particular a.c. bridge measurement may be regarded as the accuracy with which balance is achieved. It is expressed in terms of the smallest response of the detector which can be observed with reliability.

The conditions for maximum sensitivity to measure an impedance Z_1 assuming a given source Z_6 and detector Z_5 are shown in fig. 3.1.

When a certain network has been setup, interchanging the source and detector may increase the sensitivity. The

$$Z_3 = \sqrt{Z_5 \cdot Z_6} \qquad Z_2 = \sqrt{\left[\frac{Z_6 \cdot Z_1}{Z_6+Z_1}(Z_5+Z_1)\right]}$$

$$Z_4 = \sqrt{\left[\frac{Z_5 \cdot Z_1}{Z_5+Z_1}(Z_6+Z_1)\right]}$$

rule for their relative positions is the same as for the d.c. bridge : whichever one of Z_5 and Z_6 is larger than the other should connect the junction of the two largest consecutive impedances in the bridge with the junction of the smallest consecutive impedances. We can select a bridge of desired type for increasing sensitivity changes or decreasing sensitivity changes.

3.2 ANALYSIS FOR A FOUR ARM WHEAT STONE BRIDGE

Wheat stone bridge balance in unaffected when the source and detector are interchanged. The criterion for obtaining maximum sensitivity has been expressed in number of ways : for example, 'Considering the battery and the galvanometer, the one having the higher resistance should join the junction of the two highest resistance bridge arms to the junction of the two lowest'. The classical Analysis of this problem is complicated by two peripheral factors -

(1) Maximum sensitivity is obtained at maximum source voltage, which in turn is determined by the allowable power dissipation. Hence, the two circuit arrangements should be compared not on the basis of equal voltages, but on the basis of equal peak power dissipation.

(2) The measurement accuracy depends on the galvanometer damping which in turn is determined by the bridge resistance seen at the galvanometer terminals. Hence a comparison of sensitivity values of various bridge arrangements is of limited value unless the galvanometer-damping ratios are identical.

According to fig. 3.2, the dimensionless sensitivity function S_{Ri} can be defined by expressing the unbalance voltage ed asa function of the source voltage E. Thus

$$S_{Ri} = \frac{\partial ed}{\partial Ri / Ri} \quad \text{at null}$$

It designates the null sensitivity to a fractional change in the resistance Ri.

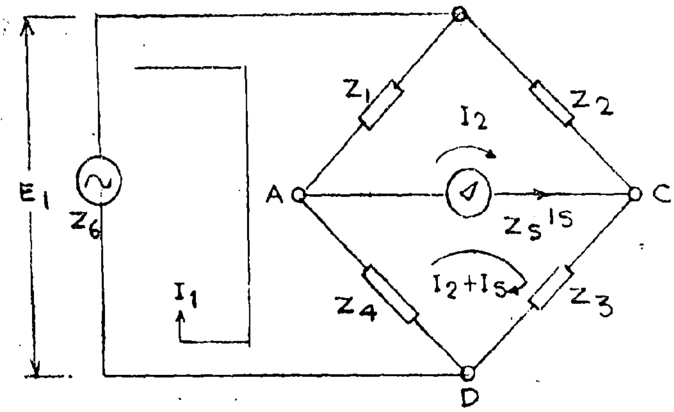
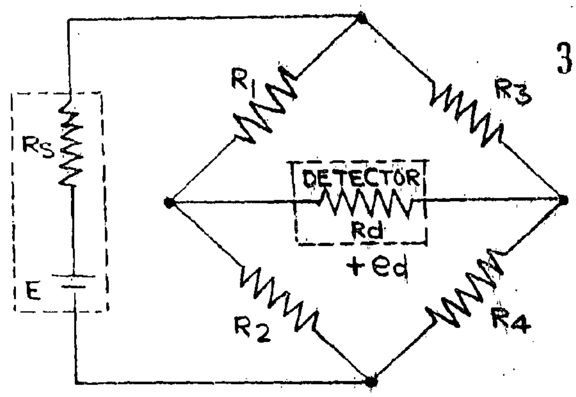


FIG. 3.1



WHEAT-STONE BRIDGE

FIG. 3.2

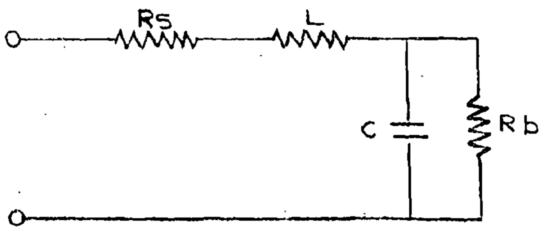


FIG. 3.3

EQUIVALENT CIRCUIT

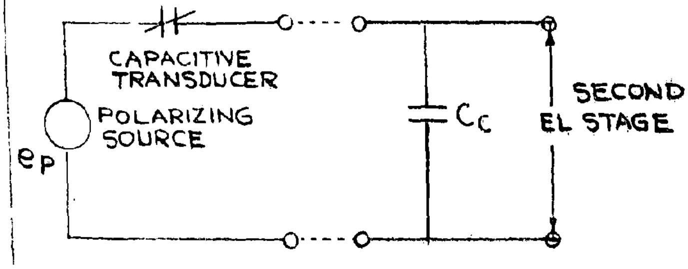


FIG. 3.4

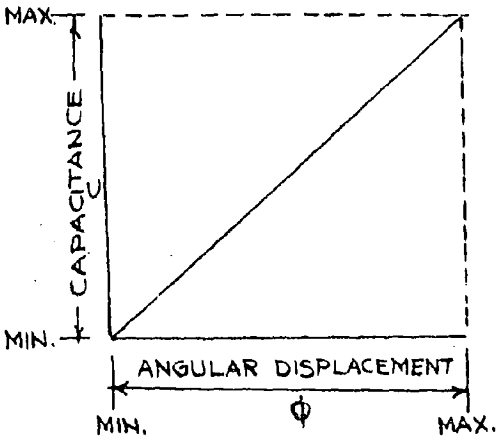
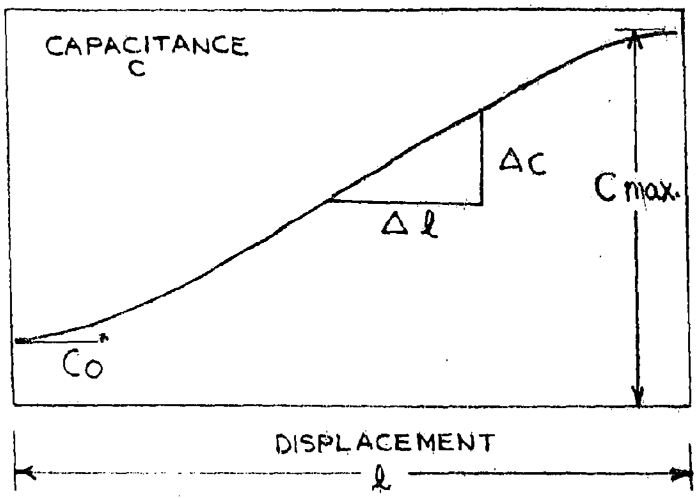


FIG 3.52



TRANSFER CHARACTERSTIC

FIG. 3.53

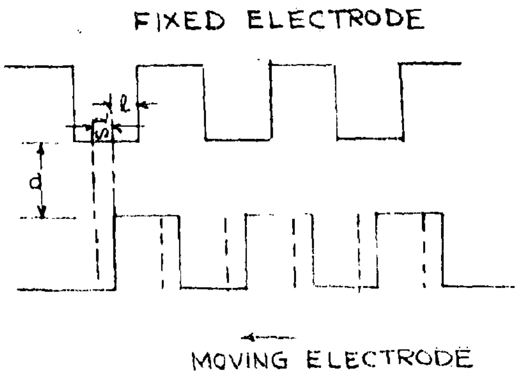


FIG 3.54

SERRATED TRANSDUCER

3.2.1 Analysis of Ideal Bridge :

The simple case of zero source impedance and detector conductance $R_S = 0$ and $Rd = \infty$ is analysed :

$$\frac{ed}{E} = \frac{R_2}{R_1+R_2} - \frac{R_4}{R_3+R_4} = \frac{R_2R_3-R_1R_4}{(R_1+R_2)(R_3+R_4)}$$

R_4 is chosen as the unknown resister to be measured. The analysis is restricted to a bridge with two fixed and one adjustable bridge arm. There are two configurations -

(i) The two fixed resistors are connected across the source, e, R_1 and R_2 are fixed R_3 is adjustable.

(2) The two fixed arms are connected across the detector, i.e. R_1 and R_3 are fixed, R_2 is adjustable.

These two configurations are equivalent to interchanging

Case 1 : R_3 Adjustable :

Sensitivity is given by

$$\frac{\partial ed}{\partial R_3} = \frac{R_4 E}{(R_3+R_4)^2}$$

⇒ dimensionless sensitivity function

$$S_{Rs} = \left|\frac{R_3\ R_4}{(R_3+R_4)^2}\right|_{R_1R_4=R_2R_3} = \frac{(R_1/R_2)}{[1+(R_1/R_2)]^2}$$

Since R_1 and R_2 are fixed bridge arms, the sensitivity is constant, independent of the value of the unknown resistor R_4, which is being balanced. Maximum sensitivity is obtained for equal bridge arms $R_1 = R_2$ and is -

$$S_{max} = 1/4$$

Case 2 : R_2 Adjustable :

This case requires the computation of -

$$\frac{\partial ed}{\partial R_2} = \frac{R_1 E}{(R_1+R_2)^2}$$

$$S_{R_2} = \left| \frac{R_1 R_2}{(R_1+R_2)^2} \right|_{R_1 R_4 = R_2 R_3} = \frac{R_3/R_4}{[1+(R_3/R_4)]^2}$$

The bridge sensitivity is not constant, but depends on the value of the unknown R_4, the peak value of sensitivity is again 1/4 and occurs for the equal arm bridge $R_4 = R_3$.

From the point of view of uniform sensitivity, Case 1 is clearly superior. We can expect a similar result when source resistance and detector conductance are small compared to the bridge-arm parameters.

3.3 GENERAL WHEAT STONE BRIDGE

When the source and detector resistances are of the same order of magnitude as the bridge arm, the analysis of the ideal bridge no longer suffices, and the general bridge must be considered.

Case 1 : Fixed R_1 and R_2, and variable R_3

The relevant sensitivity function is -

$$SR_3 = \frac{R_1 R_2 R_d R_4}{[(R_1+R_2+R_s)R_4+R_2R_s]\,[R_1R_4+(R_1R_2+R_1R_d+R_2R_d)]}.$$

and it vanishes for both zero and infinite R_4. Its maximum is found by the differentiation procedure -

$$S_{max} = \frac{(R_1/R_2)/[1+(R_1/R_2)]^2}{\left[\sqrt{\frac{R_s}{R_d}\frac{R_1/R_2}{[1+(R_1/R_2)]^2}}+\sqrt{[\frac{1+R_S}{R_1+R_2}]\ [1+\frac{1}{(1/R_1+1/R_2)Rd}]}\right]^2}$$

and it occurs at a value of R_4 equal to

$$R_{opt} = \sqrt{\frac{R_S R_d}{R_1/R_2}}\ \frac{\sqrt{1+\frac{1}{(1/R_1+1/R_2)Rd}}}{\sqrt{1+R_S/(R_1+R_2)}}$$

Case 2 : Fixed R_1 and R_3 and variable R_2

The sensitivity function is -

$$SR_2 = \frac{R_1\ R_3\ R_4\ R_d}{[(R_1+R_3+R_d)R_4+R_3\ R_d]\ [R_1R_4+(R_1R_3+R_1R_S+R_3R_S)]}$$

It again vanishes for zero and infinite R_4. The expression is -

$$S_{max.} = \frac{1}{\left[1+\sqrt{[1+(R_1/R_3)/R_d][1+(1/R_1+1/R_3)R_S]}\right]^2}$$

$$R_{opt.} = R_3\sqrt{\frac{1+(1/R_1+1/R_3)R_S}{1+(R_1+R_3)/R_d}}$$

3.4 SCHERING BRIDGE (2)

In fig. 3.1, Z_4 is variable

Current Sensitivity (2) - The current sensitivity of a network to a change in any balancing adjustment may be obtained by -

$$I_S = \frac{Z_1Z_3 - Z_2Z_4}{\Delta} E.$$

Assuming Z_1, Z_2, Z_3, Z_5 and Z_6 to be given and that adjustments are made to Z_4

$$\frac{\partial I_5}{\partial Z_4} = \frac{-Z_2 \Delta - (Z_1 Z_3 - Z_2 Z_4) . \partial \Delta / \partial Z_4}{\Delta^2} E$$

$Z_1 Z_3 - Z_2 Z_4 = 0$, the rate of change at balance is

$$\left| \frac{\partial I_5}{\partial Z_4} \right|_0 = \frac{Z_2}{\Delta_0} . E$$

where Δ_0 is the value of Δ at balance.

$$\Delta_0 = \frac{1}{Z_2} \left[(Z_2+Z_3)Z_5 + (Z_1+Z_2)Z_3 \right] \cdot \left[(Z_1+Z_2)Z_6 + Z_1(Z_2+Z_3) \right]$$

and so

$$\left(\frac{\partial I_5}{\partial Z_4}\right)_0 = \frac{-Z_2^2}{(Z_1+Z_2)(Z_2+Z_3)\left[Z_5 + \frac{(Z_1+Z_2)}{(Z_2+Z_3)} Z_3\right] \cdot \left[Z_6 + \frac{(Z_2+Z_3)}{(Z_1+Z_2)} Z_1\right]} E$$

Finite increments near balance, put $Z_2 = Z_1 Z_3 / Z_4$ in the numerator, then -

$$\partial I_5 \approx \frac{-Z_1 \; Z_2 \; Z_3}{(Z_1+Z_2)(Z_2+Z_3)\left[Z_5 + \frac{(Z_1+Z_2)}{(Z_2+Z_3)} Z_3\right] \cdot \left[Z_6 + \frac{(Z_2+Z_3)}{(Z_1+Z_2)} Z_1\right]} \cdot \frac{\partial Z_4}{Z_4} \cdot E$$

expresses the increment of current at balance in terms of a fractional increase $\partial Z_4 / Z_4$ in the branch Z_4. Let the voltage E to be maintained between A and C i.e. the impedance Z_6 be disregarded -

$$\partial I_5 \approx \frac{-Z_2 \; Z_3}{(Z_2+Z_3)^2 \left[Z_5 + \frac{(Z_1+Z_2)}{(Z_2+Z_3)} Z_3\right]} \cdot \frac{\partial Z_4}{Z_4} \cdot E$$

$$\approx -\frac{-1}{\frac{(Z_1+Z_2)(Z_2+Z_3)}{Z_2}\left[1+Z_5\frac{(Z_2+Z_3)}{(Z_1+Z_2)Z_3}\right]}\cdot\frac{\partial Z_4}{Z_4}\cdot E$$

Now

$$\frac{(Z_1+Z_2)(Z_2+Z_3)}{Z_2} = \frac{Z_1Z_2+Z_2^2+Z_2Z_3+Z_1Z_3}{Z_2}$$

$$= Z_1+Z_2+Z_3+Z_4$$

when $Z_1Z_3 = Z_2Z_4$, Also if Z_{BD} is the combined impedance of (Z_1+Z_2) and (Z_3+Z_4) in parallel, i.e. the impedance of the network connected to the detector terminals is -

$$Z_{BD} = \frac{(Z_1+Z_2)(Z_3+Z_4)}{Z_1+Z_2+Z_3+Z_4}$$

But $Z_1+Z_2+Z_3+Z_4 = (Z_2+Z_3)(Z_3+Z_4)/Z_3$ when $Z_1Z_3 = Z_2Z_4$

so that

$$Z_{BD} = \frac{(Z_1+Z_2)}{(Z_2+Z_3)}\cdot Z_3$$

Substituting, at balance, the rate of increase is -

$$\frac{\partial I_5}{\partial Z_4} = -\frac{1}{(Z_1+Z_2+Z_3+Z_4)\left[1+\frac{Z_5}{Z_{BD}}\right]}\cdot\frac{1}{Z_4}\cdot E$$

and the increment is

$$\partial I_5 = \frac{1}{(Z_1+Z_2+Z_3+Z_4)\left[1+\frac{Z_5}{Z_{BD}}\right]}\cdot\frac{\partial Z_4}{Z_4}\cdot E$$

<u>Voltage Sensitivity (2)</u> : Let a sinuoidal voltage E be applied to points B and D (1). If the detector branch-points A,C. are joined to an infinitely high impedance - represented

very closely by an amplifier - then the voltage between A and C -

$$V = \frac{Z_1Z_3 - Z_2Z_4}{(Z_1+Z_2)(Z_3+Z_4)} \cdot E$$

Let Z_1 to be measured, Z_2 and Z_3 fixed impedances and Z_4 the adjustable impedance -

$$\frac{\partial V}{\partial Z_4} = [\frac{-Z_2}{(Z_1+Z_2)(Z_3+Z_4)} - \frac{Z_1Z_3-Z_2Z_4}{(Z_1+Z_2)(Z_3+Z_4)^2}]E$$

When the bridge is balanced, $Z_1Z_3-Z_2Z_4 = 0$, the rate of change is -

$$(\frac{\partial V}{\partial Z_4})_0 = - \frac{Z_2}{(Z_1+Z_2)(Z_3+Z_4)} \cdot E$$

Now to small finite increments in Z_4 near balance, put $\sigma = \partial Z_4/Z_4$ fractional change in Z_4 from balance and $A = Z_1/Z_2 = Z_4/Z_3$. Then voltage -

$$\partial V = - \frac{A}{(1+A)^2} \sigma E$$

<u>Value of σ</u>

Taking $Z = R+j x$ as impedance of any given adjustable branch at balance, slight change can be made either in R or in x. Adjusting R gives $\partial Z = \partial R$ with x, unaltered, and in general-

$$\sigma = \frac{\partial Z}{Z} = \frac{\partial R}{R} \cdot \frac{R}{R+jx} = \frac{\partial R}{R} \cos \phi \; \angle -\phi$$

where

ϕ = arc tan x/R is the phase angle of the adjustable branch.

If x is slightly changed from the balance value with R unaltered, $\partial Z = j.\partial x$ and in general.

$$\sigma = \frac{\partial Z}{Z} = \frac{\partial x}{x} \cdot \frac{j\, x}{R+jx} = \frac{\partial x}{x} \sin\phi \;\angle \pi/2 - \phi$$

3.5 SENSITIVITY ANALYSIS OF CAPACITIVE PICK-UPS

3.5.1 Two Plate Capacitor :

For a two plate capacitor the capacitance,

$$C = \frac{\epsilon A}{d} = \frac{\epsilon l w}{d} \text{ F}$$

where

l is the length of overlapping part of platesin m and

w is the width of overlapping part of plates in m.

Sensitivity using change in Area of Plates

$$\text{Sensitivity } S = \frac{\partial C}{\partial l} = \epsilon \frac{w}{d} \text{ F/m}$$

The sensitivity is constant and therefore there is linear relationship between capacitance and displacement.

Sensitivity for fractional change in capacitance

$$S^1 = \frac{\partial C}{C \partial l} = \frac{1}{l}$$

Thin type of capacitive transducer is suitable for measurement oflinear displacements ranging from 1 to 10 cm. The accuracy is as high as 0.005 %.

Sensitivity with variable separation :

$$S = \frac{\partial C}{\partial d} = \frac{-\epsilon A}{d^2}$$

It is clear that sensitivity of this type of transducer is not constant but varies over the range of transducer. Transducer exhibits non-linear characteristics.

Sensitivity for fractional change in capacitance.

$$S^1 = \frac{\partial C}{C \partial d} = -\frac{1}{d}$$

Sensitivity S^1 increase in inverse proportion to the plate separation d and independent of the other dimensions of the capacitor. Response characteristics is linear.

<u>Sensitivity with variation of dielectric constant</u>

$$\text{Initial capacitance} = C = \frac{\epsilon_0 w l_1}{d} + \frac{\epsilon_0 \epsilon_r w l_2}{d}$$

$$= \epsilon_0 \frac{w}{d} [l_1 + \epsilon_r l_2]$$

Let dielectric be moved through a distance in the x direction indicated. The capacitance changes from C to $C + \Delta C$, and

$$C + \Delta C = \epsilon_0 \frac{w}{d} (l_1 - x) + \epsilon_0 \epsilon_r \frac{w}{d} (l_2 + x)$$

$$= \epsilon_0 \frac{w}{d} [l_1 - x + \epsilon_r (l_2 + x]$$

$$= \epsilon_0 \frac{w}{d} [l_1 + \epsilon_r l_1 + x(\epsilon_r - 1)]$$

$$= C + \epsilon_0 \frac{wx}{d} (\epsilon_r - 1)$$

$$\Delta C = \epsilon_0 \frac{wx}{d} (\epsilon_r - 1)$$

$$\text{Sensitivity} \quad S = \frac{\partial C}{\partial \epsilon_r} = \frac{\epsilon_0 w l_2}{d}$$

So sensitivity is constant.

Sensitivity for fractional change in capacitance

$$S^1 = \frac{\partial C}{C\,\partial\epsilon_r} = \frac{l_2}{l_1+\epsilon_r l_2} = \frac{l_2/l_1}{1+\epsilon_r \frac{l_2}{l_1}}$$

$$S^1 = \frac{B}{1+\epsilon_r B}$$

where $B = \frac{l_2}{l_1}$

3.5.2 Cylindrical Capacitor :

For cylindrical capacitor the capacitance is :

$$C = \frac{2\pi\epsilon l}{\log_e(D_2/D_1)}\ F$$

where,

l is the length of overlapping part of cylinders in m,

D_2 is the inner diameter of outer cylindrical electrode in m, and

D_1 is the outer diameter of inner cylindrical electrode in m.

Sensitivity Using change in Area of Plates

$$\text{Sensitivity, } S = \frac{\partial C}{\partial l} = \frac{2\pi\epsilon}{\log_e(D_2/D_1)}$$

Therefore, the sensitivity is constant and the relationship between capacitance and displacement in linear

For fractional change in capacitance,

$$\text{Sensitivity } S^1 = \frac{\partial C}{C\,\partial l} = 1/l$$

Sensitivity Using change in D_2

$$\text{Sensitivity } S = \frac{\partial C}{\partial D_2}$$

$$= -\frac{2\pi\epsilon l}{\left[\log_e(D_2/D_1)\right]^2} \quad \frac{1}{(D_2/D_1)} \cdot \frac{1}{D_1}$$

$$= -\frac{2\pi\epsilon l}{\left[\log_e(D_2/D_1)\right]^2} \cdot \frac{D_1}{D_2} \cdot \frac{1}{D_1}$$

$$= -\frac{2\pi\epsilon l}{D_2\left[\log_e(D_2/D_1)\right]^2}$$

for fractional change in capacitance

$$S^1 = \frac{\partial C}{C\partial D_2} = -\frac{1}{D_2 \log_e(D_2/D_1)}$$

<u>Sensitivity using change in 'D_1'</u>

$$S = \frac{\partial C}{\partial D_1} = -\frac{2\pi\epsilon l}{\left[\log_e(D_2/D_1)\right]^2} \cdot \frac{1}{(D_2/D_1)} \cdot -\frac{D_2}{(D_1)^2}$$

$$= +\frac{2\pi\epsilon l}{\left[\log_e(D_2/D_1)\right]^2} \cdot \frac{D_1}{D_2} \cdot \frac{D_2}{(D_1)^2}$$

$$= \frac{2\pi\epsilon l}{D_1\left[\log_e(D_2/D_1)\right]^2}$$

For fractional change in capacitance

$$S^1 = \frac{\partial C}{C\partial D_1} = \frac{1}{D_1 \log_e(D_2/D_1)}$$

<u>Sensitivity using change in dielectric constant</u>

$$S = \frac{\partial C}{\partial \epsilon_r} = \frac{2\pi\epsilon_0 l}{\log_e(D_2/D_1)}$$

Sensitivity is constant.

3.6 DIFFERENTIAL CAPACITOR (5)

This capacitor has three plates two fixed plates P_1 and P_2 and a movable plate M which together form the two capacitors C_1 and C_2. In the centre position, the distance between M and either plate is d, the capacitors C_1 and C_2 are equal. If plate M is moved by a small amount x in response to an applied mechanical signal. One capacitor will increased and the other one decreased. The subsequent stage (which converts a change of capacitance into an output voltage or current) measures either the difference between both capacitors or their ratio.

$$C_1 = \frac{\epsilon a}{d+x} \quad , \qquad C_2 = \frac{\epsilon a}{d-x}$$

Two different applications of this type of capacitive transducer can be distinguish as follows :

(a) The stage following the transducer response to the difference of the partial capacitances C_1-C_2. Usually an A-C voltage E is applied between plates P_1 and P_2 and the difference of the partial voltages (E_1-E_2) is measured. The partial voltages are :

$$E_1 = \frac{EC_2}{C_1+C_2} \qquad E_2 = \frac{EC_1}{C_1+C_2}$$

$$E_1 = E\,\frac{d+x}{2d} \qquad E_2 = E\,\frac{d-x}{2d}$$

difference of partial voltages is

$$E = E_1-E_2 = E.\,\frac{x}{d}$$

Relationship between output voltage ΔE and the displacement of the middle electrode x is linear and independent of the capacitor plate area or the dielectric constant.

The sensitivity of the system is

$$S = \frac{\Delta E}{\Delta x} = E/d$$

If stray capacitance can not be neglected (e.g. the capacitance at the input of subsequent stage) the sensitivity will be reduced, and non linearity will arise between the displacement x and the output

$$E = E.\ \frac{2x}{d} \cdot \frac{1}{(1+B)}\ [1+ \frac{B}{1+B}(\frac{2x}{a})^2+(\frac{B}{1+B})^2\ (\frac{2x}{a})^4+\ldots\ ]$$

where $B = C_s/C_1$ is the ratio of stray capacitance C_S to the capacitance C_1 or C_2 if the middle plate M is in the centre position. For B = 1/4 and x/d = 1/5. The sensitivity is reduced by 1/5 and deviation from linearity is 1 percent.

(b) The subsequent stage responds to the ratio C_1/C_2 (e.g. balanced bridge ratio meters)

For such systems the relationship between the output signal and displacement of middle electrode is

$$C_2/C_1 = N = \frac{d+x}{d-x}$$

The output varies in a non-linear fashion with the displacement x, only for very small displacements, when x << d, does

$$N = 1 + \frac{x}{d}$$

For $\frac{x}{d} = \frac{1}{5}$, The deviation from linearity is about 20 percent.

3.7 EQUIVALENT CIRCUIT OF CAPACITOR (4)

At low frequencies the losses of a condenser are represented by a parallel resistance R_p which represents

(a) a d.c. leakage conductance which can be neglected even at very low frequencies,

(b) dielectric losses in the insulating supports of the live electrode, and

(c) losses in the gap dielectric.

The dielectric losses (b) in the insulating structure constitute a conductance component of $1/R_p$ which increases with frequency and the dissipation factor ($\frac{1}{R_p wc}$) is thus roughly independent of frequency. The gap losses in air condenser are normally negligible, but with solid dielectrics they clearly depend on the low frequency dissipation factor of the dielectric material used. The resulting losses caused by interfacial polarization often become smaller with increasing frequency.

At high frequencies the series resistance R_S represents the resistance of the leads, metal supports, and plates of the condenser.

The series inductance L however, is of practical importance. It represents the total inductance of the current path between the terminal of the transducer. If a cable is attached to the transducer, L includes also the cable inductance, as shown in fig. 3.3.

$$Z = R_S + jwL + \frac{Rp/jwc}{R+\frac{1}{jwc}}$$

$$= R_s + \frac{R_p}{1+w^2Rp^2C^2} + jw\,[1- \frac{CR_p^{\,2}}{1+w^2Rp^2C^2}]$$

the effective reactance is

$$Xeff. = \frac{1}{j\,w\,C_{eff}}$$. where C_{eff} = effective capacitance.

$$\frac{1}{jwC_{eff}} = jw\,[L - \frac{CR_p^{\,2}}{1+w^2Rp^2C^2}]$$

or $$\frac{1}{w\,C_{eff}} = -wL + \frac{wCRp^2}{1+w^2Rp^2C^2}$$

or $$w\,C_{eff} = \frac{1+w^2Rp^2C^2}{wCRp^2-wL(1+w^2Rp^2C^2)}$$

In a capacitor $w^2C^2Rp^2$ is very large as compared to 1.

$$w\,C_{eff} = \frac{w^2Rp^2C^2}{wCRp^2-w^3Rp^2C^2L} = \frac{w\,C}{1-w^2LC}$$

or $$C_{eff} = \frac{C}{1-w^2LC}$$

$$R_{eff} = R_s + \frac{Rp}{1+w^2Rp^2C^2}$$

At low freq. effect of series resistance R_s and series inductance are neglegible.

$$R_{eff} = \frac{Rp}{1+w^2\,Rp^2C^2}$$

$$\text{loss angle } \tan\delta = \frac{(wCRp^2 - wL - w^3Rp^2C^2L)}{R_s + w^2Rp^2R_sC + Rp}$$

$$\simeq \frac{1 - w^2LC}{wR_s + 1/wCRp}$$

$$\simeq wCR_s + \frac{1}{wCR_p}$$

The effective change in capacitance is -

$$\frac{\delta C_{eff}}{C_{eff}} = \frac{\delta C/C}{1-w^2LC}$$

3.8 EFFECT OF STRAY CAPACITANCE (8)

Stray capacitance can be defined as, any occurring with in a circuit other than intentionally inserted by capacitors e.g. capacitance of connecting wires, giving rise to parasitic oscillation.

As shown in fig. 3.4 the capacitive transducers are connected to the second stage of the instrumentation system through cables. The cables are a source of loading.

Let C is the capacitance of transducer in F and

C_c is the capacitance of the cable in F.

If we neglect the leakage resistance, the output impedance of transducer is $Z_0 = 1/jwC$.

Impedance of load (taking cable as load)

$Z_L = 1/jwC_c$

$$E_L = \frac{E_0}{Z_0 + Z_L} \cdot Z_L = \frac{E_0}{1/jwC + 1/jwC_c} \cdot \frac{1}{jwC_c}$$

$$= \frac{E_O}{\frac{C_c + C_O}{jwCC_c}} \cdot \frac{1}{jwC_c}$$

$$E_L = \frac{E_O \cdot jwCC_c}{C + C_c} \cdot \frac{1}{jwC_c}$$

$$E_L = \frac{C}{C + C_c} \cdot E_O$$

In this case

$$C_{eff} = \frac{C\ C_c}{C+C_c} \quad \text{Initial capacitance} = C$$

$$\Delta C = \frac{C\ C_c}{C+C_c} - C$$

$$\Delta C = -\frac{C^2}{C+C_c}$$

3.9 METHOD TO INCREASE THE SENSITIVITY (4)

There are two methods to increase the sensitivity :

(i) Rotary Motion, a single and differential transducer, and

(ii) Serrated type transducers.

(i) Rotary Motion

Fig.25.2 shows a two-plate capacitor. One plate is fixed and the other is movable. The angular displacement to be measured is applied to movable plate. The angular displacement changes the effective area between the plates and thus changes the capacitance. The capacitance is max. when the two plates complately overlap each other i.e. when $\theta = 180^o$.

Max. value of capacitance $C_{max} = \frac{\epsilon A}{d} = \frac{\pi \epsilon r^2}{2d}$

Capacitance at angle θ is $C = \frac{\epsilon r^2}{2d}\,\theta$

θ = angular displacement in radian

Sensitivity $S = \frac{\partial C}{\partial \theta} = \frac{\epsilon r^2}{2d}$

The variation of capacitance with angular displacement is linear as shown in fig. 3.52.

The sensitivity can be increased by multiple plate arrangements.

(ii) Serrated type transducer (4)

High sensitivity can be obtained by using serrated type transducer. A longitudinal shift of one capacitance plate by an amount ∂l against the other has the effect of changing the capacitance from minimum to the maximum value. The transfer characteristic is shown in fig. 3.53. A sensitivity of the order of 1μF/0.0001 in has been obtained.

Consider a pair of flat serrated plates, as shown in fig. 3.54. A small relative movement in the plane of the plate causes a change in capacity. The movement must be kept small in comparison with the width of the teech, otherwise, the capacitance deflection relationship yields ambiguous results.

$C = \frac{n\ l\ b}{3.6\pi d}$ (pF)

where the dimensions (cm) are

l is the active length of tooth pair,

b is the width of teeth, normal to plane of drawing, d is the distance between teeth in close proximity and

n is the number of pairs of teeth.

The variation in capacitance ∂C due to small deflection ∂l is

$$\partial C = \frac{nb(l+\partial l)}{3.6\pi d} - C$$

Hence fractional change in capacitance,

$$\frac{\partial C}{C} = \frac{\partial l}{l}$$

$$\text{Sensitivity } S = \frac{\partial C}{\partial l} = \frac{nb}{3.6\pi d}$$

3.10 SENSITIVITY ANALYSIS OF CAPACITIVE BRIDGES

Let a sinusoidal voltage E be applied to points B and D as shown in fig. 3.1. If the detector branch points A,C are joined to a infinitely high impedance represented very closely by an amplifier then the voltage between A and C -

$$V = \frac{Z_1Z_3 - Z_2Z_4}{(Z_1+Z_2)(Z_3+Z_4)} E$$

For Schering Bridge :

$$Z_1S = r_1 + \frac{1}{jwC_1} \qquad = r_1 - \frac{1}{wC_1}$$

$$Z_2S = 0 + \frac{1}{jwC_2} \qquad = 0 - \frac{1}{wC_2}$$

$$Z_3S = R_3 + j\,0 \qquad = R_3 + j\,0$$

$$Z_4S = \frac{R_4}{1+jwC_4R_4} = \frac{R_4}{1+w^2C_4{}^2R_4{}^2} - \frac{jwR_4{}^2C_4}{1+w^2C_4{}^2R_4{}^2}$$

$$\frac{\partial V}{\partial Z_4} = -\frac{Z_2}{(Z_1+Z_2)(Z_3+Z_4)}\cdot E$$

$$\partial V = -\frac{A}{(1+A)^2}\cdot\frac{\partial Z_4}{Z_4}\cdot E$$

$$\sigma = \frac{\partial Z_4}{Z_4}\cdot \quad A = Z_1/Z_2$$

$$\partial V = -\frac{A}{(1+A)^2}\cdot \sigma E$$

$$\frac{\partial}{\partial R_4}(Z_4) = \frac{\partial}{\sigma R_4}\left(\frac{R_4}{1+jwC_4R_4}\right)$$

$$= \frac{(1+jwC_4R_4)\times 1-R_4\times jwC_4}{(1+jwC_4R_4)^2}$$

$$\frac{\partial Z_4}{Z_4} = \frac{\partial R_4}{Z_4}\cdot\frac{1}{(1+jwC_4R_4)^2}$$

$$= \frac{\partial R_4}{R_4\cdot Z_4}\cdot\frac{R_4}{(1+jwC_4R_4)^2}$$

$$= \frac{\partial R_4}{R_4}\cdot\frac{Z_4}{Z_4\cdot(1+jwC_4R_4)}$$

$$= \frac{\partial R_4}{R_4}\cdot\frac{1}{(1+jwC_4R_4)}$$

$$\frac{\partial V}{E} = -\frac{A}{(1+A)^2}\cdot\frac{\partial R_4}{R_4}\cdot\left(\frac{1}{1+jwC_4R_4}\right)$$

$$SS_1 = \frac{\partial V/E}{\partial R_4/R_4} = -\frac{A}{(1+A)^2}\cdot\frac{1}{(1+jwC_4R_4)}$$

$$\frac{\partial}{\partial C_4}(Z_4) = \frac{\partial}{\partial C_4}\cdot\left(\frac{R_4}{1+jwC_4R_4}\right)$$

$$= \frac{(1+jwC_4R_4)\times 0-R_4\times jwR_4}{(1+jwC_4R_4)^2}$$

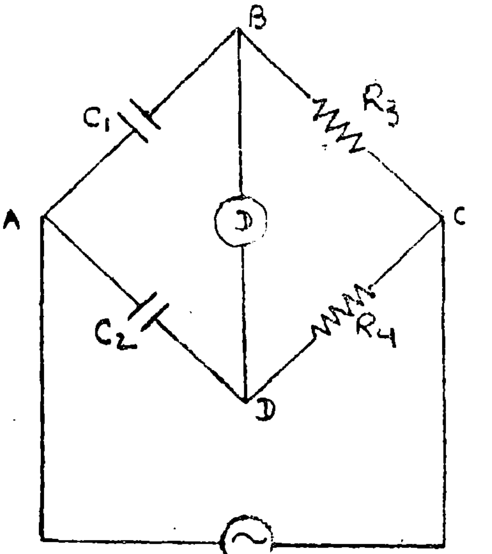


FIG. DE SAUTY'S BRIDGE

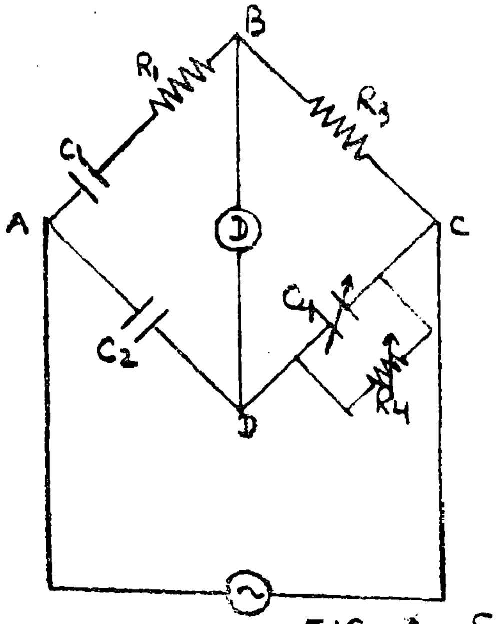


FIG. SCHERING BRIDGE

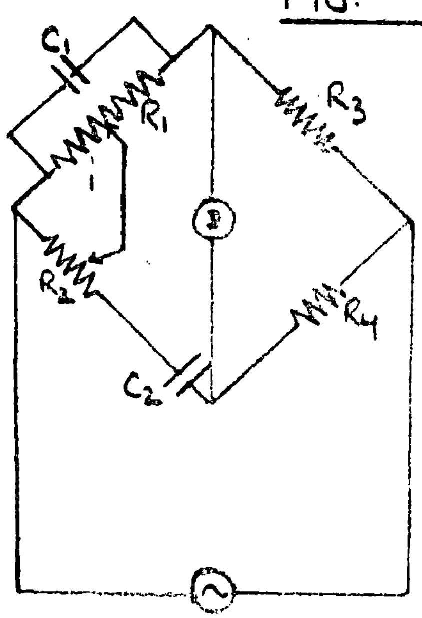


FIG. WIEN'S BRIDGE

$$\partial Z_4 = \partial C_4 \left(\frac{-jwR_4{}^2}{(1+jwC_4R_4)^2} \right)$$

$$\frac{\partial Z_4}{Z_4} = \frac{\partial C_4}{Z_4} \cdot \frac{C_4}{C_4} \left(- \frac{jwR_4{}^2}{(1+jwC_4R_4)^2} \right)$$

$$\frac{\partial Z_4}{Z_4} = \frac{\partial C_4}{C_4} \cdot \frac{Z_4}{Z_4} \times \frac{-jwC_4R_4}{(1+jwC_4R_4)}$$

$$SS_2 = \frac{\partial V/E}{\partial C_4/C_4} = \frac{A}{(1+A)^2} \cdot \frac{jwC_4R_4}{(1+jwC_4R_4)}$$

For De Sauty's Bridge

$$Z_{1D} = \frac{1}{jwC_1}, \quad Z_{2D} = \frac{1}{jwC_2}, \quad Z_{3D} = R_3, \quad Z_{4D} = R_4$$

$$V = \frac{Z_1Z_3 - Z_2Z_4}{(Z_1+Z_2)(Z_3+Z_4)} \cdot E$$

$$\partial V = - \frac{A}{(1+A)^2} \cdot E \cdot \frac{\partial R_3}{R_3}$$

$$SD = \frac{\partial V/E}{\partial R_3/R_3} = - \frac{A}{(1+A)^2}$$

For Wein's Bridge

$$Z_{1w} = \frac{R_1}{1+jwC_1R_1}, \quad Z_{2w} = R_2 - \frac{j}{wC_2}, \quad Z_{3w} = R_3, \quad Z_{4w} = R_4$$

$$S_w = \frac{\partial V/E}{\partial R_1/R_1} = - \frac{A}{(1+A)^2} \cdot \frac{1}{(1+jwC_1R_1)}$$

PROGRAM FOR SENSITIVITY ANALYSIS OF BRIDGES

A general programme has been developed for sensitivity analysis of the bridge. Fig. 3.6 shows the flow chart for the steps.

```
COMPLEX  ZS1, ZS2, ZS3, ZS4, ZW1, ZW2, ZW3, ZW4,
         ZD1, ZD2, ZD3, ZD4, AS, ZSK, AD,AW, ZWK
OPEN (UNIT = 1, DEVICE = 'DSK', FILE = 'S.DAT')
READ (1,*) R1, R2, R3, R4, C1, C2, C3, PI
     ω = 2. * PI * 50.
XD1 = XS1 = -1./(ω*C1)
Xw2 = XD2 = XS2 = -1./(ω * C2)
     XS4 = -ω*C4*R4*R4/(1+ω*ω*C4*C4*R4*R4)
     RS1 = R1
Rw3 = RD3 = RS3 = R3
     RS4 = R4/(1+ω*ω*C4*C4*R4*R4)
     ZS1 = C MPLX (RS1, XS1)
     ZS2 = CMPLX (O., XS2)
     ZS3 = CMPLX (RS3, O.)
     ZS4 = CMPLX (RS4, XS4)
     RSK = 1.
     XSK = ω*C4*R4
     ZSK = CMPLX (RSK, XSK)
     AS = CMPLX (ZS1/ZS2)
RW4 = RD4 = R4
     ZD1 = CMPLX (O., XD1)
     ZD2 = CMPLX (O., XD2)
     ZD3 = CMPLX (RD3, O)
```

```
ZD4 = CMPLX (RD4, O.)
AD = CMPLX (ZD1/ZD2)
XW1 = -(ω*C1*R1*R1)/(1+ω*ω*C1*C1*R1*R1)
RW1 = R1/(1+ω*ω*C1*C1*R1*R1)
RW2 = R2
RDK = 1.
XDK = ω*C1*R1
ZW1 = CMPLX (RW1, XW1)
ZW2 = CMPLX (RW2, XW2)
ZW3 = CMPLX (RW3, O.)
ZW4 = CMPLX (RW4, O.)
ZWK = CMPLX (RDK, XDK)
AW = CMPLX (ZW1/ZW2)
SS1 = ABS [AS/((1+AS) * (1+AS) * ZSK)]
SS2 = ABS [AS * XSK/((1+AS) * (1+AS) * ZSK)]
SD = ABS [-AD/[(1+AD) * (1+AD) ]]
SW = ABS [-AW/((1+AW) x (1+AW) * ZWK) ]
PRINT * , SS1, SS2, SD, SW
      STOP
      END
```

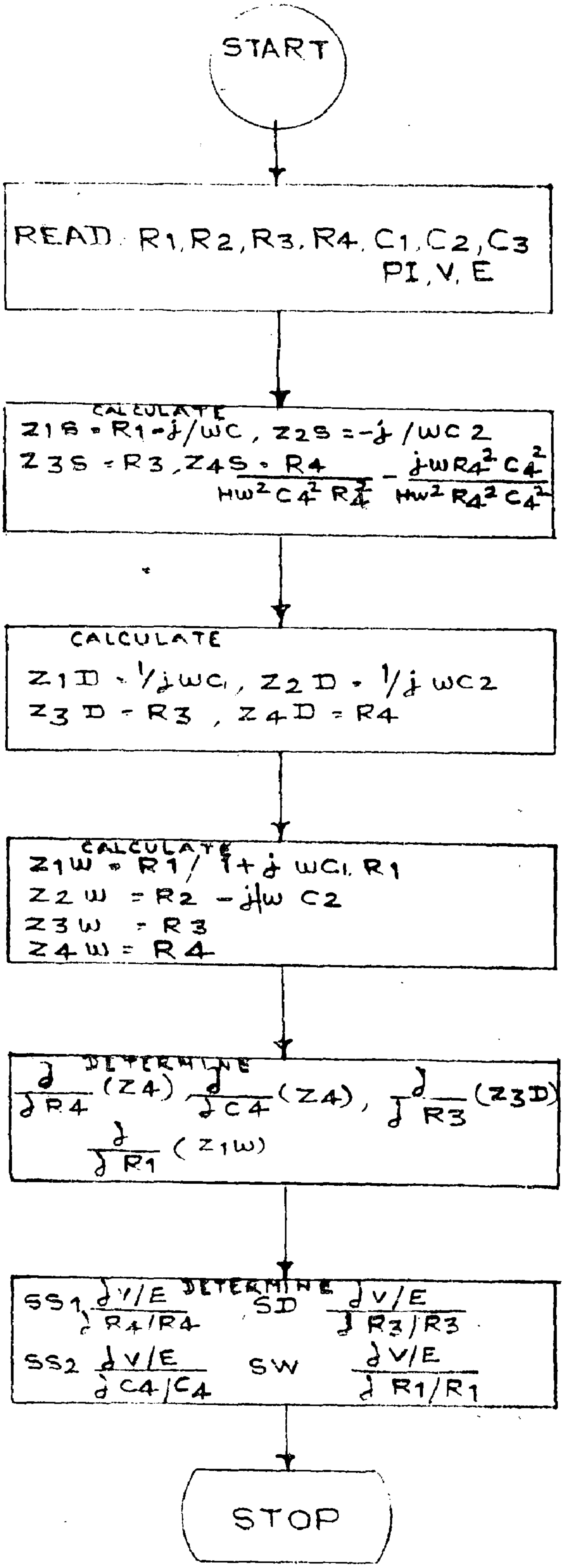


FIG.:- 3.6 - FLOW CHART

3.11 RESULTS

(i) Let for a two plate capacitor, two plates are 25 mm apart and area 625 mm^2 in area.

Sensitivity of this may be calculated as follows :

$$C = \frac{\epsilon A}{d} = \frac{\epsilon \ell w}{d} \qquad = 8.85\times10^{-12} \text{ F/m}$$

Change in Area of Plates : by causing displacement of one plate

$$C = \frac{(l-x)w}{d}$$

$$\text{Sensitivity } \frac{\partial C}{\partial x} = -\frac{\epsilon w}{d} = \frac{\epsilon w}{d} \text{ (neglecting sign)}$$

$$= \frac{8.85\times10^{-12}\times25\times10^{-3}\times100}{.25\times10^{-3}} = 885 \text{ PF/m}$$

$$= .885 \text{ PF/mm}$$

and whatever be the displacement sensitivity will always be constant.

Change in distance between plates :

$$C = \frac{\epsilon \ell w}{d}$$

$$S = \frac{\partial C}{\partial d} = -\frac{\epsilon \ell w}{d^2} = -\frac{8.85\times10^{-12}\times25\times25\times10^{-6}}{d^2}$$

Sl.No.	Value d in mm	Sensitivity in PF/mm.
1.	.25	88.50
2.	.22	114.28
3.	.20	138.28
4.	.18	170.71
5.	.16	216.06
6.	.14	282.20
7.	.12	384.11
8.	.10	553.12
9.	.08	864.25
10.	.06	1536
11.	.04	3457.03
12.	.02	13828
13	.01	55312.5

Result shows that as the distance between the plates decreases sensitivity goes on increasing.

Change in dielectric constant

$$C = \frac{\epsilon A}{d} = \frac{\epsilon_0 \epsilon_r l w}{d}$$

$$S = \frac{\partial C}{\partial \epsilon_r} = \frac{\epsilon_0 l w}{d} = \frac{8.85\times10^{-12}\times625\times10^{-6}}{.25\times10^{-3}}$$

$$= 22125\times10^{-15}$$

$= 22.125 \times 10^{-12}$ PF/m

$= 0.22125$ PF/mm.

Sensitivity will be constant.

(ii) Let for a cylindrical capacitor

Inner dia = 3 mm, outer dia = 3.1 mm , length = 20 mm

$$C = \frac{2\pi \epsilon \ell}{\log_e (D_2/D_1)} .F$$

Sensitivity using change in Area of plates

$$S = \frac{\partial C}{\partial \ell} = \frac{2\pi \epsilon}{\log_e (D_2/D_1)} = \frac{2\pi \times 8.85 \times 10^{-12}}{\log_e \left(\frac{3.1 \times 10^{-3}}{3 \times 10^{-3}}\right)}$$

$= 1695.8431$ PF/m

$= 1.695$ PF/mm

Sensitivity is constant.

Sensitivity using change in 'D_2'

$$S = \frac{\partial C}{\partial D_2} \quad , \quad S = \frac{\partial C}{\partial D_2} = -\frac{2\pi \epsilon \ell}{D_2 \left[\log_e (D_2/D_1)\right]^2}$$

Change in D_2 (in mm)		Sensitivity in PF/mm
1.	2.9	333.67
2.	2.7	37.105
3.	2.5	13.382
4.	2.3	6.849
5.	2.8	83.44
6.	2.6	20.88

Sensitivity using change in 'D_1'

$$S = \frac{\partial C}{\partial D_1} = \frac{2\pi \epsilon l}{D_1 \left[\log_e(D_2/D_1)\right]^2}$$

Change in D_2 in mm		Sensitivity in PF/mm
1.	2.9	86.22
2.	2.8	38.33
3.	2.7	21.58
4.	2.6	13.82

It shows that as D_1 decreases sensitivity decreases.

Sensitivity using change in dielectric constant

$$S = \frac{\partial C}{\partial \epsilon_r} = \frac{2\pi \epsilon_0 l}{\log_e(D_2/D_1)}$$

$$= 33916.862 \times 10^{-15}$$

$$= 33.916 \text{ PF/m} = .033916 \text{ PF/mm}$$

Sensitivity is constant.

(iii) Let in a differential capacitor distance between middle and side plate is 50 mm and x = .01 mm

$$S = E/d$$

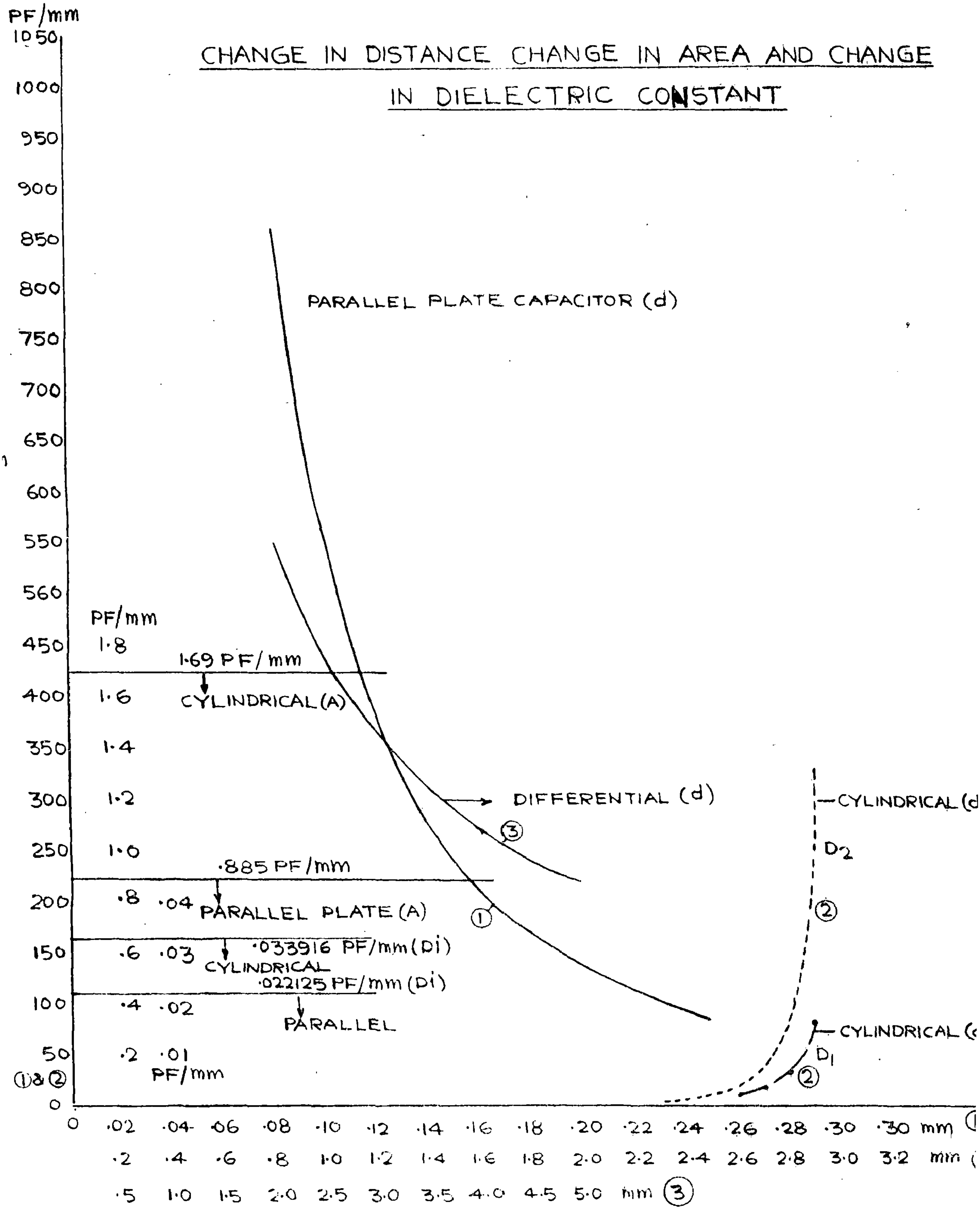

CHANGE IN DISTANCE CHANGE IN AREA AND CHANGE IN DIELECTRIC CONSTANT
PF/mm
1050
1000
950
900
850
800
750
700
650
600
550
560
450
400
350
300
250
200
150
100
50
0
①&②
PF/mm
1·8
1·6
1·4
1·2
1·0
·8
·6
·4
·2
·04
·03
·02
·01
PF/mm
PARALLEL PLATE CAPACITOR (d)
1·69 PF/mm
CYLINDRICAL (A)
DIFFERENTIAL (d)
③
·885 PF/mm
PARALLEL PLATE (A)
①
·033916 PF/mm (Di)
CYLINDRICAL
·022125 PF/mm (Di)
PARALLEL
CYLINDRICAL (d
D2
②
CYLINDRICAL (
D1
②
0 ·02 ·04 ·06 ·08 ·10 ·12 ·14 ·16 ·18 ·20 ·22 ·24 ·26 ·28 ·30 ·30 mm ①
·2 ·4 ·6 ·8 1·0 1·2 1·4 1·6 1·8 2·0 2·2 2·4 2·6 2·8 3·0 3·2 mm
·5 1·0 1·5 2·0 2·5 3·0 3·5 4·0 4·5 5·0 mm ③

FIG. 3·7

Sensitivity using change in distance between middle and side plates

	Change in d in mm	Sensitivity in V/mm
1.	5	44
2.	4.5	48.88
3.	4.00	55.0
4.	3.5	62.85
5.	3.0	73.33
6.	2.5	88
7.	2.0	110

It shows that with a decrease in distance between middle and side plate, sensitivity increases.

(iv) Sensitivity of Bridges

For De Sauty's Bridge

Let $C_1 = 100\ \mu F$, $C_2 = 150\ \mu F$

$R_3 = 5000\ \Omega$, $R_4 = 5000\ \Omega$

$$S = -\frac{A}{(1+A)^2} \qquad A = Z_1/Z_2 = \frac{1/j\ wC_1}{1/j\ wC_2} = C_2/C_1$$

$$S = -\frac{C_2/C_1}{(1+C_2/C_1)^2} = \frac{(150/100)}{(1+\frac{150}{100})^2} = 0.24$$

(with the change in R_3)

Sensitivity will always be constant.

For Wien's Bridge

$$S_w = \frac{\partial V/E}{\partial R_1/R_1} = -\frac{A}{(1+A)^2} \cdot \frac{1}{(1+jwC_1R_1)}$$

$Z_1 = R_1/(1+jwC_1R_1)$, $Z_2 = R_2 - j/wC_2$

$R_1 = 2000\,\Omega$, $C_1 = 100\ \mu F$, $C_2 = 150\ \mu F$, $R_2 = 3000\,\Omega$

$R_3 = 5000\,\Omega$, $R_4 = 5000\,\Omega$

	Value of R_1 in Ω	S_w (Sensitivity)
1.	2000	1.65459×10^{-4}
2.	1800	1.8377806×10^{-4}
3.	1500	2.2057088×10^{-4}
4.	1200	2.7564457×10^{-4}
5.	900	3.6732506×10^{-4}
6.	500	6.5933832×10^{-4}
7.	300	10.97×10^{-4}
8.	200	16.057×10^{-4}

As the value of R_1 decreases, sensitivity increases.

For Schering Bridge

(a) $$SS_1 = \frac{\partial V/E}{\partial R_4/R_4} = -\frac{A}{(1+A)^2} \cdot \frac{1}{(1+jwC_4R_4)}$$

$A = Z_1/Z_2$, $Z_1 = R_1 - j/wC_1$

$Z_2 = -\,j/wC_2$

$A = \underline{94.211939}$

	Value of R_4 in Ω	Sensitivity SS_1
1.	5000	5.51611×10^{-5}
2.	4700	5.86819×10^{-5}
3.	4500	6.12899×10^{-5}
4.	4200	6.56676×10^{-5}
5.	4000	6.89509×10^{-5}
6.	3500	7.88005×10^{-5}
7.	3000	9.1933×10^{-5}
8.	2500	1.10317×10^{-4}
9.	2000	1.37892×10^{-4}
10.	1500	1.83843×10^{-4}
11.	1000	2.75712×10^{-4}
12.	500	5.50844×10^{-4}
13.	400	6.88011×10^{-4}
14.	300	9.15789×10^{-4}
15.	200	1.36706×10^{-3}

As value of R_4 decreases sensitivity increases.

(b) $$SS_2 = \frac{A}{(1+A)^2} \cdot \frac{jwC_4R_4}{(1+jwC_4R_4)}$$

$$A = Z_1/Z_2 = 94.211939$$

$$\frac{1}{(1+A)^2} = 1.1031 \times 10^{-4}$$

$$\frac{A}{(1+A)^2} = 103.92518 \times 10^{-4}$$

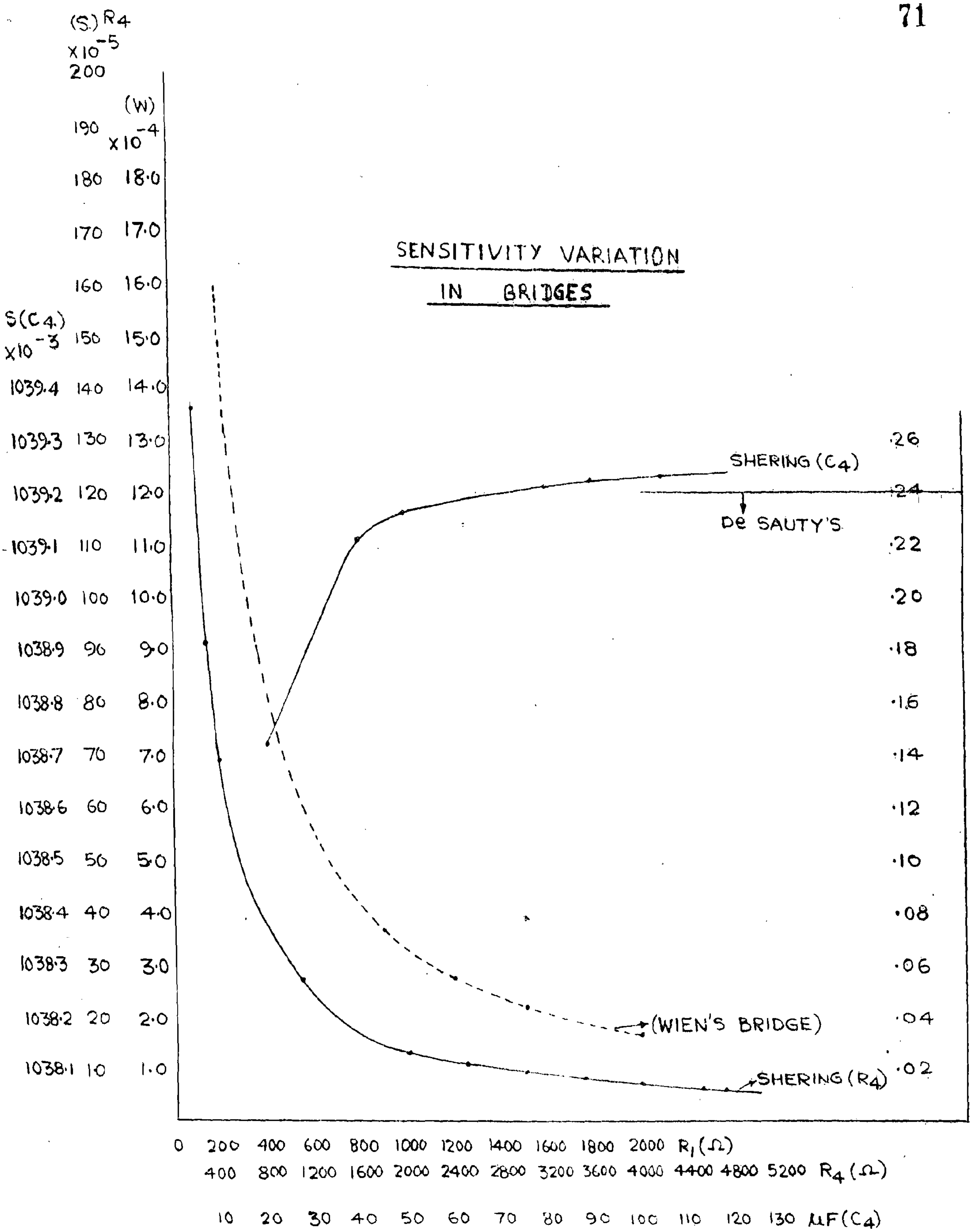

SENSITIVITY VARIATION
IN BRIDGES
(S) R4 x10-5
(W) x10-4
S(C4) x10-3
SHERING (C4)
De SAUTY'S
(WIEN'S BRIDGE)
SHERING (R4)
0 200 400 600 800 1000 1200 1400 1600 1800 2000 R1 (Ω)
400 800 1200 1600 2000 2400 2800 3200 3600 4000 4400 4800 5200 R4 (Ω)
10 20 30 40 50 60 70 80 90 100 110 120 130 µF(C4)

FIG. 3·8

	Value of C_4 in μF	Sensitivity SS_2
1.	120	103.92351×10^{-4}
2.	110	103.92342×10^{-4}
3.	100	103.92294×10^{-4}
4.	90	103.92252×10^{-4}
5.	80	103.92187×10^{-4}
6.	50	103.91658×10^{-4}
7.	40	103.911×10^{-4}
8.	30	103.90157×10^{-4}
9.	20	103.8722×10^{-4}

As the value of C_4 decreases sensitivity decreases to a very lesser amount.

(v) Unit Sensitivity of Bridges

For De Sauty's Bridge : $\frac{S}{S_0} = \frac{.24}{.24} = 1.0$

	Value of R_1 in Ω	Unit Sensitivity S/S_0
1.	2000	.1030426
2.	1800	.1144512
3.	1500	.1373646
4.	1200	.1716628
5.	900	.2287585
6.	500	.416152
7.	300	.6831772
8.	200	1.00

For Schering Bridge : S/S_o for 200 is 1.00

(a)	Value of R_4 in	Unit sensitivity S/S_o
1.	5000	.0403501
2.	4700	.429256
3.	4500	.0448333
4.	4200	.0480356
5.	4000	.0504373
6.	3500	.0576423
7.	3000	.0672486
8.	2500	.0806965
9.	2000	.1008675
10.	1500	.1344805
11.	1000	.2016824
12.	500	.4029406
13.	400	.5032778
14.	300	.6698967
15.	200	1.00

(b) S/S_o for 20 μF is 1.00

	Value of C_4 in μf	S/S_o
1.	120	1.0004939
2.	110	1.0004931
3.	100	1.0004884

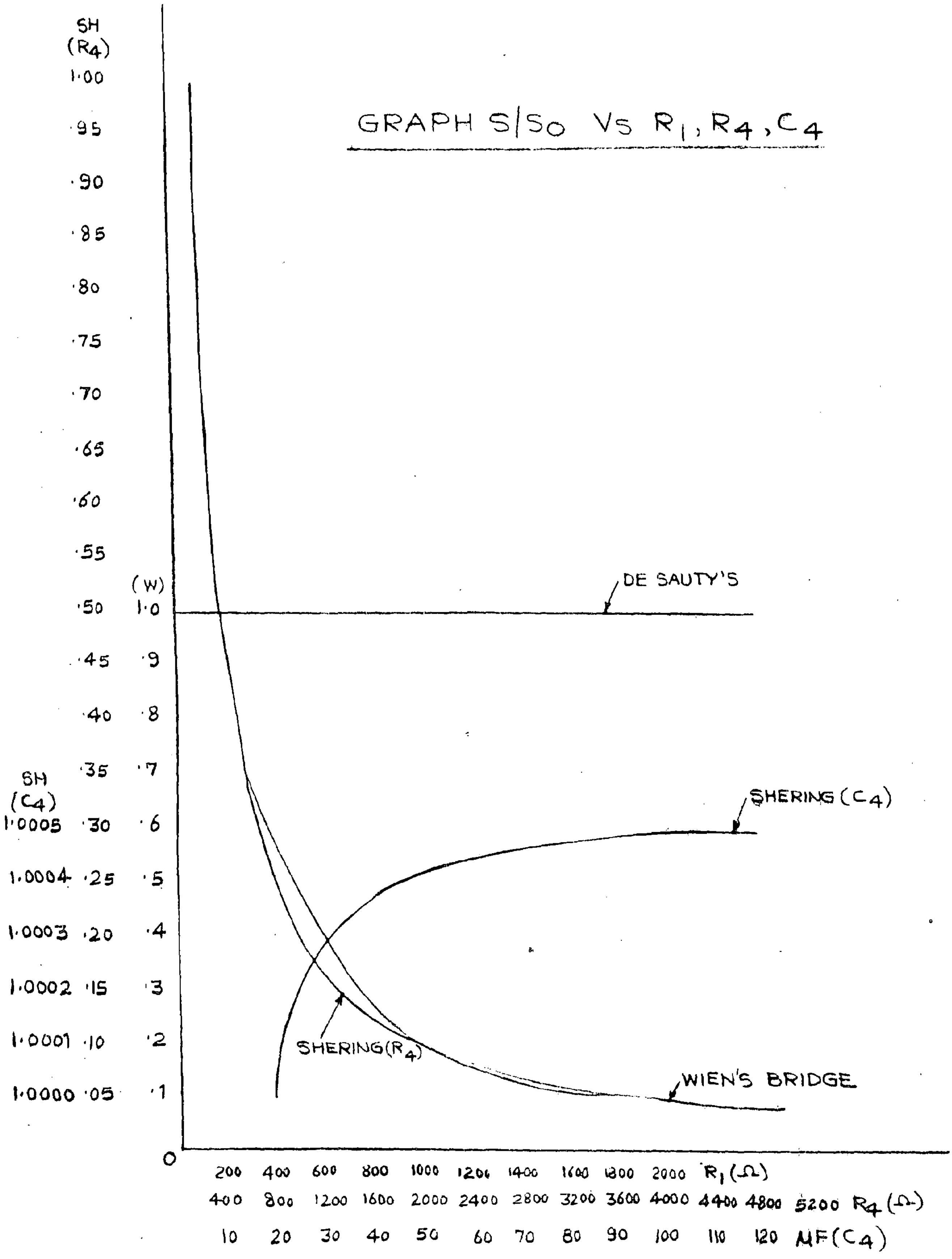

GRAPH S/So Vs R1, R4, C4
SH (R4)
1.00
·95
·90
·85
·80
·75
·70
·65
·60
·55
·50
·45
·40
·35
·30
·25
·20
·15
·10
·05
(W)
1·0
·9
·8
·7
·6
·5
·4
·3
·2
·1
SH (C4)
1·0005
1·0004
1·0003
1·0002
1·0001
1·0000
0
DE SAUTY'S
SHERING (C4)
SHERING(R4)
WIEN'S BRIDGE
200 400 600 800 1000 1200 1400 1600 1800 2000 R1 (Ω)
400 800 1200 1600 2000 2400 2800 3200 3600 4000 4400 4800 5200 R4 (Ω)
10 20 30 40 50 60 70 80 90 100 110 120 MF(C4)

FIG 3·9

4.	90	1.0004844
5.	80	1.0004781
6.	50	1.0004272
7.	40	1.0003735
8.	30	1.0002827

(vi) Effect of humidity on change in capacitance

$$C = \frac{1.39Ht^{1.3}}{273+2t} \pm 2 \text{ parts in } 1,00,000$$

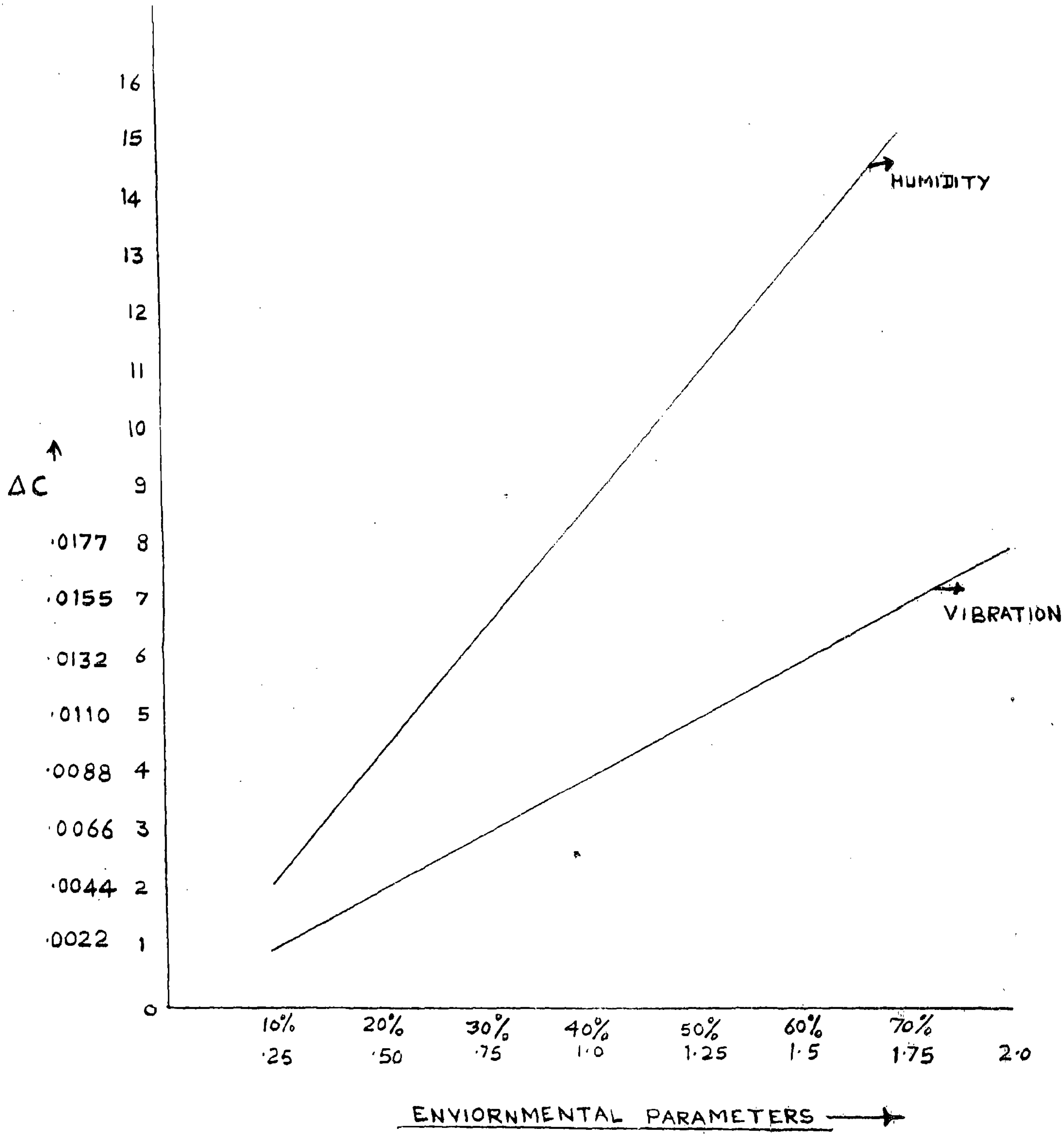
H = relative humidity % = 0 - 70 %

t (temp.) = $10^{o}C$ - $30^{o}C$

At temp. t = $20^{o}C$.

	Relative humidity	Change in capacitance ΔC
1.	10 %	2.18
2.	20 %	4.36
3.	30 %	6.55
4.	40 %	8.73
5.	50 %	10.91
6.	60 %	13.09
7.	70 %	15.27

As the relative humidity increases ΔC increases.


16
15
14
13
12
11
10
ΔC
9
·0177 8
·0155 7
·0132 6
·0110 5
·0088 4
·0066 3
·0044 2
·0022 1
0
HUMIDITY
VIBRATION
10% ·25
20% ·50
30% ·75
40% 1·0
50% 1·25
60% 1·5
70% 1·75
2·0
ENVIORNMENTAL PARAMETERS

(vii) **Effect of Vibration**

$$\partial C = (-\,\partial/d\ \sin wt).C_o$$

$$C_o = \frac{\epsilon a}{d}$$

$$\partial C = (1-\frac{\partial}{a}\sin wt).\ \frac{\epsilon a}{d}$$

$$\partial C = -\,\frac{\epsilon a}{d^2}\,.\partial = -\ 8.85\times 10^{-12}\times\partial$$

Let area of plate is 625 mm^2, distance between two plates is 25 mm.

	Value of ∂ in mm	Change in capacitance in PF
1.	.25	.0022
2.	.50	.0044
3.	.75	.0066
4.	1.00	.0088
5.	1.25	.0110
6.	1.50	.0132
7.	1.75	.0155
8.	2.00	.0177

****

CHAPTER-IV

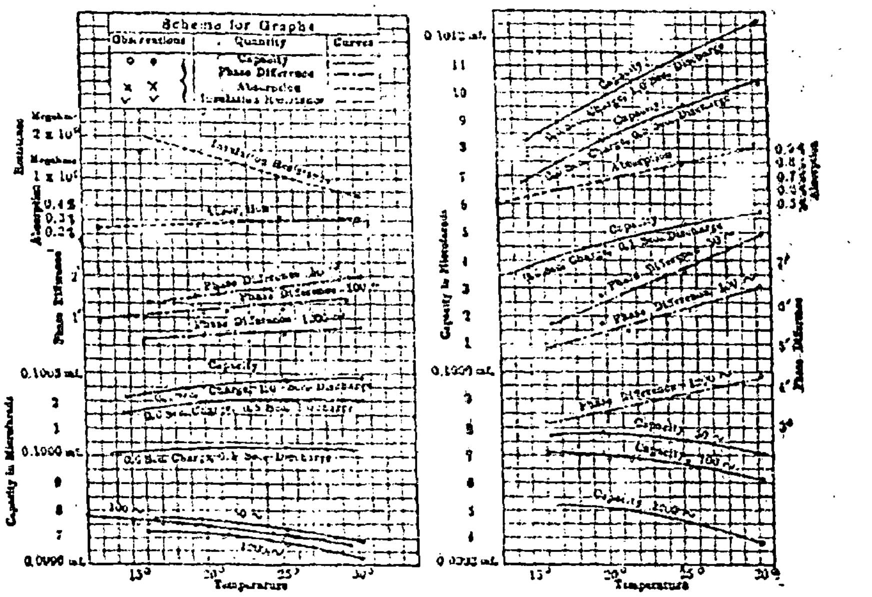
INFLUENCE OF ENVIRONMENTAL PARAMETERS

4.1 TEMPERATURE EFFECT (3) :

Temperature has an appreciable effect on the behaviour of condensers having solid dielectrics. It is not possible to give a definite statement as to the temperature Coefficient of the capacitance of a particular condenser, for the temperature effects are dependent on the particular cycle of operations to which the condenser is subjected. This is illustrated in fig. 4.11 which are typical of good and poor mica condensers. The best mica condensers when subject to the ordinary fluctuation of room temperature may show variation in the capacitance of 2 or 3 parts in 10000.

The active portion of any condenser intended for use as a standard must be firmly confined between clamps, so that its geometry and, consequently, the capacitance of the condenser may be definite. Condensers without clamps are greatly affected by temperature and, when taken through a cyclic variation of temperature (for instance, 17°C, 30°C, 17°C), do not return to their initial capacitances. This permanent alteration may be as much as 3 or 4 parts in 10,000.

Change of temperature adversely affects the sensitivity of the transducer.



A B

Fig 4·11 [redacted].—Characteristics of good (*A*) and poor (*B*) mica condensers.
from Frank -A· Laws, "Electrical Measurements"

4.2 PRESSURE EFFECT (6)

Changes of atmospheric pressure cause in mica condensers minute changes of capacitance which may be detected by the most refined methods of measurement. The changes are subject to a considerable time lag and may be of the order of magnitude 1 or 2 parts in 100,000 for 1 cm. change of pressure. Usually, if the pressure is reduced, the condenser expands, and as the increase in the distance between the plates produces more effect their increase of size, the capacitance is decreased. Firmly clamped condensers are but very slightly affected. Sensitivity is adversely affected by change in the pressure.

4.3 EFFECT OF HUMIDITY :

The presence of water vapour in the atmosphere affects the behaviour of an air capacitor in two ways, it may increase the power factor, and it must increase the capacitance at least in proportion to the increase in permittivity of the air. The former effect is well known and can be largely avoided by suitable design e.g. in three-terminal instruments the latter effect is usually treated as negligible especially at audio frequency.

The formula giving the permittivity of moist air in terms of temperature, pressure and humidity can be expressed in carious forms, that given by Lea, who considered the effect of atmospheric humidity on the stability of LC oscillators, is :

$$k = L + \frac{211}{T}(P + \frac{48}{T} P_s H) \times 10^{-6}$$

where

k is the permittivity of moist air

T is the absolute temperature, °K.

P is the pressure of moist air in mm Hg.

P_s is the pressure of saturated water vapour at temperature T, in mm Hg.

H is the relative humidity in % .

From this expression it can be seen that total change in permittivity, and hence in the capacitance of a perfect air capacitor, which can take place as between wet and dry air is about 2 parts in 10,000 at 20°C. Variations in capacitance of the order of 1 part in 10,000 must reasonably be expected in an ordinary room.

A knowledge of the variation to be expected in the capacitance of an air capacitor due to change in atmospheric humidity will usually be required to only a few parts in 1,00,000. changes in parometric pressure over the range 730-770 mm Hg may be ignored, and the saturation vapour pressure, Ps, may be taken to vary with temperature, T, according to a law of the form

$$P_s = A\,T^n$$

where

A and n are constants.

If these assumptions are made, the formula for the increase in capacitance, C over that in dry air, due solely to changes in the permittivity of air, will be

$$C = \frac{1.39\ Ht^{1.3}}{273+2t} \pm 2 \text{ parts in } 1,00,000$$

where,

H = relative humidity in %

t = temperature in ^{o}C.

This formula applies over the range 0-70% relative humidity and 10^{o}-$30^{o}C$ temperature.

It must be emphasized that the formula is completely empirical, and only applies over the range of parometric pressure 730-770 mm Hg, 0-70% relative humidity, and 10^{o}-$30^{o}C$ temperature, it may, however, be of use as giving a fair indication of the minimum probable change in capacitance, without the need of tables of saturation vapour pressure. Due to presence of humidity sensitivity is increased.

4.4 CAPACITANCE TRANSDUCER WITH SOLID DIELECTRIC OF VARIABLE PERMITTIVITY i.e. EFFECT OF MOISTURE CONTENT (4)

As the moisture content of a fabric changes there persists an increase in permittivity of the solid dielectric.

The effect of fringing eliminated by means of guard plate arrangement as shown in fig. 4.12. The capacitance of a condenser with two parallel plates of active area A(cm^2) at a distance a (cm) apart, and with a solid dielectric material of constant thickness d (cm), but variable permittivity ϵ , is -

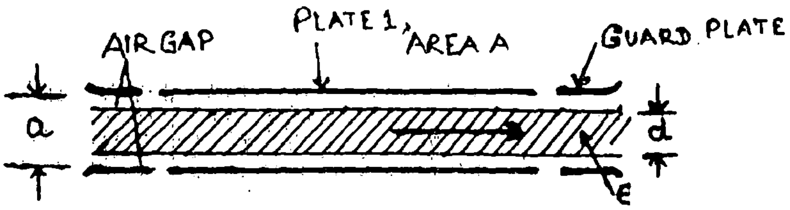


FIG. 4.12

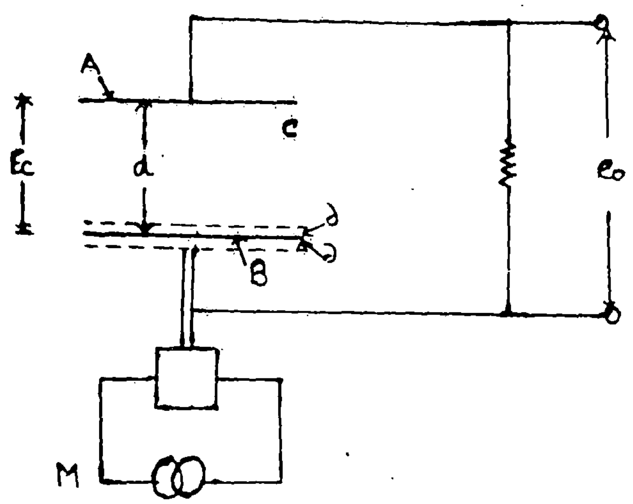


FIG. 4.13

$$C = \frac{A}{(a-d+d/\epsilon)}$$

Let due to change in the moisture content of a fabric, an increase in permittivity of the solid dielectric is ∂ which increases the capacitance by ∂C, hence

$$C + \partial C = \frac{A}{(a-d+\frac{d}{(\epsilon+\partial\epsilon)})}$$

Hence fractional change in capacitance $\partial C/C$ can be shown to be

$$\frac{\partial C}{C} = \frac{\partial\epsilon}{\epsilon} N_2 \frac{1}{1+N_3(\partial\epsilon/\epsilon)}$$

where the sensitivity factor

$$N_2 = \frac{1}{1+\epsilon(a-d)/d}$$

and the non-linearity factor

$$N_3 = \frac{\epsilon(a-d)/d}{1+\epsilon(a-d)/d} = \frac{1}{1+(d/\epsilon(a-d))}$$

It is seen that a material of low permittivity gives the highest sensitivity and best linearity.

4.5 EFFECT OF VIBRATION (4)

Let a system consists of two electrodes A and B which together form a capacitor C_0 as shown in fig. 4.13. The surface of one electrode may be altered by applying the material to be investigated, to it. If E_c is the potential difference between the electrode surfaces, $Q = C_0E_c$. charge of the capacitor. Any change of capacitance will cause a current (neglecting R) of

$$i = \frac{dQ}{dt} = E_c \frac{dC_o}{dt} + C_o \frac{dE_c}{dt}$$

under steady state condition (E_c = constant) the second term vanishes.

$$\text{i.e.}, \quad i = E_c . \frac{dC_o}{dt}$$

A driving mechanism M causes one electrode to oscillate with a frequency f (angular velocity $\omega = 2\pi f$) by an amount $\pm \partial$ about its middle position. If ∂ is small compared to the average distance d, the capacitance can be expressed by

$$C = C_o \ (1 - \partial/d \sin wt)$$

and the current is

$$i = -E_c \ \omega C_o \ \partial/d \cos wt$$

$$C = C_o(1 - \partial/d \sin wt)$$

$$C - C_o = - \partial/d \sin wt \times C_o$$

$$\partial C = (-\partial/d \sin wt).C_o$$

Sensitivity for fractional change in capacitance :

$$S = \frac{\partial C}{\partial} = - \frac{C_o}{d} \sin wt$$

$$C_o = \frac{\epsilon a}{d}$$

$$S = - \frac{\epsilon a}{d^2} \sin wt.$$

where a = area of plate.

CHAPTER-V

A NEW BRIDGE CIRCUIT FOR CONTINUOUSLY MEASURING CAPACITANCE CHANGES AND SENSITIVITY

5.1 INTRODUCTION

In capacitive devices, a central plate, usually earthed, is displaced between two fixed plates. It is desirable that during displacements, when one capacitance is increasing at the expense of the second, the linearity of the differential capacitance should provide a linear measurement. Two known methods are the ordinary bridge, and a recently developed pseudo bridge based on an operational amplifier (1). Both shown schematically in fig.5.1(a) and (b).

5.2 ANALYSIS

Assuming that the detector is of high impedance, the transfer function of the ordinary bridge -

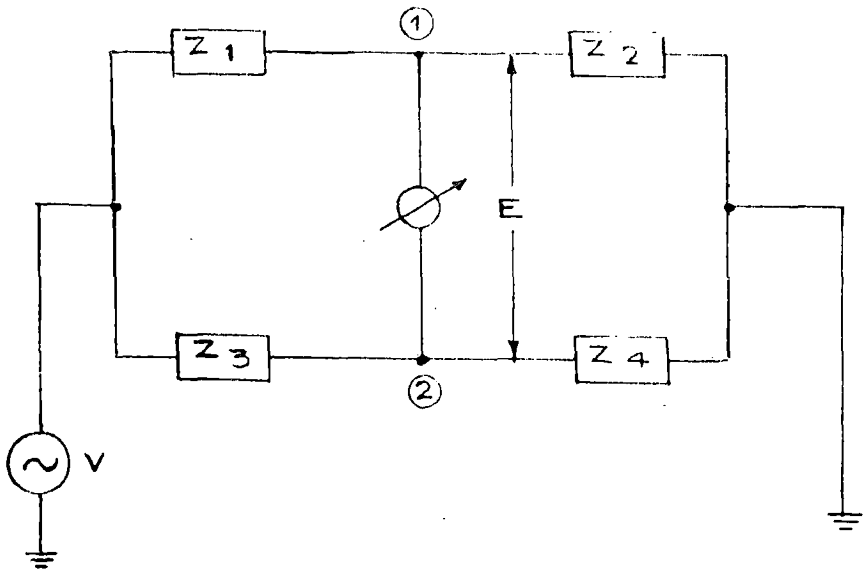
$$I_1 = \frac{V}{Z_1+Z_2} \quad , \quad I_2 = \frac{V}{Z_3+Z_4}$$

$$V_2 = \frac{V.Z_2}{Z_1+Z_2} \quad , \quad V_4 = \frac{V.Z_4}{Z_3+Z_4}$$

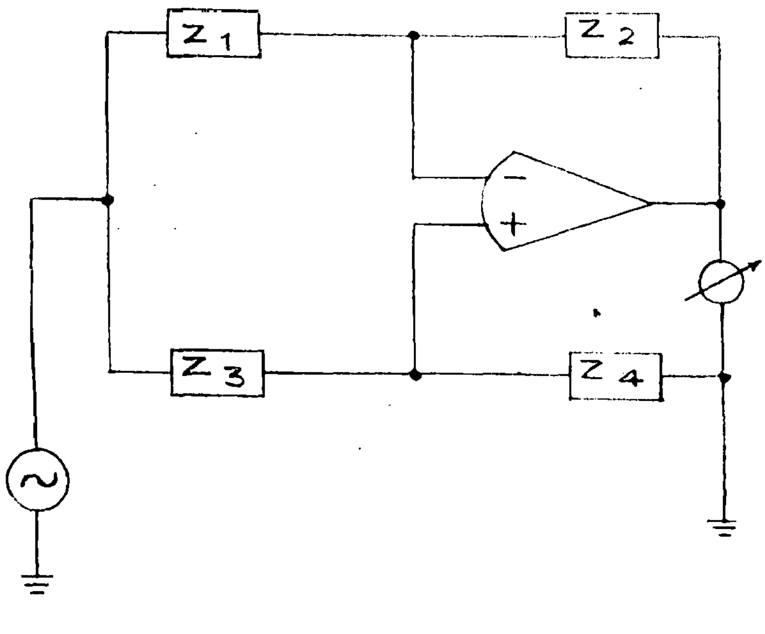
$$E = \frac{V.Z_2}{Z_1+Z_2} - \frac{V.Z_4}{Z_3+Z_4}$$

Transfer function

$$T = \frac{E}{V} = \frac{Z_2}{Z_1+Z_2} - \frac{Z_4}{Z_3+Z_4}$$



(a) ORDINARY BRIDGE
FIG. 5.1 (a)



(b) PSEUDO BRIDGE
FIG. 5.1 (b)

Close to balance, the transfer function may be considered as a linear function of impedance. For large deviation linear behaviour is not attained. Rewritten transfer function as :

$$T = \frac{Z_2/Z_1}{1+Z_2/Z_1} - \frac{Z_4/Z_3}{1+Z_4/Z_3}$$

In this case linearity at the detector is possible for large deviations from balance under the condition

$$Z_2/Z_1 \ll 1 \ , \ Z_4/Z_3 \ll 1.$$

$$T \simeq Z_2/Z_1 - Z_4/Z_3$$

In this case, linearity is achieved with a possible loss of sensitivity, and so it is not practical.

Linearity can be preserved in the pseudo bridge, transfer function is, according to -

$T = \dfrac{Z_4/Z_3 - Z_2/Z_1}{1+Z_4/Z_3}$, only Z_2/Z_1 is allowed to vary.
For a difference measurement between both sides of the bridge, this condition no longer holds. For double sided operation, the linearity is in fact even poorer than in the case of the simple bridge. An arrangement of similar type is used in a commercial device.

The arrangement shown in fig. 5.2(a) is capable of operating linearly over a considerable part of the capacitance range. This bridge comprises two similar feed-back

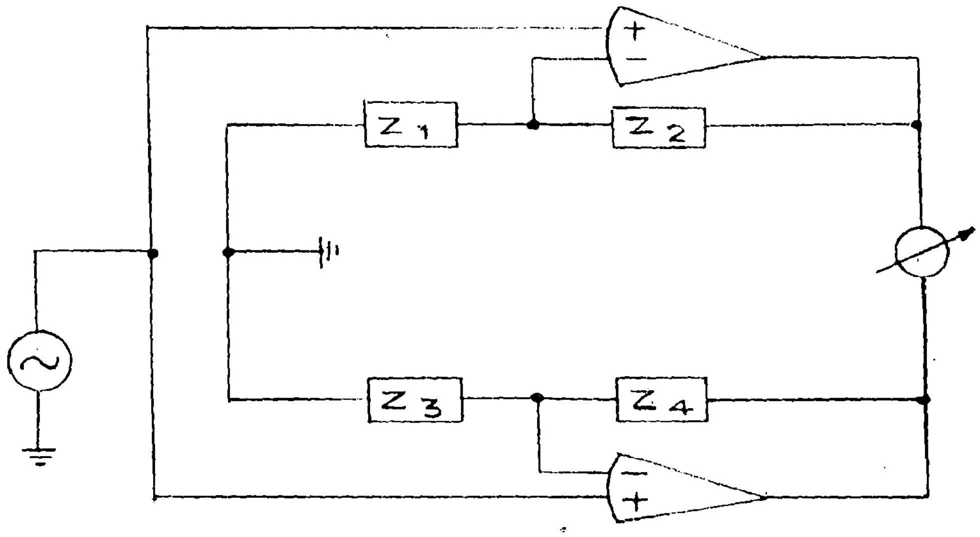


FIG. 5·2 (a)

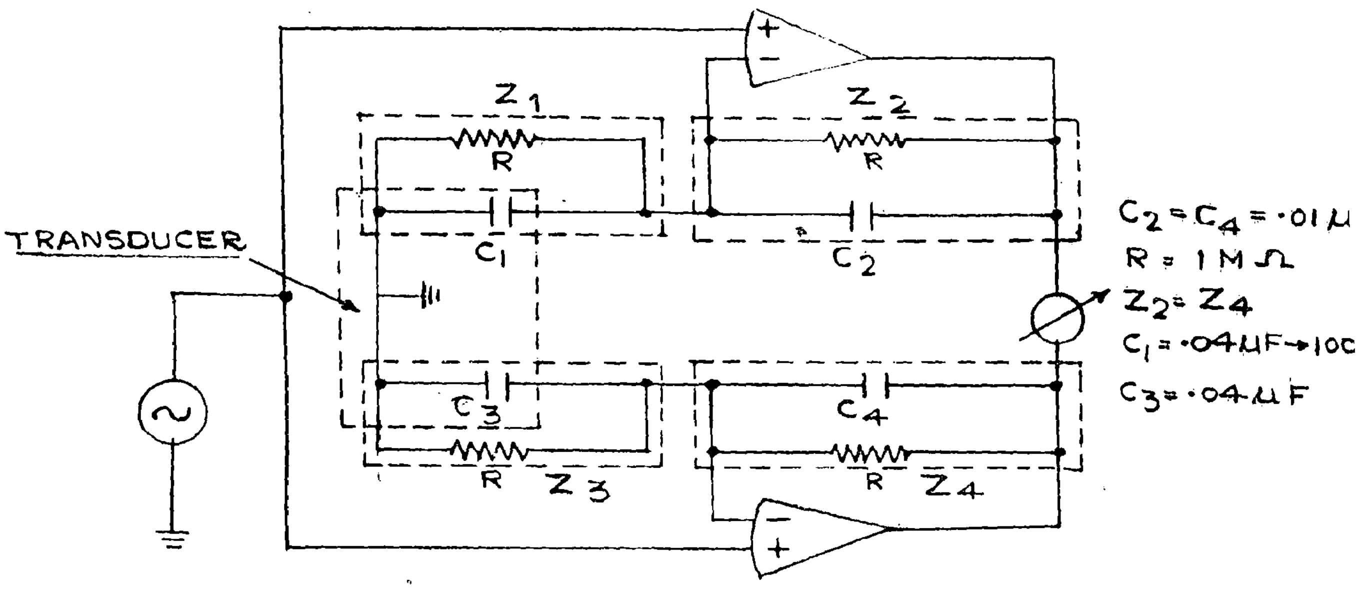


FIG. 5·2 (b)

amplifier circuits. The transfer functions for upper and lower circuits are -

$$T_U = \frac{Z_1+Z_2}{Z_1}$$

$$I_1 = \frac{V}{Z_1Z_2/Z_1+Z_2} = \frac{V(Z_1+Z_2)}{Z_1Z_2}$$

$$V_2 = \frac{V(Z_1+Z_2)}{Z_1 \cdot Z_2}$$

$$T_U = \frac{V(Z_1+Z_2)}{V Z_1} = \frac{(Z_1+Z_2)}{Z_1}$$

$$T_L = \frac{Z_3+Z_4}{Z_3}$$

$$I_2 = \frac{V}{Z_3Z_4/Z_4+Z_3} = \frac{V(Z_4+Z_3)}{Z_3 \cdot Z_4}$$

$$V_4 = \frac{V(Z_4+Z_3)}{Z_3 \cdot Z_4} \cdot Z_4$$

$$T_L = \frac{V(Z_4+Z_3)}{V.Z_3}$$

$$T_L = \left(\frac{Z_4+Z_3}{Z_3}\right)$$

These relations only hold in the case of amplifiers with a high open-loop gain. Combined transfer function of bridge :

$$T = T_U - T_L$$

$$T = Z_2/Z_1 - Z_4/Z_3$$

Z_1 and Z_3 represented by the variable capacitors in the differential transducer. If Z_1 and Z_3 purely capacitive and equal to $1/jwC_1$ and $1/jwC_3$ then

$$T = jw(Z_2C_1 - Z_4C_3)$$

If Z_2 and Z_4 are chosen to be equal, then

$$T = jw\ Z_2\ (C_1 - C_3)$$

which is proportional to the difference between the two oppositely varying capacitors. This is a truly linear capacitive instrument, both in a differential and in one-

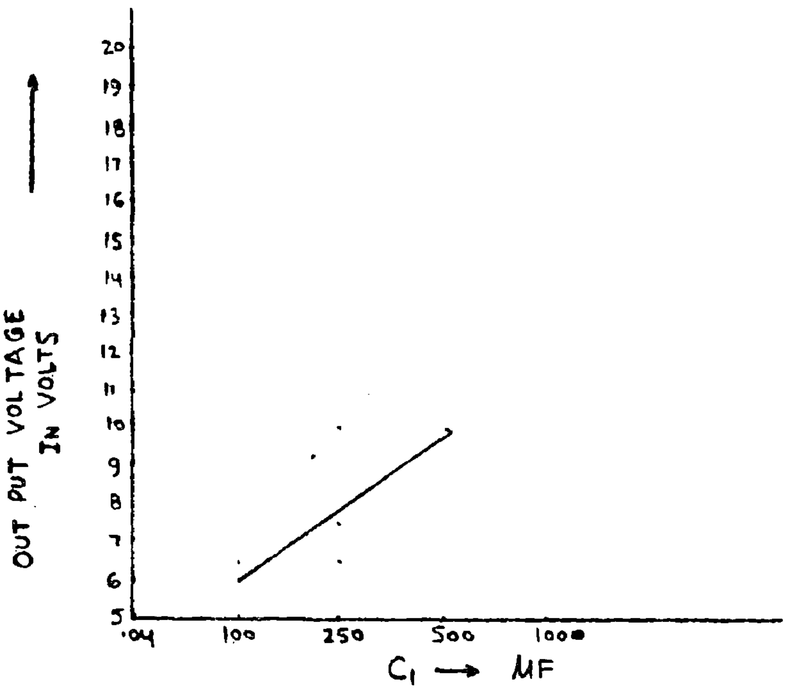

OUT PUT VOLTAGE
IN VOLTS
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
·04
100
250
500
1000
C₁ → μF

FIG. 5.3

sided operation. For the circuit fig. 5.2(b) 'T' is given by

$$Z_2 = Z_4 = Z, \quad Z_1 = \frac{1}{1/R+jwC_1} \quad \text{and} \quad Z_3 = \frac{1}{1/R+jwC_3}$$

$$T = Z[(1/R+jwC_1) - (1/R+jwC_3)]$$

$$T = jwZ(C_1-C_3)$$

This is an improved system, making use of more compatible operational amplifiers. These have knees in their frequency characteristic fàr in excess of the operating frequency and at the same time posses a higher open loop gain than the amplifiers used previously. In this way it is expected that the instrument will more closely adhere to the ideal linear expansion.

5.3 EXPERIMENTAL VARIFICATION

It is seen experimentally that when C_1 is varied from 100 μF to 1000 μF out put varies linearly as shown in fig. 5.3.

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CHAPTER-VI

CONCLUSION AND SCOPE FOR FUTURE WORK

In the present work, the sensitivity analysis of capacitive pick-ups has been carried out for different configurations. The sensitivity of bridges used for measurement of capacitance has been calculated and variation of sensitivity with the change in bridge parameter has been plotted. Influence of environmental parameters has also been studied on the value of capacitance and its sensitivity.

Bridges used for sensitivity measurement are De Sauty's, Schearing and Wien's bridge. It is seen that sensitivity of De Sauty's bridge is constant. Sensitivity of Shearing bridge has been calculated in two steps variations in resistance R_4 and variation in capacitance C_4, The sensitivity decreases with the increase in value of R_4 and increases with the increase in value of C_4. Sensitivity of Wien's bridge decreases with the increase in value of bridge parameters i.e. resistance.

Environmental parameters such as temperature, vibration, moisture, pressure adversely affects the sensitivity of capacitive pick-ups.

Sensitivity can be increased by two methods one is by Rotary motion and another by using serrated type transducer.

In future scope of the work, a briage circuit scheme for sensitivity analysis of the capacitive pick-ups can be developed by using a intelligent combination of hardware and software capabilities of microprocessors and micro-computers.

****

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