Unit 1

INTRODUCTION OF INSTRUMENTATION SYSTEM

Instrumentation (Measurement) System

It is the process of determining numerical value of quantity under measurement. M.S. or I.S. is the means to carry out measurements. It is a collective term for measuring instruments that are used for indicating, measuring and recording physical quantities.

1.1 Typical applications of Instrumentation Systems

Instrumentation systems find application across a wide range of industries and fields where precise measurement, monitoring, control, and analysis of physical quantities are essential. Here are some typical applications:

- **Industrial Process Control:** Instrumentation systems are extensively used in industries such as chemical, petrochemical, oil and gas, and manufacturing for monitoring and controlling parameters such as temperature, pressure, flow rate, level, and composition to ensure optimal process performance, efficiency, and safety.
- **Environmental Monitoring:** Instrumentation systems play a vital role in monitoring and analyzing environmental parameters such as air quality, water quality, soil composition, and weather conditions. They help in assessing environmental impact, detecting pollution, and ensuring compliance with regulatory standards.
- **Automotive and Aerospace:** Instrumentation systems are used in vehicle and aircraft design, testing, and operation for measuring parameters like speed, acceleration, temperature, pressure, vibration, and fuel efficiency. They help improve performance, reliability, and safety in automotive and aerospace applications.
- **Biomedical and Healthcare:** In biomedical and healthcare fields, instrumentation systems are utilized for monitoring vital signs, diagnosing medical conditions, conducting medical imaging (e.g., MRI, CT scans), and administering treatment (e.g., drug delivery systems). They enable healthcare professionals to make informed decisions and provide optimal patient care.
- **Energy Management:** Instrumentation systems are employed in power generation, transmission, and distribution systems to monitor and control parameters such as voltage, current, frequency, and power quality. They help optimize energy usage, improve efficiency, and ensure grid stability and reliability.
- **Research and Development:** Instrumentation systems are indispensable in scientific research and development across various disciplines, including physics, chemistry, biology, materials science, and engineering. They facilitate precise measurement, data acquisition, and analysis for experiments, simulations, and prototype testing.
- **Structural Health Monitoring:** In civil engineering, instrumentation systems are used for monitoring the structural integrity and health of buildings, bridges, dams, and other infrastructure. They help detect defects, assess structural performance, and prevent failures through real-time monitoring of parameters like strain, vibration, and temperature.

- **Telecommunications and Networking:** Instrumentation systems are employed in telecommunications and networking for testing and monitoring network performance, signal quality, and data transmission. They ensure reliable communication, troubleshoot network issues, and optimize network infrastructure.

These are just a few examples of the diverse applications of instrumentation systems across various industries and disciplines, highlighting their critical role in modern technology, research, and development.

1.2 Functional elements of Instrumentation and Measuring Systems

An instrumentation system is a collection of devices and software that operate together to measure and record physical or electrical parameters such as voltage, current, flow rate, temperature, pressure, humidity and other variables.

Is consists if sensors or transducers that convert physical or electrical quantities into electrical signals, signal conditioning circuits that amplify, filter or modify the signals, data acquisition system that digitize and store signals, and controls system that use the data to adjust the process or the system.

The main purpose of instrumentation system is to monitor or control a process or system in real time.

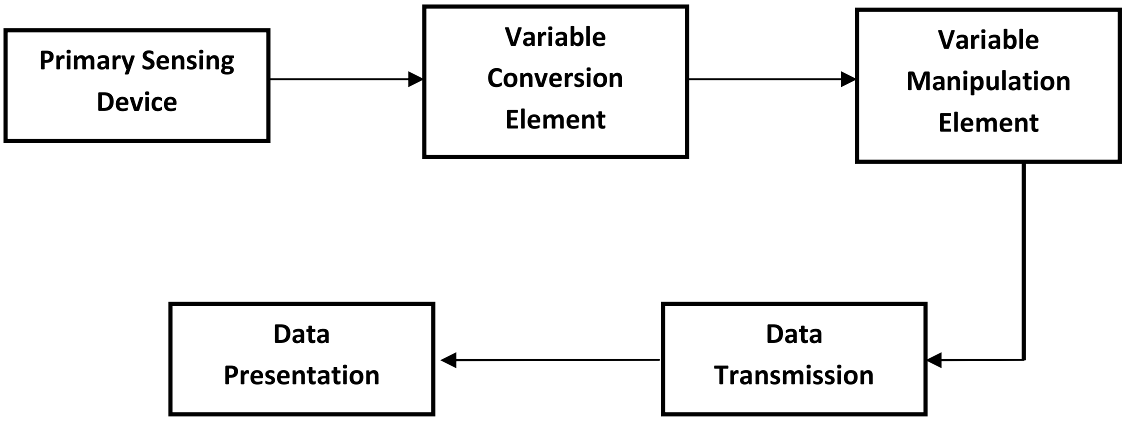


Fig: Instrumentation System

i) Primary Sensing Device

The quantity to be measured makes its first contact with the primary sensing element. This act is immediately followed by the conversion of measured into an analogous electrical signal with the help of transducers. This stage is also known as detector transducers stage.

ii) Variable Conversion Element

The output of the primary sensing element may be electrical signal of any form. It may be voltage, a frequency or some other electrical parameter. Sometimes this output is not suited to the system. For the instrument to perform the desired function, it may be necessary to convert this output to some other suitable form while preserving the information content of the original signal. This work is performed by the variable conversion element.

iii) Variable Manipulation Element

The function of this element is to manipulate the signal presented to it preserving the original nature of the signal. Manipulation here means only a change in numeric value of the signal. For example: an electric amplifier accepts a small voltage signal as input and produces an output signal which is also voltage but of greater magnitude. Thus a voltage amplifier acts as a variable manipulation.

iv) Data Transmission Element

After variable manipulation is done, it becomes necessary to transmit data from one to another. The element that performs this function is called a Data Transmission Element. For example: Space-crafts are physically separated from the earth where the control stations guiding their movements are located. Therefore, control signals are sent from these stations to space-crafts by a complicated telemetry system using radio signals.

v) Data Presentation Element

The information about the quantity under measurement has to be conveyed to the personnel handling the instrument or the system for monitoring control or analysis purposes. The information conveyed must be in a form intelligible to the personnel or to the intelligent instrument system. This is done by data presentation element.

1.3 Errors and uncertainties in Measurements and Static performance characteristics of instruments

1.3.1 Introduction to Errors

An instrument in a real practice, if measurement is performed on a certain variable the result is not always exact. The difference between instrument reading and true value is called error. It can occur in various contexts, including scientific measurement, experiment, calculations and observations.

$$Error = Measured\ Value - True\ Value$$

And, error percentage can be calculated as:

$$Error\ \% = \frac{Measured\ Value - True\ Value}{True\ Value} \times 100$$

Here are a few common types of errors:

- **Random Error:** Random errors are caused by unpredictable fluctuations in experimental conditions, measurement tools, or human factors. They affect the precision of measurements but can be minimized through repeated trials and statistical analysis.
- **Systematic Error:** Systematic errors are consistent and repeatable deviations from the true value due to flaws in experimental setup, measurement instruments, or calibration procedures. Unlike random errors, systematic errors can't be reduced by repeating measurements and often require adjustments to experimental methods or equipment calibration.
- **Instrument Error:** Instrument errors arise from inaccuracies or limitations in the measuring instruments themselves. These errors can include issues such as instrument drift, nonlinearity, or limited sensitivity.

- **Human Error:** Human errors stem from mistakes made by individuals conducting experiments, recording data, or performing calculations. They can result from misinterpretation of instructions, data entry mistakes, or inadequate training.
- **Environmental Error:** Environmental errors are caused by fluctuations or variations in environmental conditions, such as temperature, humidity, or atmospheric pressure. These factors can introduce uncertainties into measurements and experiments.
- **Interference Error:** Interference errors occur when external factors or signals interfere with the measurement process, leading to inaccuracies in the recorded data. Examples include electromagnetic interference (EMI) or cross-talk in electronic measurements.

Example

A Voltmeter having a sensitivity of $1000\Omega/V$, reads $100V$ units $150V$ scale when connected across an unknown resistor in series with a mili-ammeter. When the mili-ammeter reads $5mA$, calculate.

a. **The apparent resistance of the unknown resistor.**

b. **The actual resistance of the resistor.**

c. **The error due to the loading effect of the voltmeter**

Solution:

a. The total circuit resistor equals

$$R_T = \frac{V_T}{I_T} = \frac{100V}{5mA} = 20K\Omega$$

Neglecting the resistance of the mili-ammeter, the value of the unknown resistor is $R_x = 20K\Omega$

b. The voltmeter is in parallel with the unknown resistor

We have,

$$R_T = \frac{R_x R_v}{R_v + R_x}$$

$$or, R_T R_v + R_T R_x = R_x R_v$$

$$or, Unknown\ resistor\ value\ (R_x) = \frac{R_T R_v}{R_v - R_T} = \frac{20 \times 150}{150 - 20} = 23.07K\Omega$$

c. $\%\ Error = \frac{Actual - Appare\quad Value}{Actual\ Value} \times 100 = \frac{23.07 - 20}{23.07} \times 100 = 13.33\%$

1.3.2 Static Performance Parameters

It refers to characteristics of an instrument that describe its behavior under steady-state or static conditions. These parameters provide valuable insights into the instrument's capabilities and limitations. Here are some common static performance parameters:

i) Accuracy

It is the measure of closeness of measured value to the true value of quantity. It specifies difference between true value and measured value for circuit components like resister, inductor and capacitors. Accuracy of measurement means the conformity of the truth.

$$Accuracy = M.V. - T.V.$$

Where, M.V. is measured value and T.V. is true value.

OR

$$Accuracy = \%\ of\ rated\ value$$

For Voltmeter and Ammeter

$$Accuracy = \%\ of\ full\ scale\ reading$$

ii) Precision

It is the measure of consistency or repeatability of measurements. High degree of precision doesn't guarantee the accuracy. The accurate calibration makes the accurate measurement possible. It quantifies the degree of scatter or variability in repeated measurements of the same quantity under identical conditions. Precision is often expressed as standard deviation or variance.

iii) Resolution

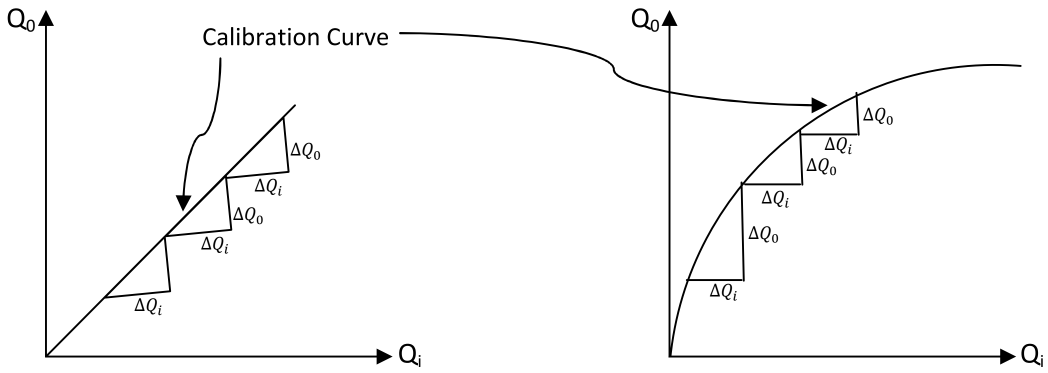
If an input is slowly increased from some arbitrary value, the output doesn't change until certain increment is exceeded. This increment is known as resolution. So, resolution is defined as smallest change in input which results in detectable change in output. In case of analog instrument, it is significant or smallest division whereas in case of digital instrument it is significant of LSB.

iv) Threshold

A threshold is a predefined value used to make decisions or classify data based on whether it falls above or below that value, crucial in signal and image processing, machine learning, and decision-making contexts. It separates data into different categories, such as signal and noise in signal processing or foreground and background in image processing. In machine learning, thresholds are commonly used for binary classification tasks, determining class labels based on predicted probabilities or scores. Selecting an appropriate threshold is essential and involves trade-offs between performance metrics like accuracy and specificity. Thresholds enable automated decision-making processes and are fundamental to various applications across different domains.

v) Sensitivity

The sensitivity of instrument is the ratio of magnitude of change in output to the change in input. It is the slope of calibration curve. When calibration curve is linear, the sensitivity is constant throughout whole range. However, if calibration curve is not linear sensitivity varies with excitation.



Constant Sensitivity

Variable Sensitivity

$$Sensitivity = \frac{Small\ chang\ \ in\ Output}{Small\ Chang\ \ in\ Input} = \frac{\Delta Q_0}{\Delta Q_i}$$

vi) Linearity

The instrument requirement property of linearity that is the output varies linearly, according to the input. If the sensitivity is constant, then he calibration curve is linear and can be expressed by equation;

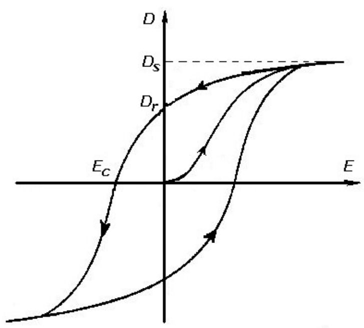
$y = mx + c$

Where,

y is output, m is slope and c is y-intercept.

However, linearity is closeness of the calibration curve of measuring system to the straight line. It is expressed as % of deviation from straight curve.

vii) Hysteresis



Hysteresis is the difference in the instrument's output for the same input value, depending on whether the input value is increasing or decreasing. It arises from internal friction or mechanical properties of the instrument and can introduce errors in measurements, particularly in applications where the input signal changes direction frequently.

viii) Dead band

It is a range of input values within which no action or response is triggered. It's typically implemented to prevent frequent or unnecessary adjustments in response to small fluctuations in input. Dead bands are commonly used in control systems to improve stability, reduce wear on mechanical components, and minimize energy consumption.

ix) Backlash

Backlash in instrumentation systems refers to the mechanical play or clearance between components, leading to delays or lost motion when changing direction. It can introduce inaccuracies in measurements, affect the responsiveness of actuators, and degrade the performance of control systems. To mitigate backlash, design considerations such as tighter tolerances and anti-backlash mechanisms can be employed.

x) Drift

It refers to a gradual change in the output or performance of the system over time, under constant operating conditions. It can be caused by factors such as aging of components, temperature variations, or changes in environmental conditions. Drift can lead to inaccuracies in measurements, affecting the reliability and consistency of the system. To mitigate drift, regular calibration and maintenance are essential, as well as the use of stable and high-quality components.

xi) Span

Span refers to the difference between the upper and lower limits of the range over which the system can accurately measure or respond to a signal. It defines the operating range of the system and is often specified in terms of engineering units (e.g., volts, amps, temperature). Span encompasses the full scale of the measurement range and is essential for setting up and calibrating the instrumentation system. Proper adjustment of span ensures that the system can accurately detect and respond to variations within the specified range, optimizing its performance and reliability.

Example

If a voltmeter having full scale voltage of 100V and accuracy of 1% is used to measure

i) 80V

Calculate the % error in both cases.

Solution:

i) $T.V. = 80V$

$M.V. = 80V \pm 1\%\ of\ 100V$

$or, 79V\ or\ 81V$

$$\therefore \%\ error = \frac{TV - MV}{TV} \times 100 = \frac{80 - 79}{80} \times 100 = 1.25\%$$

1.3.3 Impedance Loading and Matching

Impedance loading and matching are crucial concepts in instrumentation, particularly in fields like electrical engineering and physics where precise measurements are essential.

Impedance: Impedance refers to the opposition that a circuit presents to the flow of alternating current (AC). It's a combination of resistance, capacitance, and inductance and is measured in ohms. Impedance varies with frequency in AC circuits.

Loading: Loading occurs when a measurement device or instrument connected to a circuit disturbs the behavior of that circuit. It happens because the instrument introduces its own impedance into the circuit, altering the original characteristics of the circuit under test.

Impedance Loading: Impedance loading happens when the impedance of the measuring instrument affects the circuit being measured. If the impedance of the instrument is not properly matched to the impedance of the circuit, it can lead to inaccurate measurements.

Matching: Impedance matching involves adjusting the impedance of the measuring instrument to match that of the circuit under test. This ensures maximum power transfer and minimal disturbance to the circuit being measured. In essence, matching impedances minimizes reflection and ensures that the signal is accurately transmitted between the source and the load.

In instrumentation, particularly in fields like telecommunications, audio engineering, and RF engineering, impedance matching is critical for efficient signal transfer and accurate measurements. For example, in RF systems, antennas must be impedance-matched to the transmission line and subsequently to the receiver to ensure minimal signal loss and maximum power transfer.

1.3.4 Errors: Statistical analysis of error in measurement

Static tool helps to analyze uncertainty of the final result. It helps to interpret large number of readings into meaningful conclusion.

i) Arithmetic Mean

The arithmetic mean, often simply called the mean, is a fundamental concept in statistics and mathematics. It is the most commonly used measure of central tendency, representing the average value of a set of numbers.

$$\bar{x} = \frac{x_1 + x_2 + x_3 + x_4 + \ldots\ldots + x_n}{n} = \frac{\sum x}{n}$$

Where, $\bar{x}$ is arithmetic mean

$x_1, x_2, \ldots\ldots, x_n$ are readings

n is number of readings.

ii) Deviation from the mean

$d_1 = x_1 - \bar{x}$

$d_2 = x_2 - \bar{x}$

$\ldots\ldots\ldots\ldots\ldots\ldots$

$\ldots\ldots\ldots\ldots\ldots\ldots$

$d_n = x_n - \bar{x}$

Where, d_n is the deviation of the nth reading from the mean.

iii) Average Deviation from the mean

Average Deviation from the mean D can be expressed as:

$$D = \frac{|d_1| + |d_2| + |d_3| + \ldots\ldots + |d_n|}{n} = \frac{\sum |d|}{n}$$

iv) Standard Deviation

The standard deviation or the rot mean square deviation of a finite number of data is given by (n<20)

$$S.D. = s = \sqrt{\frac{{d_1}^2 + {d_2}^2 + {d_3}^2 + \ldots\ldots\ldots\ldots + {d_n}^2}{n-1}} = \sqrt{\frac{\sum {d_t}^2}{n-1}}$$

For infinite number of data (n>20)

$$S.D. = \sigma = \sqrt{\frac{\sum {d_t}^2}{n}}$$

Note: when the number of observations is greater than 20, S.D is denoted by symbol 'σ' while if the number of observations is less than 20, the symbol used is 'S'

v) Variance

The variance is square of standard deviation

i.e. $V = (S.D)^2 = \sigma^2 = \frac{\sum {d_t}^2}{n}$ (For n>20)

$S^2 = \frac{\sum {d_t}^2}{n-1}$ (For n<20)

Limiting Error

In most instruments the accuracy is guaranteed to be within a certain percentage of full scale reading. The limit of thin deviation from the specified value is defined as limiting error. If Aa be the actual quantity, As be the nominal quantity. Then $\pm\delta A$ is the limiting error, i.e.

$Aa = As \pm \delta A$

Example

1. **A $0 - 150V$ voltmeter has a guaranteed accuracy of 1% of full deflection. The voltage measured by this instrument is $75V$. Calculate the limiting error in percentage.**

Solution:

Given,

Nominal value = 150V

Relative % error (E_r) = 1% = 0.01

Since,

$$E_r = \frac{\delta A}{As}$$

$\therefore \delta A = E_r \times As = 0.01 \times 150 = 1.5V$

Now, we have;

$\delta A = 1.5V$

$As = 75V$

$E_r = ?$

Then,

$$E_r = \frac{\delta A}{As} = \frac{1.5V}{75V} = 0.02$$

$E_r = 2\%$

$\therefore$ Actual value (Aa) $= Aa \pm \delta A = 75 \pm 0.02$

2. **The measurements of resistance of resistors are: 101.2, 101.7, 101.3, 101.0, 101.5, 101.3, 101.2, 101.4, 101.3 and 101.1. Calculate**

a. **Arithmetic Mean**

b. **Average deviation from mean**

c. **Standard Deviation**

d. **Range**

e. **Probable Error**

Solution:

Given,

$x = 101.2, 101.7, 101.3, 101.0, 101.5, 101.3, 101.2, 101.4, 101.3, 101.1$

$n = 10$

a. $Arithmetic\ Mean\ \bar{x} = \frac{\sum x}{n} = \frac{101.2+101.7+101.3+101.0+101.5+101.3+101.2+101.4+101.3+101.1}{10}$

$\bar{x} = 101.3$

b. $Average\ Deviation$

We know,

$d = x - \bar{x}$

For all x

$d_1 = x_1 - \bar{x} = 101.2 - 101.3 = -0.1$

$d_2 = x_2 - \bar{x} = 101.7 - 101.3 = 0.4$

$d_3 = x_3 - \bar{x} = 101.3 - 101.3 = 0.0$

$d_4 = x_4 - \bar{x} = 101.0 - 101.3 = -0.3$

$d_5 = x_5 - \bar{x} = 101.5 - 101.3 = 0.2$

$d_6 = x_6 - \bar{x} = 101.3 - 101.3 = 0.0$

$d_7 = x_7 - \bar{x} = 101.2 - 101.3 = -0.1$

$d_8 = x_8 - \bar{x} = 101.4 - 101.3 = 0.1$

$d_9 = x_9 - \bar{x} = 101.3 - 101.3 = 0.0$

$d_{10} = x_{10} - \bar{x} = 101.1 - 101.3 = 0.2$

$Since,$

$$D = \frac{\sum |d|}{n} = \frac{1.4}{10} = 0.14$$

c. Standard Deviation

We know,

For n<20

$$S.D. = \sqrt{\frac{\sum(|d|)^2}{n-1}} = \sqrt{\frac{0.36}{10.1}} = \sqrt{\frac{1}{25}} = 0.2$$

d. $Range = Largest\ Value - Smallest\ Value = 101.5 - 101.0 = 0.5$

e. $Probable\ Error(r) = \pm 0.6745 \times S.D = \pm 0.6745 \times 0.2 = \pm 0.1349$

1.3.5 Standards of measurement

A standard of measurement is a physical representation of a unit measurement. For example, the fundamental unit of mass in international system (SI) is Kilogram, defined as the mass of cubic decimeter of water as its temperature of maximum density of 4^0C. Standards of measurements are of four types according to their function and application. They are as follows:

i) International Standards

The international standards are defined on the basis of international agreement. They are periodically evaluated and checked by absolute measurement in terms of fundamental unit. The international standards are maintained at the international Bureau of weights and measures and are not available to the ordinary user of measuring instrument for purpose of comparison or calibration.

ii) Primary Standards

The primary standards are maintained by national laboratories in different parts of the world. The primary standards, which represent the fundamental unit and some of the derived electrical and mechanical unit, are independently calibrated by absolute measurements at each of the national laboratories. One of the main functions of the primary standard is the verification and calibration of secondary standards.

iii) Secondary Standards

These are the basic reference standard used in industrial measurement laboratories. These standards are maintained by the particular involved industry and are checked locally against other reference standards in the area. The responsibility for maintenance and calibration of secondary standard lies entirely with the industrial laboratory itself. Secondary standards are generally sent to the national standards laboratory on a periodic basis for calibration and comparison against the primary standards. They are then returned to the industrial user with a ratification of their measured value in terms of the primary standard.

iv) Working Standards

Working standards are the principle tools of a measurement laboratory. They are used to check and calibrate general laboratory instrument for accuracy and performance or the perform comparison measurements in industrial applications.

v) IEEE Standards

This standard is maintained by the Institute of Electrical and Electronics Engineers, IEEE an engineering society headquartered in New York City. These standards are not physical items that are available for comparison and checking of secondary standard but are standard procedures, nomenclature, definitions etc. It gives the standard test method for testing and evaluating various electronic systems and components. For example, there is a standard method for testing and evaluating attenuators.

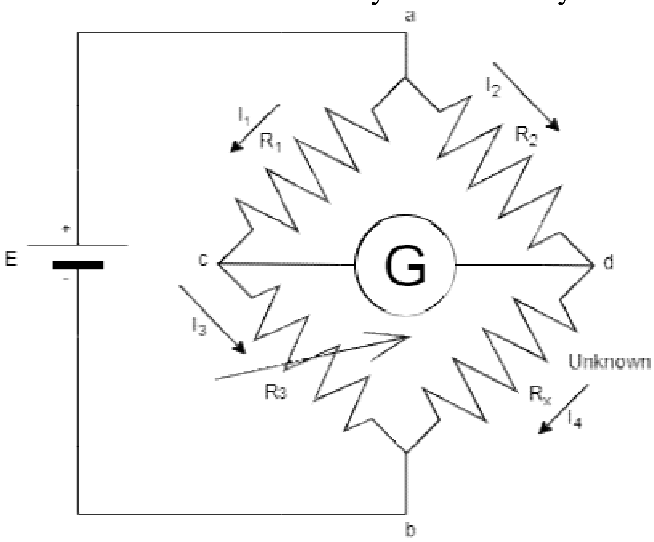
1.4 Bridge Measurement

It is used to determine unknown electrical parameters such as resistance (R), inductance (L), capacitance (C) and frequency (f). It consists of four arms, a detector and power supply; power supply may be a AC or DC.

1.4.1 DC Bridge Circuit

i) Wheatstone bridge

The Wheatstone bridge is an instrument for making comparison measurements and operates upon a null indication principle. It is a very important device used in the measurement of medium resistance due to its accuracy and reliability.



Basic Operation

Figure shows the schematic of a Wheatstone bridge. The bridge has four resistive arms together with a source of emf (a battery) and null detector, usually a galvanometer or other sensitive current meter.

The bridge is said to be balanced when the potential difference across the galvanometer is 0 V so that there is no current through the galvanometer. This condition occurs when the voltage from point 'c' to point 'd' to point 'a' or by referring to the other battery terminal, when the voltage from point 'c' to 'b' equals the voltage from point 'd' to point 'b'. Hence, the bridge is balanced.

When,

$E_{ac} = E_{ad}$

Or, $I_1 R_1 = I_2 R_2 \dots\dots\dots\dots (1)$

If the galvanometer current is zero, the following conditions also exist:

$I_1 = I_3 = \frac{E}{R_1+R_3} \dots\dots\dots\dots\dots (2)$ And

$$I_2 = I_4 = \frac{E}{R_2 + R_x} \dots\dots\dots\dots (3)$$

Combining equations (1) , (2) and (3) and simplifying, we get

$$\frac{R_1}{R_1 + R_3} = \frac{R_2}{R_2 + R_x}$$

Or, $R_1 R_x = R_2 R_3 \ldots\ldots\ldots..(4)$

Equation (4) is the well-known expression for balance of the Wheatstone bridge. If three of the resistance has known values, the fourth may be determined from equation (4). Hence, if R_x is the unknown resistor, its resistance can be expressed in terms of remaining resistors as:

$$R_x = \frac{R_2 R_3}{R_1} \ldots\ldots\ldots..(5)$$

The measurement of unknown resistance R_x is independent of the characteristics or the calibration of the null-detecting galvanometer provided that the null detector has sensitivity to indicate the balance position of the bridge with the required degree of precision.

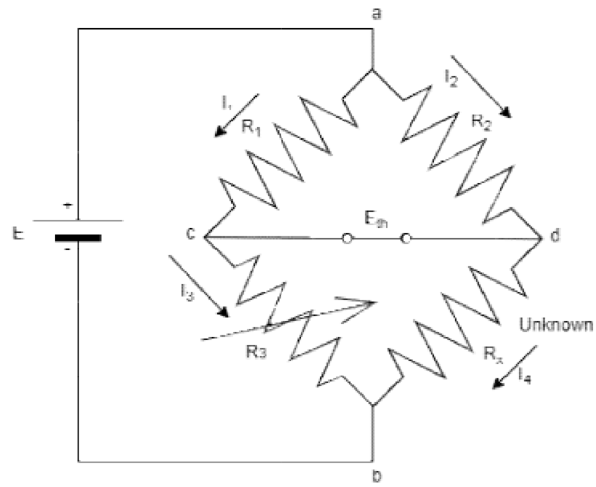
Measurement Errors

The main source of measurement error is found in the limiting errors of the three known resistors. Other errors may include the following:

- Insufficient sensitivity of the null detector
- Changes in resistance of the bridge arms due to the heating effect of the current through the resistors.
- Thermal emfs in the bridge circuit or the galvanometer circuit can also cause problems when low value resistors are being measured.
- Errors due to the resistance of leads and contacts exteriors to the actual bride circuit play a role in the measurement of very low resistance values. These errors may be reduced by using a Kelvin bridge.

Thevenin Equivalent Circuit

To determine whether or not the galvanometer has the required sensitivity to detect an unbalance condition, it is necessary to calculate the galvanometer current. The Thevenin equivalent circuit is determined by looking galvanometer terminal 'c' and 'd'. There are two steps to find Thevenin equivalent circuit.



i) Finding the voltage, E_{th} appearing the terminals 'c' and 'd' when the galvanometer is removed from the circuit. Now, the Thevenin or open circuit voltages.

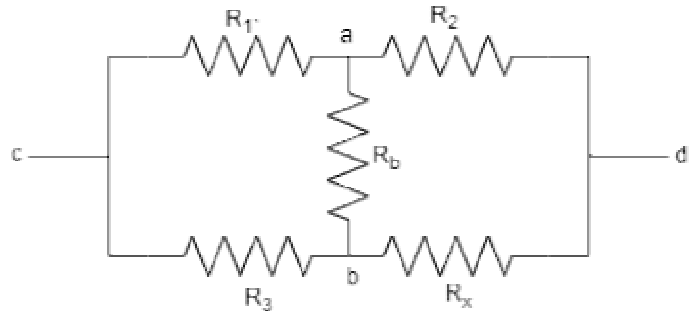
$E_{th} = E_{cd} = E_{ac} - E_{ad}$

$= I_1R_1 - I_2R_2$

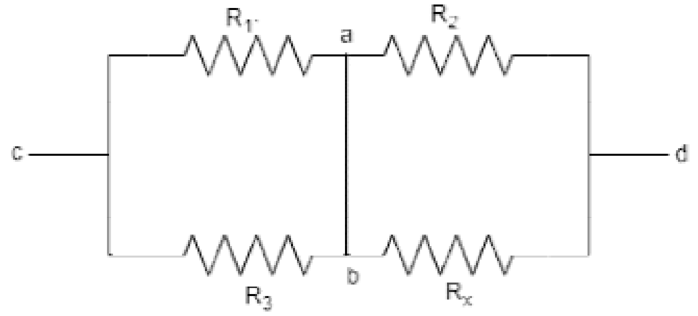
Where, $I_1 = \frac{E}{R_1+R_3}$ and $I_2 = \frac{E}{R_2+R_x}$

$\therefore E_{th} = E\left(\frac{R_1}{R_1+R_3} - \frac{R_2}{R_2+R_x}\right)$

ii) Finding the equivalent resistance looking into the terminals 'c' and'd', with the battery by its internal resistance.



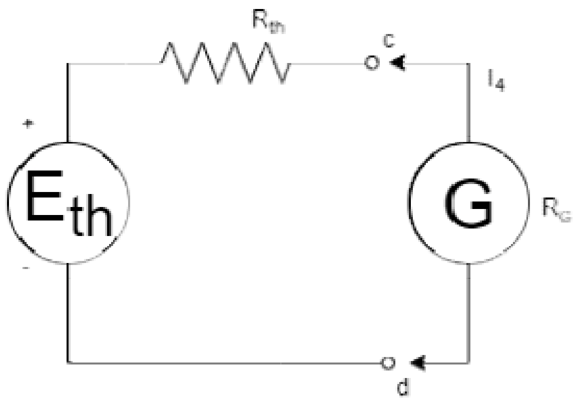
Since, in most case the internal resistance, R_b of the battery is extremely low, it can be neglected. i.e. $R_b = 0$. So,



$\therefore R_{th} = (R_1||R_3) + (R_2||R_x)$

$= \left(\frac{R_1R_3}{R_1+R_3}\right) + \left(\frac{R_2R_x}{R_2+R_x}\right)$

Hence, the complete Thevenin circuit with the galvanometer connected to terminals 'c and 'd' is



The galvanometer current, I_G with its resistance R_G is

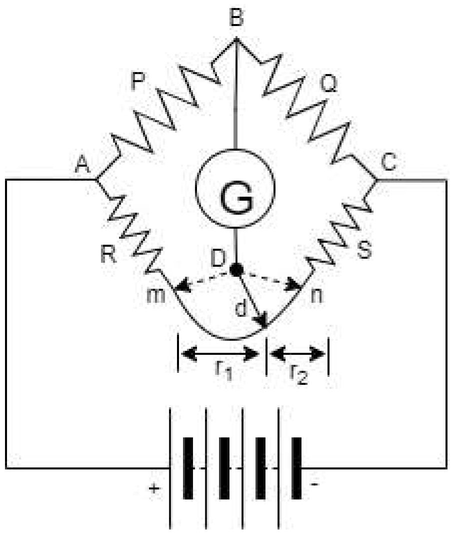
$$I_G = \frac{E_{th}}{R_{th} + R_G}$$

Limitations of Wheatstone bridge

- The use of Wheatstone bridge is limited to the measurement of resistance ranging from a few ohms to several mega ohms.
- The upper limit is set by the reduction in sensitivity to unbalance caused by high resistance values.
- The lower limit for measurement is set by the resistance of the connecting leads and by contact resistance at the binding posts.

ii) Kelvin (Thompson) Bridge

This bridge is used for measuring the unknown resistances having a value less than 1**Ω**. It is modified form of the Wheatstone bridge.



Condition for DC Bridge

$$\frac{r_1}{r_2} = \frac{P}{Q} \ldots\ldots\ldots\ldots (1)$$

At balanced condition

$$P(S + r_2) = Q(R + r_1)$$

$$or, \frac{P}{Q}(S + r_2) = (R + r_1) \ldots\ldots\ldots. (2)$$

Again,

$$\frac{r_1}{r_1 + r_2} = \frac{P}{P + Q} \ldots\ldots\ldots\ldots. (3)$$

And

$$\frac{r_2}{r_1 + r_2} = \frac{Q}{P + Q} \ldots\ldots\ldots\ldots. (4)$$

From (3) and (4)

$$\frac{r_1}{r} = \frac{P}{P+Q}$$

$$\therefore r_1 = \frac{Pr}{P+Q}$$

$$\frac{r_2}{r} = \frac{Q}{P+Q}$$

$$\therefore r_2 = \frac{Qr}{P+Q}$$

Now, from (2)

$$\frac{P}{Q}(S + r_2) = (R + r_1)$$

$$or, \quad \frac{P}{Q}\left(S + \frac{Qr}{P+Q}\right) = (R + r_1)$$

$$or, \quad \frac{P}{Q}.S + \frac{P}{Q}.\frac{Qr}{(P+Q)} = R + \frac{Pr}{P+Q}$$

$$or, \quad \frac{P.S}{Q} = R$$

$$\therefore PS = QR$$

This is the working equations of the Kelvin Bridge. For obtaining the appropriate result, it is very essentials that the ratio of their arms is equal. The unequal arm ratio causes the error in the result.

Limitations of Kelvin Bridge

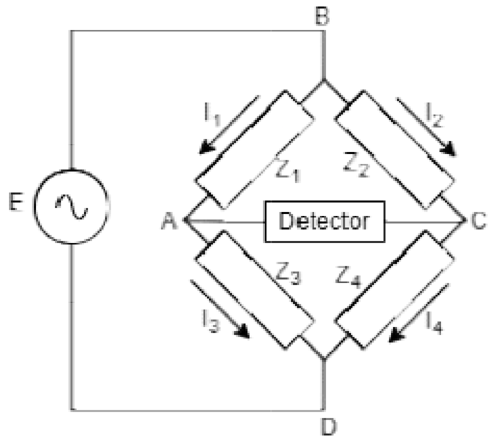
- The galvanometer with very high sensitivity has to be used for detecting the balance condition.
- For balance condition, that is difficult to connect the galvanometer to an intermediate point.

  i.e. $\frac{r_1}{r_2} = \frac{P}{Q}$

1.4.2 AC Bridge Circuit

Condition for bridge balance

The AC Bridge is a natural outgrowth of the DC Bridge and in its basic form consists of four bridge arms, a source of excitation and a null detector. The power source supplies AC voltage to the bridge at the desired frequency. For measurements at low frequencies, the power line may serve as the source of excitation voltage. The null detector must to AC unbalance currents and in its cheapest but very effective form consists of a pair of headphones or an AC amplifier.



The general form of an AC bridge is shown in figure. The four bridge arms Z_1, Z_2, Z_3 and Z_4 are impedances and the detector is represented by headphone. The balance condition in AC Bridge is reached when the detector response is zero or indicates a null. The general equation for bridge is obtained by using notation for the impedances of the bridge circuit. In complex notation, we can write

$E_{BA} = E_{BC}\ or\ I_1 Z_1 = I_2 Z_2 \dots\dots\dots (1)$

For zero detector current, i.e. the balance condition, the currents are

$I_1 = \frac{E}{Z_1+Z_3} \dots\dots\dots (2)$ And $I_2 = \frac{E}{Z_2+Z_4} \dots\dots\dots (3)$

Solving equation (1), (2) and (3) and simplifying

We get,

$$\frac{Z_1}{Z_1+Z_3} = \frac{Z_2}{Z_2+Z_4}$$

$\therefore\ Z_1 Z_4 = Z_2 Z_3 \dots\dots\dots (4)$

Or when using admittances instead of impedances,

$Y_1 Z_4 = Z_2 Z_3 \dots\dots\dots (5)$

If the impedance is written in the form $Z\measuredangle\theta$, where Z represents the magnitude and θ the phase angle of the complex impedance, equation (4) becomes

$(Z_1\measuredangle\theta_1)(Z_4\measuredangle\theta_4) = (Z_2\measuredangle\theta_2)(Z_3\measuredangle\theta_3)$

$or, Z_1 Z_4\measuredangle(\theta_1+\theta_4) = Z_2 Z_3\measuredangle(\theta_2+\theta_3) \dots\dots\dots (6)$

Equations (6) show that following two conditions must be met simultaneously when balancing an AC bridge i.e.

i. The magnitude of the impedance satisfy the relationship

   $Z_1 Z_4 = Z_2 Z_3$

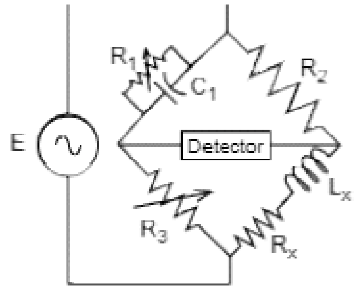
   Or the products of the magnitude of the opposite arms must be equal.

ii. The sum of the phase angles of the opposite arms must be equal i.e.

   $\measuredangle\theta_1 + \measuredangle\theta_4 = \measuredangle\theta_2 + \measuredangle\theta_3$

i) Maxwell bridge

The Maxwell Bridge measures an unknown inductance in terms of a known capacitance. The general equations for balance of the AC Bridge are;



$Z_1 Z_x = Z_2 Z_3$

$Z_x = \frac{Z_2 Z_3}{Z_1} = Z_2 Z_3 Y_1$

Where, $Z_2 = R_2, Z_3 = R_3$ and $Y_1 = \frac{1}{R_1} + j\omega C_1$

So, $Z_x = R_x + j\omega L_x = R_2 R_3 \left(\frac{1}{R_1} + j\omega C_1\right)$

Separating of the real and imaginary terms;

$R_x = \frac{R_2 R_3}{R_1} \dots \dots \dots (1)$

$L_x = R_2 R_3 C_1 \dots \dots \dots (2)$

Note: the expression for Q-factor is

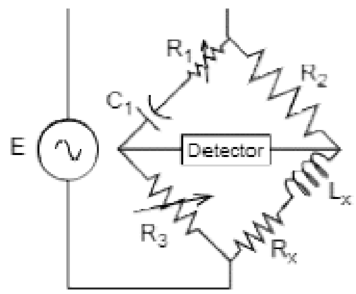
$Q = \frac{\omega L}{R}$

Limitations of Maxwell Bridge

- It is limited to the measurement of medium Q-coils (1<Q<10). It is unsuited for the measurement of coils with a very low Q-value (Q<1) because of balance convergence problems.
- This bridge requires a variable standard capacitor which may be very expensive if calibrated to a high degree of accuracy.

ii) Hay Bridge

The Hay Bridge is suited for the measurement of high Q inductors especially for those inductors having a Q greater than 10.



The general equations for AC bridge balance are;

$Z_1 Z_x = Z_2 Z_3$

Where,

$Z_1 = R_1 - \frac{j}{\omega C_1}; Z_2 = R_2$

$Z_3 = R_3; \quad Z_x = R_x + j\omega L_x$

So, $\left(R_1 - \frac{j}{\omega C_1}\right)(R_x + j\omega L_x) = R_2 R_3$

Separating the real and imaginary terms,

$$R_1 R_x + \frac{L_x}{C_1} = R_2 R_3 \ldots\ldots\ldots\ldots (1)$$

$$-\frac{R_x}{\omega C_1} + \omega L_x R_1 = 0$$

$$or, \frac{R_x}{\omega C_1} = \omega L_x R_1 \ldots\ldots\ldots\ldots (2)$$

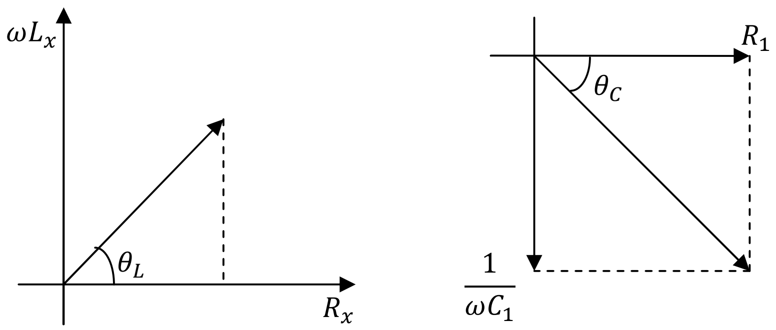
Solving the real and imaginary terms,

$$R_x = \frac{\omega^2 {C_1}^2 R_1 R_2 R_3}{1 + \omega^2 {C_1}^2 {R_1}^2}$$

And

$$L_x = \frac{R_2 R_3 C_1}{1 + \omega^2 {C_1}^2 {R_1}^2}$$

Also, the sum of the opposite sets of phase angles must be equal i.e. the inductive phase angle must be equal to the capacitive phase angle since the resistive angles are zero.



Now, the tangent of the inductive phase angle equals

$$\tan\theta_L = \frac{X_L}{R} = \frac{\omega L_x}{R_x} = Q = quality\ of\ coil$$

And that of capacitive is

$$\tan\theta_C = \frac{X_c}{R} = \frac{1}{\omega C_1 R_1}$$

When two phase angles are equal, their tangents are also equal,

$\tan\theta_L = \tan\theta_c$

$or, Q = \dfrac{1}{\omega C_1 R_1}$

And hence,

$$L_x = \frac{R_2 R_3 C_1}{1+\left(\frac{1}{Q}\right)^2}$$

For a value of Q operator than 10, the term $\left(\frac{1}{Q}\right)^2$ can be neglected.

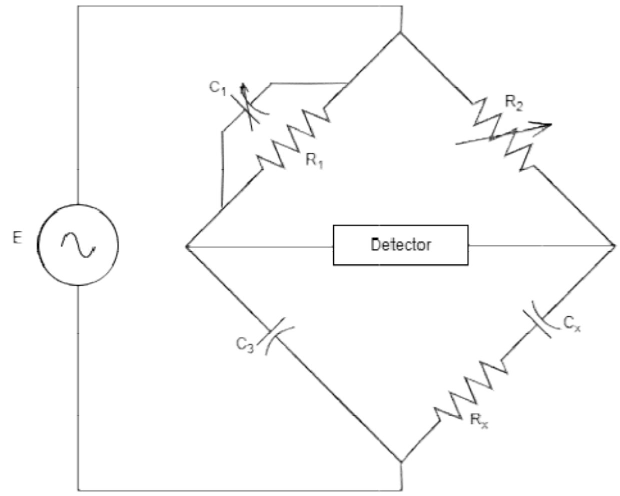
So,

$L_x = R_2 R_3 C_1$

For a value of Q smaller than 10, the term $\left(\frac{1}{Q}\right)^2$ becomes important and cannot be neglected. So, the Maxwell Bridge is more suitable in this case.

iii) Schering (Capacitance) Bridge

It is one of the most important AC Bridge extensively used for the measurement of capacitors.



The general equation for AC bridge balance is;

$Z_1 Z_x = Z_2 Z_3$

$or, Z_x = Z_2 Z_3 Y_1$

Where,

$Z_2 = R_2$

$Z_3 = \dfrac{-j}{\omega C_x}$

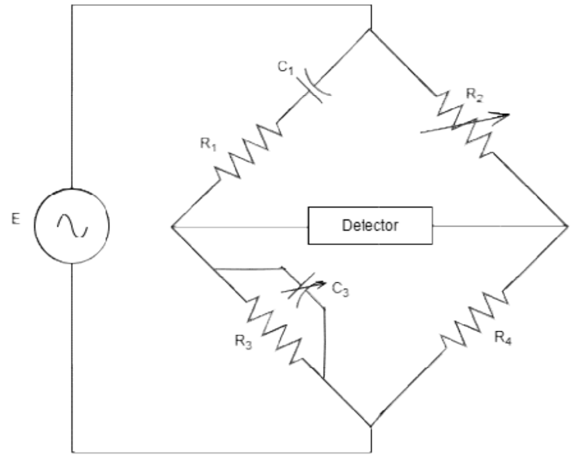
$$or, \quad Z_x = R_x - \frac{j}{\omega C_x} = R_2\left(\frac{j}{\omega C_3}\right)\left(\frac{1}{R_1} + j\omega C_1\right) = \frac{R_2 C_1}{C_3} - \frac{jR_2}{\omega C_3 R_1}$$

Equating the real and imaginary terms,

$$R_x = \frac{R_2 C_1}{C_3} = R_2 \frac{C_1}{C_3} \; and \; C_x = C_3 \frac{R_1}{R_2}$$

iv) Wien Bridge

It is an AC bridge used to measure the frequency. A Wien Bridge is used as notch filter in the harmonic distortion analyzer. The Wien Bridge also finds application in audio and HF oscillators as the frequency determining element.



The general equation for the bridge is,

$$Z_1 Z_4 = Z_2 Z_3$$

$$or, Z_2 = Z_1 Z_4 Y_3$$

Where,

$$Z_1 = R_2; \; Z_4 = R_4$$

$$Z_1 = R_1 - \frac{j}{\omega C_1} \; and \; Y_3 = \frac{1}{R_3} + j\omega C_3$$

Now, $Z_2 = R_2 = \left(R_1 - \frac{j}{\omega C_1}\right)(R_4)\left(\frac{1}{R_3} + j\omega C_3\right)$

$$= \frac{R_1 R_4}{R_3} + \frac{R_4 C_3}{C_1} + j\omega C_3 R_1 R_4 - \frac{jR_4}{\omega C_1 R_3}$$

Equating real and imaginary terms,

$$R_2 = \frac{R_1 R_4}{R_3} + \frac{R_4 C_3}{C_1} \; which \; reduces \; to,$$

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{C_3}{C_4} \ldots\ldots\ldots\ldots(1)$$

And

$$\omega C_3 R_1 R_4 - \frac{R_4}{\omega C_1 R_3} = 0$$

$$or, \quad \omega C_3 R_1 R_4 = \frac{R_4}{\omega C_1 R_3}$$

$$or, \qquad \omega^2 = \frac{1}{C_1C_3R_1R_3}$$

$$or, \qquad \omega = \frac{1}{\sqrt{C_1C_3R_1R_3}}$$

$$\therefore \ f = \frac{1}{2\pi\sqrt{C_1C_3R_1R_3}} \ldots\ldots\ldots\ldots (2)$$

In most Wien Bridge circuits, the components are chosen such that $R_1 = R_3$ and $C_1 = C_3$. So, equation (1) and (2) becomes,

$\frac{R_2}{R_4} = 2$

And

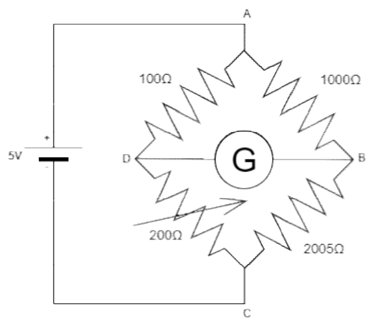
$f = \frac{1}{2\pi RC}$ Is the general expression for the frequency of the Wien Bridge.

Application of Wien Bridge

- ❖ It is primarily used in AC bridges to measure frequency.
- ❖ It may be employed in harmonic distortion analyzer it is used as a notch filter.
- ❖ It is used in audio and HF oscillators as the frequency determining device.

Example

1. **Figure shows the schematic diagram of a Wheatstone bridge with values of their bridge elements as shown. The battery voltage is 5V and its internal resistance is negligible. The galvanometer has a current sensitivity of 10mm/μA and an internal resistance of 100Ω calculate the deflection of the galvanometer caused by the 5Ω unbalance in the arm BC.**



Solution:

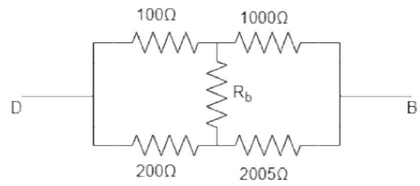
Since, we are interested in finding the current in the galvanometer, the Thevenin equivalent is determined w.r.t. galvanometer terminals B and D.

The potential difference from B to D with the galvanometer removed from the circuit is the Thevenin voltage i.e.

$$E_{th} = E_{DB} = E\left(\frac{R_1}{R_1 + R_3} - \frac{R_2}{R_2 + R_4}\right) = 5 \times \left(\frac{100}{100 + 200} - \frac{1000}{1000 + 2005}\right)$$

$\cong 2.77mV$

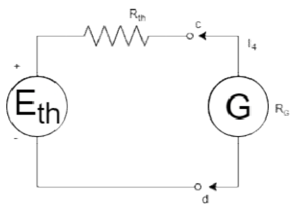
The equivalent Thevenin resistance looking into terminals B and D replacing the battery with its internal resistance is



Since internal resistance of battery, R_b is zero **Ω**, the equivalent is

$$R_{th} = (R_1||R_4) + (R_2||R_4) = \left(\frac{100 \times 200}{100 + 200} + \frac{1000 \times 2005}{1000 + 2005}\right) = 734\Omega$$

The Thevenin equivalent circuit is given as:



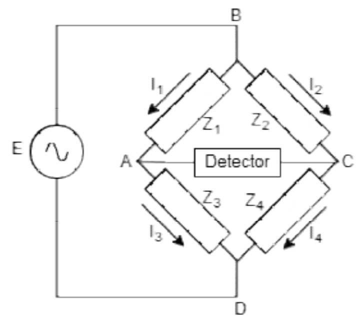
When the galvanometer is now connected to the output terminals of the equivalent circuit, the current I_G through the galvanometer is

$$I_G = \frac{E_{th}}{R_{th} + R_G} = \frac{2.77mV}{234\Omega + 100\Omega} = 3.32\mu A$$

Now, the galvanometer deflection is $d = 3.32\mu A \times \frac{10mm}{\mu A} = 33.2mm$

2. **The AC bridge is in balance with the following constants: arm AB, $R = 450\Omega$; arm BC, $R = 300\Omega$ in series with $C = 0.265$μF; arm CD, $unknown$; arm DA, $R = 200\Omega$ in series with $L = 15.9mH$. The oscillator frequency is $1KH$. Find the constants of arm CD.**

   Solution:



The general equation for AC bridge balance is

$$Z_1Z_4 = Z_2Z_3$$

$Where,$

$$Z_1 = R = 450\Omega$$

$$Z_2 = R - \frac{j}{\omega C} = (300 - j600)\Omega$$

$Z_3 = R + j\omega L = (200 + j100)\Omega$

$Z_4 = unknwon$

Now, $Z_4 = \frac{Z_2 Z_3}{Z_1} = \frac{(300-j600)(200+j100)}{450} = (266.67 - j200)\Omega = \left(R_4 - \frac{j}{\omega C_4}\right)$

This result indicates that Z_4 has a resistor 266.67Ω in series with capacitor at a frequency of 1KHz. Since capacitive reactance

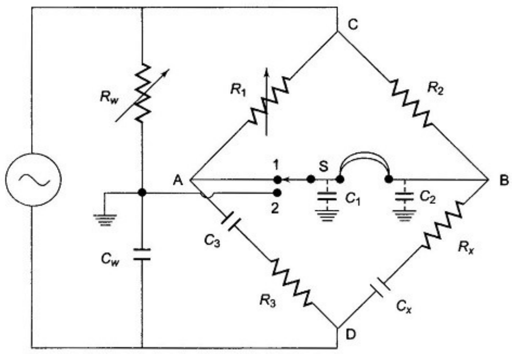
$$X_{c4} = \frac{1}{2\pi f C_4} = \frac{1}{2\pi \times 1000 \times 200} = 0.7958\mu F$$

And R_4 = 266.67Ω

1.4.2 Wagner Ground Connection

The Wagner ground connection is used for removing the earth capacitance from the bridges. It is a type of voltage divider circuit used to reduce the error which occurs because of stray capacitance. The Wagner Earth device provides high accuracy to the bridge.

At high frequency, stray capacitance is included between the bridge elements, ground and between the arms of the bridge. This stray element causes the error in the measurement. One of the ways of controlling these capacitances is too enclosed the bridge elements into the shield. Another way of eliminating this stray capacitance is to places the Wagner Earth device between the elements of the bridge.



In above figure, $C_1$and C_2 are the stray capacitances. In Wagner's Ground Connection, another arm, consisting of R_w and C_w forming a potential divider, is used. The junction of R_w and C_w is grounded and is called Wagner Ground Connection.

The detector is connected to point 1 and R_1 is adjusted for null or minimum sound in the headphones. The switch S is then connected to point 2, which connects the detector to the Wagner ground point. Resistor R_w is now adjusted for minimum sound. When the switch 'S' is connected to point 1, again there will be some imbalance. Resistors R_1 and R_3 are then adjusted for minimum sound and this procedure is repeated until a null is obtained on both switch positions 1 and 2. This is the ground potential. Stray capacitances C_1 and C_2 are then effectively short-circuited and have no effect on the normal bridge balance.

The capacitances from point C to D to ground are also eliminated by the addition of Wagner's ground connection, since the current through these capacitors enters Wagner's ground connection. The addition of the Wagner ground connection does not affect the balance conditions, since the procedure for measurement remains unaltered.

1.5 Physical variable and Transducer

1.5.1 Physical Variable and their types

Physical variables are the variables to be measured in an instrumentation system, which make its first contact with primary sensing elements. It is the information for the measurement system in the form of a physical phenomenon or an electrical signal. Types of physical variables:

- **Process variables:** Temperature, pressure and flow rate are the process variables which are widely employed in process and production plants.
- **Electrical variables:** Current voltage resistance, inductance, capacitance, frequency, phase angle, power are the electrical variables.
- **Mechanical variables:** Spring (Force to displacement), monometer (pressure to displacement), thermocouple (temperature to electric current), Hydrometer (specific gravity to displacement), Turbines (Linear to angular velocity) etc. are the mechanical variables.
- **Bio-physical variables:** Here, the information is taken from living beings ECG (Electro Cardio Graph) for heart, EEG (Electro Encephilo Graph for Brain), EMG (Electro Mio Graph for muscular), excitation, restoring potential are the bio-physical variables.

1.5.2 Transducer Principle and Operation

Transducer is a device which converts non-electrical quantity into an electrical form in order to use electrical methods and techniques for measurement, manipulation or control.

Basic Requirement of Transducer

The main function of the transducer is to respond only for the measurement under specified limit for which it is designed.

- **Ruggedness**: It should be capable of withstanding overload and some safety arrangement should be provided for the overload protection.
- **Linearity:** Its input- output characteristics should be linear.
- **Repeatability:** It should reproduce same output signals when the input signal is applied again and again under fixed environment condition.
- **High quality output signals**: The ratio of Signal to Noise (SNR) should be high and the amplitude of the output signal should be up to detectable level.
- **High Reliability and Stability (minimum error)**: We should get minimum error in measurement for temperature variations, vibrations and other various changes in surrounding.
- **Good Dynamic Response**: Its output should be faithful to input when taken as a function of time.

Working principle of Transducer

A transducer consisting of a sensing element and transduction element, first responds to a physical change in the particular factor which the sensing element senses and generates an output. This output is generally in terms of physical forces like strain or displacement. The output of the sensing element generally acts as an input for the transduction element which then converts the output signal of the sensing element into a proportional output as an electrical signal.

$Fig\text{: } Working\ of\ transducer$

- **Sensing Element:** It is the part of a transducer that responds to the physical sensation. The response of the sensing element depends on the physical phenomenon.
- **Transduction Element:** The transduction element of the transducer converts the output of the sensing element into an electrical signal. The transduction element is also called the secondary transducer.

1.5.3 Input and Output Characteristics and applications of transducers

Characteristics Transducer:

It can be classified into two types

i) Input Characteristics

The input characteristics are further divided as,

a. Types of Input and operating range

Type of input which can be any physical quantity is generally determined. A physical quantity may be measured through the use of transducer, however the choice of particular transducer i.e. selected for the purpose depends upon the useful range of input quantity over which the transducer can be used. The upper limit while the lower limit of range normally decided by the transduction error.

b. Load Effect

Ideally, the transducer has no loading effect in the input quantity being measured but in actual practice it is impossible. The magnitude of loading effect can be expressed in terms of force power or energy extracted from the quantity under measurement for the working of transducer. Transducer that is selected for the particular application should ideally abstract no force, power or energy from the quantity under measurement.

ii) Output Characteristics

The output characteristics are classified as,

a. Types of output

The type of output may be available from the transducer is in the form of voltage, current, impedance etc. These output quantities may or may not be the later stage of instrumentation system. They may have to be manipulated, calculated i.e. their magnitude changes or they have to be change in their format by signal conditioning equipment.

b. Output Impedance

It determines the amount of power that can be transferred to the successive stage for the given output signal level. If the output impedance of a transducer is low as compared with the load impedance of successive stage, it has the characteristics of constant voltage.

On the other hand if the output impedance of the transducer is higher than the load impedance, it has the characteristics of constant current source. When the output impedance of transducer is equal to that of following stage, matching takes place and maximum power transfer from the next stage.

c. Useful output range

The output range of a transducer is limited at the lower end by noise signal. The upper limit is set by the maximum useful input level.

Applications of Transducer

- ❖ A transducer measures load on the engines.
- ❖ They are used to detect the movement of muscles; this process is known as acceleromyograph.
- ❖ Transducers are used in an ultrasound machine.
- ❖ The transducers in a speaker convert electrical signals into acoustic sound.
- ❖ A transducer is used in the antenna to convert electromagnetic waves into an electrical signal.

1.5.3.1 Resistive

The transducer whose resistance varies because of the environmental effects such type of transducer is known as the resistive transducer. The change in resistance is measured by the Ac or DC measuring devices. The resistive transducer is used for measuring the physical quantities like temperature, displacement, vibration etc.

The resistive transducer converts the physical quantities into variable resistance which is easily measured by the meters.

Applications of Resistive Transducer

❖ **Potentiometer**

The translation and rotary potentiometer are the examples of the resistive transducers. The resistance of their conductor varies with the variation in their lengths which is used for the measurement of displacement.

❖ **Strain Gauge**

The resistance of their semiconductor material changes when the strain occurs on it. This property of metals is used for the measurement of the pressure, force-displacement etc.

❖ **Thermistor**

It works on the principle that the temperature coefficient of the thermistor material varies with the temperature. The thermistor has the negative temperature coefficient. The negative temperature coefficient means the temperature is inversely proportional to resistance.

❖ **Resistance Thermometer**

The resistance of the metal changes because of changes in temperature, this property of conductor is used for measuring the temperature.

Pros

- ➢ Fast response

- ➢ Available in various size having high resistance
- ➢ Low-cost
- ➢ Operation is very easy and used in various applications

Cons

- ➢ High power consumption
- ➢ Noisy

1.5.3.2 Capacitive

A capacitive transducer is a type of sensor or device that measures changes in capacitance to detect and quantify certain physical quantities, such as displacement, pressure, humidity, or fluid level. Capacitance is the ability of a system to store an electrical charge.

The capacitance of the transducer is directly proportional to the physical quantity being measured. By measuring the change in capacitance, the transducer can provide an output signal that corresponds to the magnitude of the measured quantity.

Capacitive transducers offer several advantages, including high sensitivity, good linearity, wide frequency response, and low power consumption. They can be used in various applications such as touch screens, accelerometers, pressure sensors, level sensors, and humidity sensors. Capacitive transducers require appropriate signal conditioning and readout circuitry to convert the capacitance change into a measurable signal.

Applications

- ❖ Used for linear and angular displacements
- ❖ Used in mechanical components for the measurement of liquid level, density, weight, volume etc.
- ❖ Used to measure pressure and force

Pros

- ➢ Exhibit good frequency response
- ➢ Low force needed
- ➢ Input impedance is high
- ➢ Very sensitive in nature

Cons

- ➢ Sometimes it exhibit non-linear behavior on account of edge effects.
- ➢ Measurement is affected due to lack of proper insulation of the transducer
- ➢ Natural phenomena (moisture, dust) can easily affect

1.5.3.3 Inductive

Inductive Transducer is the self-generating types otherwise the passive type transducer. The first type like self-generating uses the principle of fundamental electrical generator. The electric generator principle is when a motion among a conductor as well as magnetic field induces a voltage within the conductor. The motion among the conductor and the field can be supplied by transforms in the measured. An inductive transducer (electromechanical) is an electrical device used to convert physical motion into modifying within inductance.

Inductive transducers work on the principle of inductance change due to any appreciable change in the quantity to be measured i.e. measured. For example, LVDT, a kind of inductive transducers, measures displacement in terms of voltage difference between its two secondary voltages.

Applications

- Used in proximity sensor to measure position, touchpad, dynamic motion etc.
- Used for detecting the kind of metals
- Applicable for detecting the movement of the apparatus which include belt conveyor and bucket elevator etc.

Pros

- Reduced load effect
- Strong

Cons

- Working temp. must be under the curie temperature
- Sensitive to the magnetic field.

1.6 Measurement of Mechanical variables

Measurement of mechanical variables such as displacement, strain, velocity, acceleration, and vibration is critical in various engineering and industrial applications.

Displacement: Displacement refers to the change in position of an object from its original location. It can be measured using various devices, including linear variable differential transformers (LVDTs), potentiometers, encoders, and laser displacement sensors. These sensors detect changes in position and convert them into electrical signals proportional to the displacement.

Strain: Strain is a measure of deformation in a material under stress. It can be measured using strain gauges, which are devices that change resistance in response to deformation. Strain gauges are often bonded to the surface of a material, and changes in resistance are measured using Wheatstone bridge circuits to determine strain.

Velocity: Velocity is the rate of change of displacement with respect to time. It can be measured using various techniques, including Doppler radar, laser Doppler velocimetry, and tachometers. These devices measure the speed of an object by detecting changes in frequency or phase shift of reflected waves or by directly measuring rotational speed.

Acceleration: Acceleration is the rate of change of velocity with respect to time. It can be measured using accelerometers, which are devices that detect changes in acceleration and convert them into electrical signals. Accelerometers come in various types, including piezoelectric, capacitive, and MEMS (Micro-Electro-Mechanical Systems) accelerometers.

Vibration: Vibration refers to oscillatory motion around an equilibrium point. Vibration can be measured using accelerometers, velocity sensors, or displacement sensors, depending on the frequency range and amplitude of the vibration. Vibration analysis techniques, such as Fourier analysis and spectral analysis, are used to characterize and analyze vibration signals.

1.7 Measurement of Process variables

Measurement of process variables such as temperature, pressure, level, fluid flow, chemical constituents in gases or liquids, pH, and humidity is crucial in various industrial and scientific applications.

Temperature: Temperature measurement is essential for monitoring and controlling thermal processes. Common temperature measurement devices include thermocouples, resistance temperature detectors (RTDs), thermistors, and infrared thermometers. These devices measure temperature by detecting changes in electrical resistance, voltage, or infrared radiation emitted by objects.

Pressure: Pressure measurement is important for monitoring fluid and gas systems, as well as for controlling processes such as filtration, distillation, and compression. Pressure can be measured using devices such as pressure transducers, pressure gauges, manometers, and pressure sensors based on piezoelectric or capacitive principles.

Level: Level measurement is used to monitor the height of liquids or solids in tanks, vessels, or containers. Common level measurement techniques include ultrasonic, radar, capacitance, float, and differential pressure methods. These methods detect changes in pressure, capacitance, or signal reflection to determine the level of the substance.

Fluid Flow: Fluid flow measurement is essential for monitoring and controlling the flow rates of liquids and gases in pipelines, ducts, and channels. Various flow measurement devices are available, including flowmeters such as orifice plates, venturi tubes, magnetic flowmeters, ultrasonic flowmeters, and turbine flowmeters. These devices measure flow velocity, pressure, or volumetric flow rate to calculate the flow rate.

Chemical Constituents: Measurement of chemical constituents in gases or liquids involves analyzing the composition and concentration of substances such as gases, liquids, or solutes. Techniques include spectroscopy (UV-Vis, IR, NIR), chromatography (GC, HPLC), mass spectrometry (MS), and electrochemical sensors. These methods provide quantitative analysis of chemical components in samples.

pH: pH measurement is used to determine the acidity or alkalinity of a solution. pH meters and pH electrodes are commonly used for pH measurement, based on the principle of electrochemical potential difference between acidic and basic solutions.

Humidity: Humidity measurement is essential for monitoring and controlling moisture levels in various applications, including HVAC systems, cleanrooms, and environmental monitoring. Devices such as hygrometers, capacitive sensors, and psychrometers are used to measure relative humidity, dew point, or absolute humidity.

1.8 Measurement of Bio-physical variables

Measurement of biophysical variables such as blood pressure and myoelectric potentials (MEPs) plays a crucial role in medical diagnostics, physiological monitoring, and biomechanical analysis.

Blood Pressure: Blood pressure measurement is essential for assessing cardiovascular health and diagnosing conditions such as hypertension. It is typically measured using a sphygmomanometer, which consists of an inflatable cuff and a pressure gauge. The cuff is wrapped around the upper arm and inflated to occlude the brachial artery. As the cuff pressure is slowly released, the pressure at which blood begins to flow through the artery (systolic pressure) and the pressure at which blood flow becomes unimpeded (diastolic pressure) are recorded.

Myoelectric Potentials (MEPs): Myoelectric potentials are electrical signals generated by muscle activity. They are commonly measured in electromyography (EMG) studies to assess muscle function, diagnose neuromuscular disorders, and evaluate movement patterns. Surface electrodes or needle electrodes are placed on or inserted into the skin overlying the muscle of interest to detect the electrical activity. The detected signals are amplified, filtered, and recorded using electromyography equipment.

1.9 Calibration and Error in Transducer

Calibration is a critical process in ensuring the accuracy and reliability of transducers, which are devices that convert one form of energy into another.

Calibration Process:

Calibration involves comparing the output of a transducer to a known reference standard or measurement device. The transducer's response is adjusted or calibrated to match the reference standard, ensuring accurate measurements.

During calibration, the transducer is subjected to known input conditions or test signals, and its output response is recorded and compared to the expected values. Any discrepancies or errors are identified, and adjustments are made to minimize or correct them.

Calibration may involve adjusting parameters such as sensitivity, offset, linearity, and hysteresis to optimize the transducer's performance across its operating range.

Types of Errors:

Systematic Errors: These errors result from inherent inaccuracies or biases in the transducer's design, construction, or calibration process. Systematic errors can include zero offset errors, sensitivity errors, and nonlinearities.

Random Errors: Random errors are caused by fluctuations or variability in measurement conditions, environmental factors, or electronic noise. They can affect the precision and repeatability of measurements but can be minimized through averaging or statistical analysis.

Environmental Errors: Environmental factors such as temperature, humidity, and electromagnetic interference can introduce errors in transducer measurements. Environmental testing and calibration under controlled conditions can help mitigate these errors.

Error Analysis and Compensation:

Error analysis involves identifying and quantifying the sources of error in transducer measurements. This may include conducting calibration tests under different operating conditions and analyzing the data to determine the magnitude and nature of errors.

Error compensation techniques, such as linearization algorithms or temperature compensation circuits, can be implemented to minimize the effects of systematic errors and environmental variations on transducer performance.

Regular Maintenance and Recalibration:

To ensure continued accuracy and reliability, transducers should undergo regular maintenance and recalibration according to recommended intervals or based on usage patterns. This helps detect and correct any drift or degradation in performance over time.

By effectively managing calibration and errors in transducers, engineers can ensure accurate and reliable measurement data, which is essential for various applications across industries such as automotive, aerospace, manufacturing, and healthcare.

1.10 Measurement of voltage and current

Measurement of voltage and current is fundamental in electrical engineering for assessing the performance, safety, and efficiency of electrical systems. Moving coil and moving iron instruments are traditional types of analog instruments used for such measurements.

Moving Coil Instruments:

Principle: Moving coil instruments operate based on the interaction between a magnetic field and a current-carrying coil. When current flows through the coil, it experiences a torque proportional to the product of the current and the magnetic field strength, causing the coil to rotate.

Voltage Measurement: In a voltmeter configuration, the coil is connected in parallel with a high resistance (known as a multiplier resistor). The voltage to be measured is applied across the coil, causing it to deflect, and the degree of deflection is proportional to the voltage.

Current Measurement: In an ammeter configuration, the coil is connected in series with the circuit carrying the current to be measured. The current flows through the coil, generating a torque that deflects the coil, and the degree of deflection is proportional to the current.

Moving Iron Instruments:

Principle: Moving iron instruments operate based on the attraction or repulsion between a movable iron piece and a fixed coil or magnet. When current flows through the coil, it creates a magnetic field that interacts with the iron piece, causing it to move.

Voltage Measurement: Similar to moving coil voltmeters, moving iron voltmeters use the attraction between the iron piece and a fixed coil to measure voltage. The iron piece moves in response to the magnetic field created by the voltage being measured, and the degree of movement is proportional to the voltage.

Current Measurement: Moving iron ammeters use the repulsion between the iron piece and a fixed coil to measure current. The iron piece moves away from the coil when current flows through it, and the degree of movement is proportional to the current.

1.11 Measurement of low, medium and high resistances

Measurement of resistances across a wide range, including low, medium, and high values, is essential in various electronic, electrical, and industrial applications.

Low Resistances: Low resistance measurements, typically in the range of milliohms to ohms, require techniques that minimize the effects of lead resistance and contact resistance. This is crucial for accurately measuring small resistances, such as those found in circuit traces, connectors, or electrical contacts.

Four-wire resistance measurement, also known as Kelvin sensing or Kelvin connection, is commonly used for low resistance measurements. It involves passing a known current through the resistance using two current-carrying wires (the "source" wires) and measuring the voltage drop across the resistance using two separate sensing wires (the "sense" wires). This method eliminates errors introduced by the resistance of the lead wires and ensures accurate measurement of the resistance under test.

Medium Resistances: Medium resistance measurements, typically in the range of ohms to kilohms, can be performed using standard two-wire or four-wire measurement techniques. Two-wire resistance measurement is simpler but may introduce errors due to lead resistance. Four-wire measurement is more accurate and is often used when precision is required.

Various instruments, such as digital multimeters (DMMs) and benchtop multimeters, are commonly used for medium resistance measurements. These instruments provide accurate and reliable measurements across a wide range of resistance values.

High Resistances: High resistance measurements, typically in the range of kilohms to teraohms, require techniques that minimize leakage currents and stray capacitance. These measurements are commonly performed using instruments such as insulation resistance testers, megohmmeters, or electrometers.

Insulation resistance testing is used to measure the resistance between two points in an electrical insulation system, such as wires, cables, or electrical components. Megohmmeters apply a high voltage (typically 500V to 5000V) to the insulation and measure the resulting leakage current to calculate the insulation resistance.

Assignment

1. **A Voltmeter having a sensitivity of $1000\Omega/V$, reads $40V$ units $150V$ scale when connected across an unknown resistor in series with a mili-ammeter. When the mili-ammeter reads $800mA$, calculate.**
   a. **The apparent resistance of the unknown resistor.**
   b. **The actual resistance of the resistor.**
   c. **The error due to the loading effect of the voltmeter**
2. **If a voltmeter having full scale voltage of 100V and accuracy of 1% is used to measure**
   i) **12V**

   Calculate the % error in both cases.
3. **An AC bridge with terminals A, B, C, D (consecutively marked) has in arm AB a pure resistance; arm BC a resistance of 800Ω in parallel with a capacitor of 0.5μF; arm CD a resistance 400Ω in series with a capacitor 1μF; arm DA a resistance of 1000Ω. Obtain the value of frequency for which the bridge can be balanced by first deriving the balance equations. Also, calculate the calue if resistance in arm AB to produce balance.**