Measurements in energy systems

Unit 1: Measurements characteristics

INTRODUCTION

Measurements are the basic means of acquiring knowledge about the parameters and variables involved in the operation of a physical system. Measurement generally involves using an **instrument** as a physical means of determining a quantity or variable. An instrument or a measuring instrument is, therefore, defined as a *device for determining* the value or magnitude of a quantity or variable. The electrical measuring instrument, as its name implies, is based on electrical principles for its measurement function.

True or Expected Value**:** The true or expected value of a quantity to be measured may be defined as the average of an infinite number of measured values when the average deviation due to the various contributing factors tends to zero. It also refers to a value of the quantity under consideration that would be obtained by a method (known as exemplar method) agreed upon by experts. In other words, it is the most probable value that calculations indicate and one should expect to measure.

Note that the value of the unknown obtained by making use of primary standards and measuring instruments considered its true value.

CLASSIFICATION OF MEASURING INSTRUMENTS

Firstly: Measuring instruments can be classified into two groups:

(*a*) Absolute (or primary) instruments.

(*b*) Secondary instruments.

- Absolute Instruments

• These instruments give the value of the electrical quantity in terms of absolute quantities (or some constants) of the instruments and their deflections.

• In this type of instruments no calibration or comparison with other instruments is necessary.

• They are generally not used in laboratories and are seldom used in practice by electricians and engineers. They are mostly used as means of standard measurements and are maintained by national laboratories and similar institutions.

• Examples of absolute instruments are:

* Tangent galvanometer

* Raleigh current balance

* Absolute electrometer.

- Secondary Instruments

• They are direct reading instruments. The quantity to be measured by these instruments can be determined from the deflection of the instruments.

• They are often calibrated by comparing them either with some absolute instruments or with those, which have already been calibrated.

• The deflections obtained with secondary instruments will be meaningless until it is not calibrated.

• These instruments are used in general for all laboratory purposes.

• Some of the very widely used secondary instruments are ammeters, voltmeter, wattmeter, energy meter (watt-hour meter), ampere-hour meters etc.

Classification of Secondary Instruments

(*a*) Classification based on the various effects of electric current (or voltage) upon which their operation depend. They are:

• **Magnetic effect:** Used in ammeters, voltmeters, watt-meters, integrating meters etc.

• **Heating effect:** Used in ammeters and voltmeters.

• **Chemical effect:** Used in dc ampere-hour meters.

• **Electrostatic effect:** Used in voltmeters.

• **Electromagnetic induction effect:** Used in ac ammeters, voltmeters, watt meters and integrating meters.

Generally, the magnetic effect and the electromagnetic induction effect are utilized for the construction of the commercial instruments. Some of the instruments are also named based on the above effect such as electrostatic voltmeter, induction instruments, etc.

(*b*) Classification based on the Nature of their Operations

We have the following instruments.

• **Indicating instruments:** Indicating instruments indicate, generally the quantity to be measured by means of a pointer, which moves on a scale. Examples are ammeter, voltmeter, wattmeter etc.

• **Recording instruments:** These instruments record continuously the variation of any electrical quantity with respect to time. In principle, these are indicating instruments but so arranged that a permanent continuous record of the indication be made on a chart or dial.

The recording is generally made by a pen on a graph paper which is rotated on a dice or drum at a uniform speed. The amount of the quantity at any time (instant) may be read from the traced chart. These instruments record any variation in the quantity with time.

Any electrical quantity like current, voltage, power etc., (which may be measured by the indicating instruments) may be arranged to be recorded by a suitable recording mechanism.

• **Integrating instruments:** These instruments record the consumption of the total quantity of electricity, energy etc., during a particular period. That is, these instruments totalize events over a specified period of time. No indication of the rate or variation or the amount at a particular instant are available from them. Some widely used integrating instruments are Ampere-hour meter: kilowatt-hour (kWh) meter, kilovolt-ampere-hour
(kVAR-h) meter.

(*c*) Classification based on the Kind of Current that can be measured.

Under this heading, we have:

• Direct current (dc) instruments

• Alternating current (ac) instruments

• Both direct current and alternating current instruments (dc/ac instruments).

(*d*) Classification based on the method used.

Under this category, we have:

• **Direct measuring instruments:** These instruments converts the energy of the measured quantity directly into energy that actuates the instrument and the value of the unknown quantity is measured, displayed, or recorded directly. These instruments are most widely used in engineering practice because they are simple and inexpensive. In addition, time involved in the measurement is shortest. Examples are Ammeter, Voltmeter, and Wattmeter etc.

• **Comparison instruments:** These instruments measure the unknown quantity by comparison with a standard. Examples are dc and ac bridges and potentiometers. They are used when a higher accuracy of measurements desired.

(*e*) Classification based on the Accuracy Class of Instruments.

♦Secondly: Classifications of Instruments:

1- **Gage / measurement system**

2- **Active:** like digital devices **/** **Passive:** like Analog devices *Passive sensors* do not add energy as part of the measurement process, but may remove energy in their operation, ie energy is converted to measurable quantity

- One example of a *passive sensor* is a thermocouple, which converts a physical temperature into a voltage signal *Active sensors* add energy to the measurement environment as part of the measurement process

- An example of an active sensor is a radar or sonar, where actively out-sended radio (radar) or acoustic (sonar) waves reflect off of some object and thus measures its range from the sensor

3- **Null type:** like scale **/ Deflection type**

Null Instrument - A measuring device that balances the measurand against a known value, thus achieving a null condition. Two inputs are essential to the null instrument.

Null measurement devices usually consist of

1. automatic or manual feedback system that allows the comparison of known standard value,
2. an iterative balancing operation using some type of comparator
3. and a null deflection at parity

Advantages:

- Minimizes measurement loading errors (i.e. alter the value of the measured signal). Effective when the measurand is a very small value.
- minimizes interaction between the measuring system and the measurand, by balancing the unknown input against a known standard input
- Achieving perfect parity (zero condition) is limited only by the state of the art of the circuit or scheme being employed

Disadvantages:

- Slow - an iterative balancing operation requires more time to execute than simply measuring sensor input. Not suitable for fast measurements i.e. only for static measurements

Example.:

- An equal arm balance scale with manual balance feedback
- Potentiometer: AB is the potentiometer wire with resistance R_1.

The EMF of a standard DC source is e volts. The rheostat resistance is R . If the null point is obtained at point C, then the EMF of e and e_1 are equal

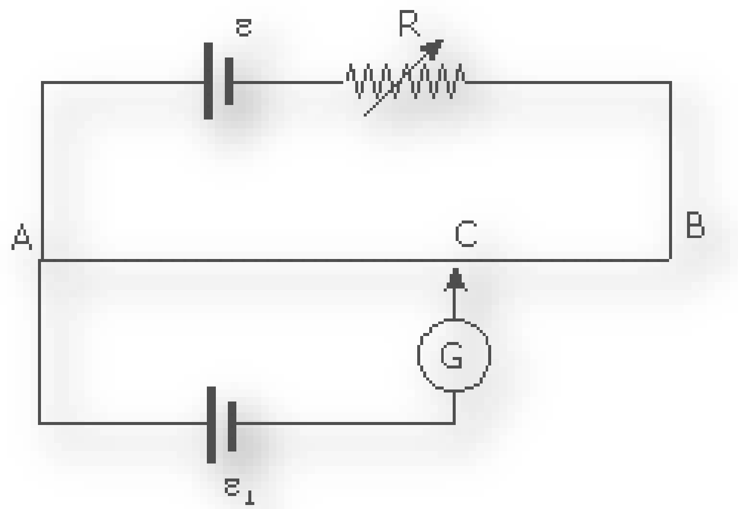


Fig.1: Potentiometer

Deflection instrument - a measuring device whose output deflects (deviates) proportional to the magnitude of the measurand

Deflection instruments are the most common measuring instruments

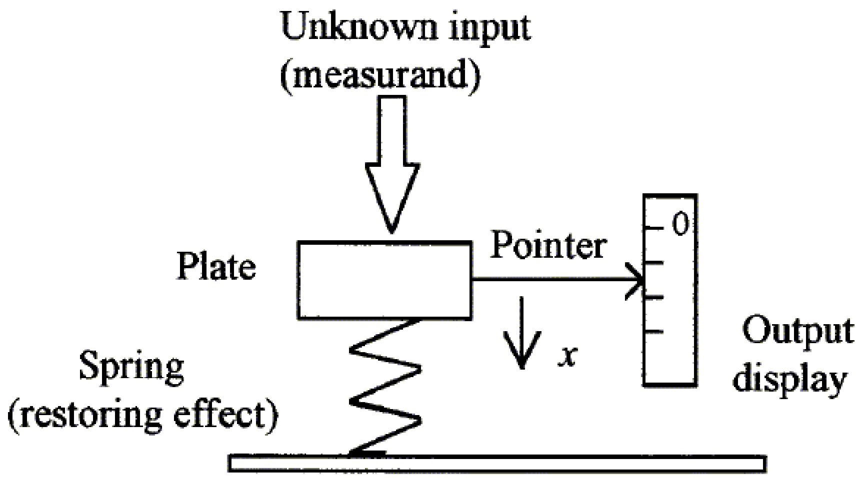
Advantages:

- high dynamic response i.e. can be used for fast measurements
- can be designed for either static or dynamic measurements or both

Disadvantages:

- By deriving its energy from the measurand, the act of measurement will influence the measurand and change the value of the variable being measured. This change is called a loading error.

  Example: Spring scale as a deflection instrument. Scale has to be calibrated



A deflection instrument requires input from only one source, but may introduce a loading error.

Fig.2: Spring scale as a deflection instrument.

4- **Indicating / Signal output:** indicating instruments are those, which indicate the value of quantity that is being measured at the time at which it is measured. Such instruments consist essentially of a pointer that moves over a calibrated scale & which is attached to a moving system pivoted in bearing. The moving system is subjected to the following three torques:

1. A deflecting (or operating) torque;
2. A controlling (or restoring) torque;
3. A damping torque.

- The deflecting torque is produced by making one of the magnetic, heating, chemical, electrostatic and electromagnetic induction effect of current or voltage and cause the moving system of the instrument to move from its zero position.
- The method of producing this torque depends upon the type of instrument.

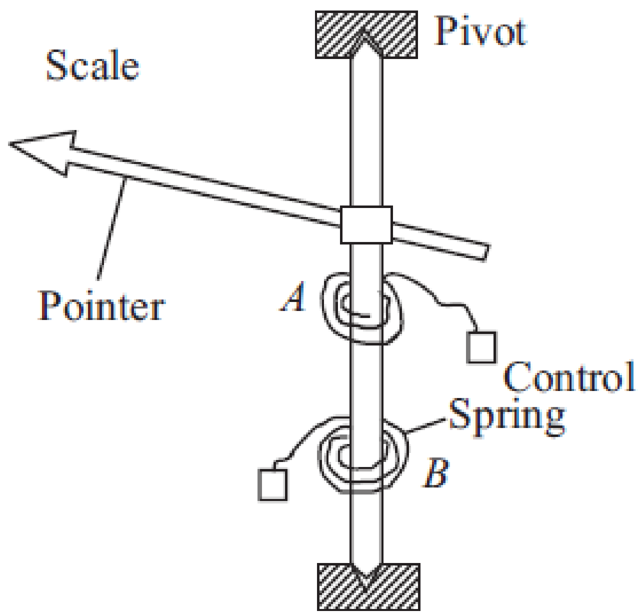


Fig.3: Spring control

- The magnitude of the moving system would be somewhat indefinite under the influence of deflecting torque, unless the controlling torque existed to oppose the deflecting torque.
- It increases with increase in deflection of moving system.
- Under the influence of controlling torque, the pointer will return to its zero position on removing the source producing the deflecting torque.
- Without controlling torque, the pointer will swing at its maximum position & will not return to zero after removing the source.
- Controlling torque is produced either by spring or gravity control.

Spring Control:

When the pointer is deflected one spring unwinds itself while the other is twisted. This twist in the spring produces restoring (Controlling) torque, which is proportional to the angle of deflection of the moving systems.

- In gravity controlled instruments, *a small adjustable weight is attached to the* spindle of the moving system such that the deflecting torque produced by the instrument has to act against the action of gravity.
- Thus, a controlling torque is obtained. This weight is called the *control weight. Another adjustable weight is also attached is the moving system for zero adjustment and balancing* purpose. This weight is called *Balance weight.*

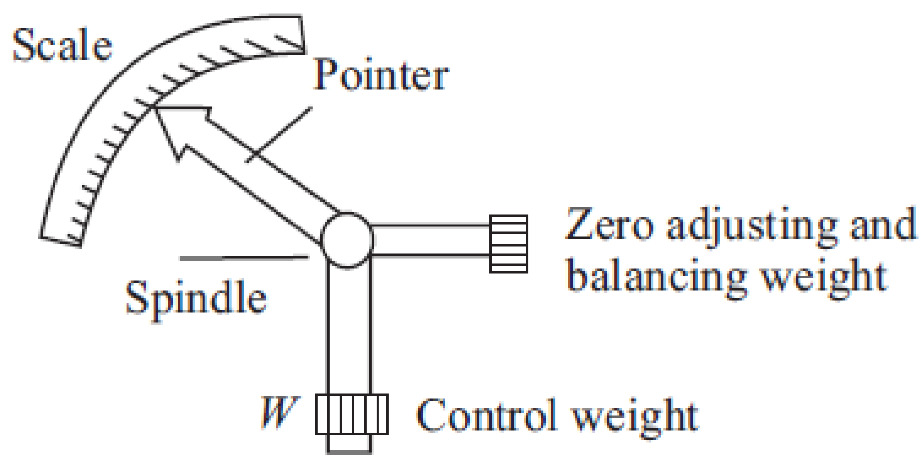


Fig.4: controlling torque

3. A damping torque.

- We have already seen that the moving system of the instrument will tend to move under the action of the deflecting torque.

- However, because of the control torque, it will try to occupy a position of rest when the two torques are equal and opposite.
- However, due to inertia of the moving system, the pointer will not come to rest immediately but oscillate about its final deflected position as shown in figure and takes appreciable time to come to steady state.
- To overcome this difficulty a damping torque is to be developed by using a damping device attached to the moving system.
- The damping torque is proportional to the speed of rotation of the moving system, that is

$$T_v = k_v \frac{d\theta}{dt} \qquad (1)$$

where k_v = damping torque constant

$\frac{d\theta}{dt}$ = speed of rotation of the moving system

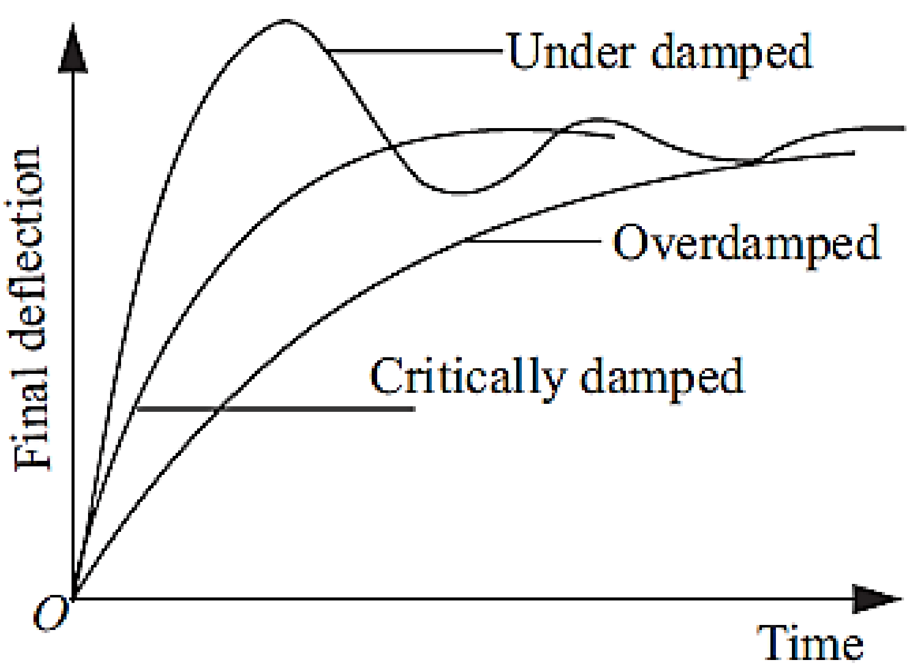


Fig.5: damped conditions

1. under damped condition:

The response is oscillatory

2. over damped condition:

The response is sluggish and it rises very slowly from its zero position to final position.

3. Critically damped condition:

When the response settles quickly without any oscillation, the system is said to be critically damped.

The damping torque is produced by the following methods:

1. Air Friction Damping 2.Fluid Friction Damping
3. Eddy Current Damping 4.Electromagnetic Damping

5- Manual / Automatic: like pressure devices

6- Smart / Non Smart

7- Contact / Contactless

8- **Analog** / **digital:** These days a number of measuring instruments, both **analog** as well as **digital** ones, are available for the measurement of electrical quantities like voltage, current, power energy, frequency, power factor, *etc*. The instruments considered are analog devices in which the output or display is a continuous-time signal and bears a fixed relationship to the input.

Analog instruments may be divided into three groups:

(*a*) **Electromechanical instruments**;

(*b*) **Electronic instruments**, which are often constructed by the addition of electronic circuits to electromechanical indicators thus increasing their sensitivity and input impedances.

(*c*) **Graphical instruments** which are electromechanical and electronic instruments having a modified display arrangement so that a graphical trace, that is, a display of instantaneous values against time is obtained.

This unit presents general concepts related to the working principles and construction and certain features common to many electrical indicating instruments particularly of electromechanical types.

Comparison between **Analog** and **Digital instruments**

	Analog	**Digital**
1. Signal	Analog signal is a continuous signal, which represents physical measurements.	Digital signals are discrete time signals generated by digital modulation.
2. Waves	Denoted by sine waves	Denoted by square waves
3. Representation	Uses continuous range of values to represent information	Uses discrete or discontinuous values to represent information
4. Example	Human voice in air, analog electronic devices.	Computers, CDs, DVDs, and other digital electronic devices.
5. Technology	Analog technology records waveforms as they are.	Samples analog waveforms into a limited set of numbers and records them.
6. Data transmissions	Subjected to deterioration by noise during transmission and write/read cycle.	Noise minimized
7. Response to Noise	More likely to get affected reducing accuracy	Less affected since noise response are analog in nature

	Analog	Digital
8. Flexibility	Analog hardware is not flexible.	Digital hardware is flexible in implementation.
9. Uses	Can be used in analog devices only. Best suited for audio and video transmission.	Best suited for Computing and digital electronics.
10. Applications	Thermometer	PCs, PDAs
11. Bandwidth	Analog signal processing can be done in real time and consumes less bandwidth.	There is no guarantee that digital signal processing can be done in real time and consumes more bandwidth to carry out the same information.
12. Memory	Stored in the form of wave signal	Stored in the form of binary bit
13. Power	Analog instrument draws large power	Digital instrument draws only negligible power
14. Cost	Low cost and portable	Cost is high and not easily portable
15. Impedance	Low	High order of 100 mega ohm
16. Errors	Analog instruments usually have a scale, which is cramped at lower end, and give considerable observational errors.	Digital instruments are free from observational errors like parallax and approximation errors.
17. Reliability	Good	Better reliability than Analog

Characteristics of Measurements

To choose the instrument, most suited to a particular measurement application, we have to know the system characteristics. The performance characteristics may be broadly divided into two groups, namely '*static*' and '*dynamic*' characteristics.

- All calibrations and specifications of an instrument are only valid under controlled conditions of temperature, pressure etc.
- These standard ambient conditions are usually defined in the instrument specification.
- As variations occur in the ambient temperature, etc., certain static instrument characteristics change, and the sensitivity to disturbance is a measure of the magnitude of this change.
- Such environmental changes affect instruments in two main ways, known as zero drift and sensitivity drift.
- Zero drift sometimes known by the alternative term, bias.
- **Bandwidth:** The bandwidth of an instrument relates to the maximum range of frequency over which it is suitable for use. It is normally quoted in terms of 3 *dB* (*dB* = decibel) point. For an amplifier, it is the range of frequencies between which the gain or amplitude ratio is constant to within 3 *dB* (this corresponds 30% reduction in gain).
- **Reproducibility**: It is the degree of closeness with which a given value may be repeatedly measured. It is specified in terms of scale readings over a given period of time.
- **Repeatability**: It is defined as the variation of scale reading & random in nature Drift.

Static characteristics

The performance criteria for the measurement of quantities that remain constant, or vary only quite slowly.

Dynamic characteristics

The relationship between the system input and output when the measured quantity (measurand) is varying rapidly.

Static Characteristics

1- **Accuracy:** It is defined in terms of the closeness with which an instrument reading approaches the true or expected (desired) value of the variable being measured.

2- **Precision:** It is measure of the consistency of reproducibility (repeatability) of the measurement (*i.e.*, the successive reading do not differ). For a given fixed value of an input variable, precision is a measure of the degree to which successive measurement differ from one another.

3- **Sensitivity:** It is defined by the change in the output or response of the instrument for a unit change of input or measured variable.

4- **Resolution:** Resolution is the smallest change in a measured variable (or measurand) to which the instrument will respond.

5- **Impedance**: In the ideal case, the act of measurement should not alter the value of the measured signal. Any such alteration is a loading error. Loading errors can be minimized by *impedance matching* of the source with the measuring instrument – reduce the power needed for measurement

The power loss through the measuring instrument where *Z(W)* is the input impedance of the measuring instrument, and *E(V)* is the source voltage potential being measured

To minimize the power loss, the input impedance should be large

$$P = \frac{E^2}{Z}$$

6- **Range**: The input range defines the minimum and maximum value of the variable to measure.

The output rage defines the minimum and maximum value of the signal given by an instrument.

Assume a temperature transducer which temperature range is from 100°C to 250°C and the output range is given from 4 to 10 mV.

7- **Span**: The span is the maximum change of the input and the output span is the maximum change of the output.

Input span:

$$I_{MAX} - I_{MIN}$$

Output span:

$$\mathrm{O}_{\mathrm{MAX}} - \mathrm{O}_{\mathrm{MIN}}$$

8- **Hysteresis and Backlash:** Careful observation of the output/input relationship of a block will sometimes reveal different results as the signals vary in direction of the movement.

Mechanical systems will often show a small difference in length as the direction of the applied force is reversed.

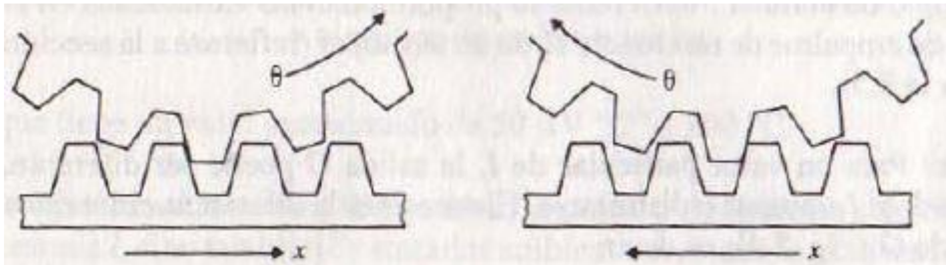


Fig.6: Backlash

The same effect arises as a magnetic field is reversed in a magnetic material.

This characteristic is called hysteresis

Where this is caused by a mechanism that gives a sharp change, such as caused by the looseness of a joint in a mechanical joint, it is easy to detect and is known as backlash.

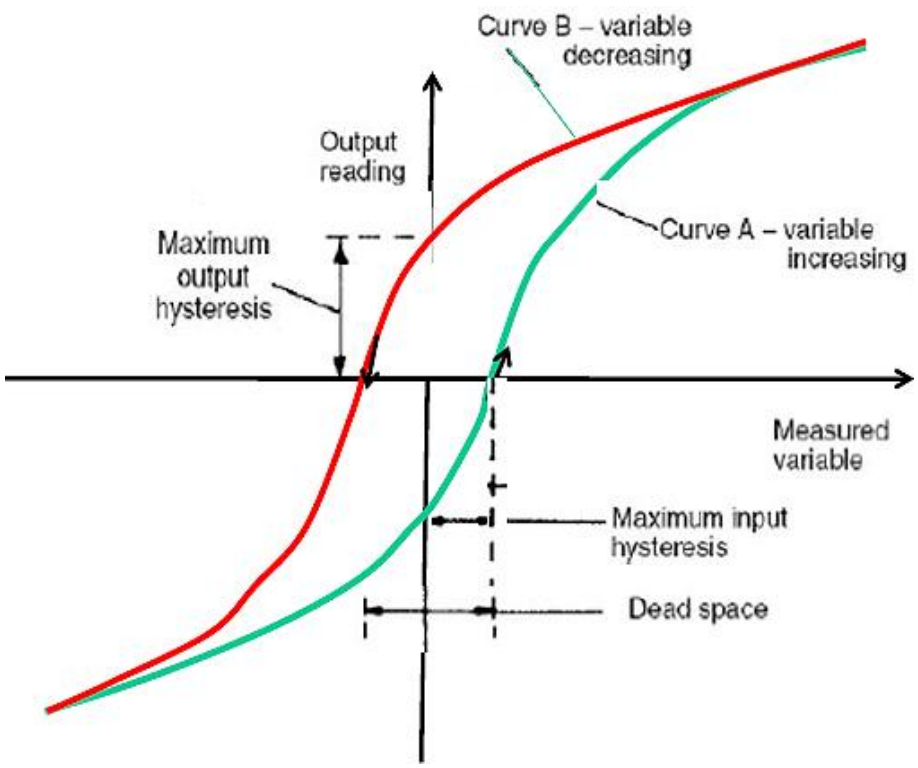


Fig.7: Hysteresis

9- **Instrument Drift:** This caused by variations taking place in the parts of the instrumentation over time.

Prime sources occur as chemical structural changes and changing mechanical stresses.

Drift is a complex phenomenon for which the observed effects are that the sensitivity and offset values vary.

It also can alter the accuracy of the instrument differently at the various amplitudes of the signal present.

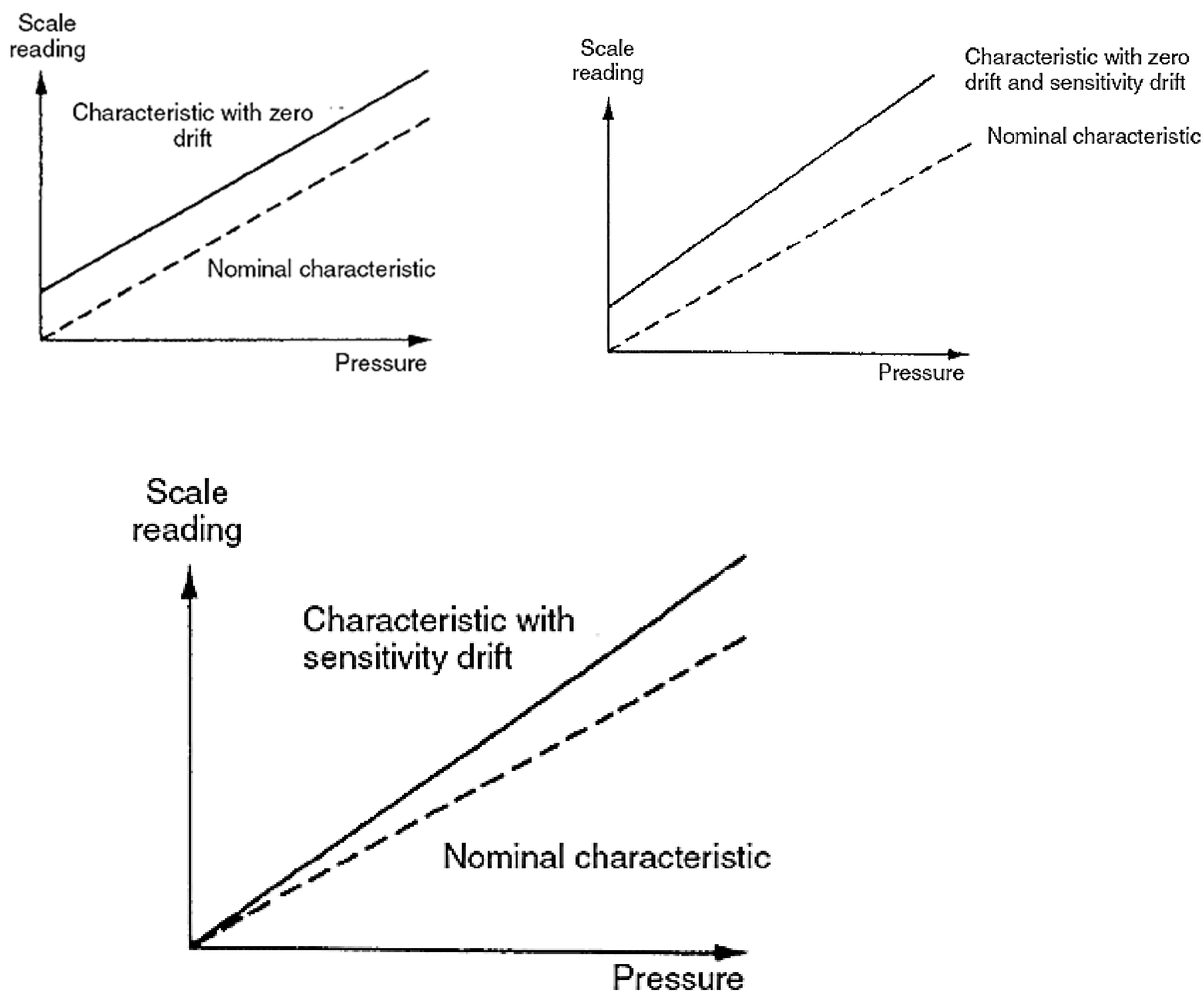


Fig.8: Instrument Drift

10- **Linearity:** It is normally desirable that the output reading of an instrument is linearly proportional to the quantity being measured.

An instrument considered if the relationship between output and input can be fitted in a line.

$$O - O_{MIN} = \left\{ \frac{O_{MAX} - O_{MIN}}{I_{MAX} - I_{MIN}} \right\} \times \left(I - I_{MIN} \right) \tag{2}$$

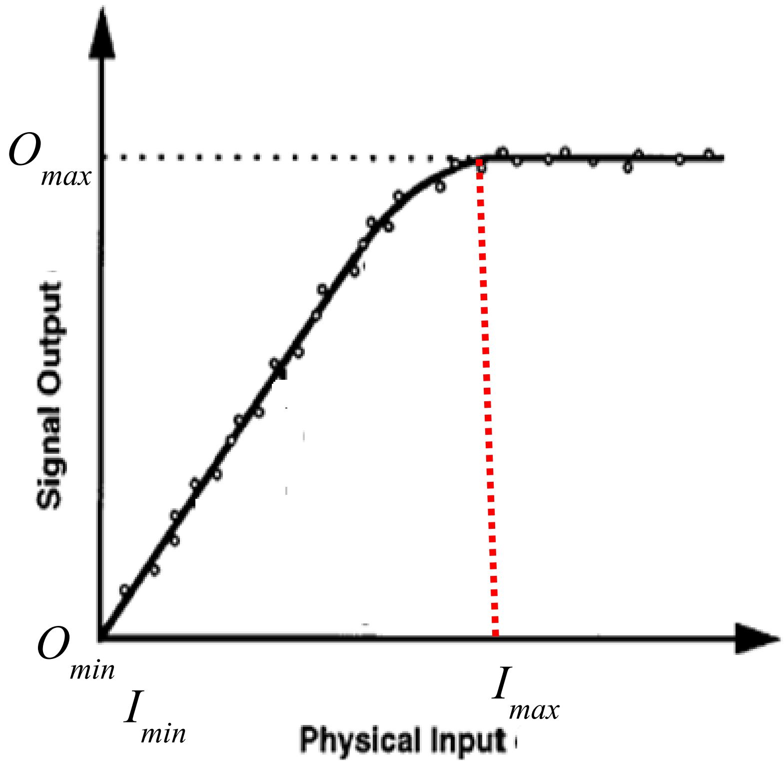


Fig.9: Linearity

11- Threshold or Dead Space: If the instrument input is increased very gradually from zero, there will be some minimum value below which no output change can be detected. This minimum value defines the threshold of the instrument.

Alternatively, Dead space is defined as the range of different input values over which there is no change in output value.

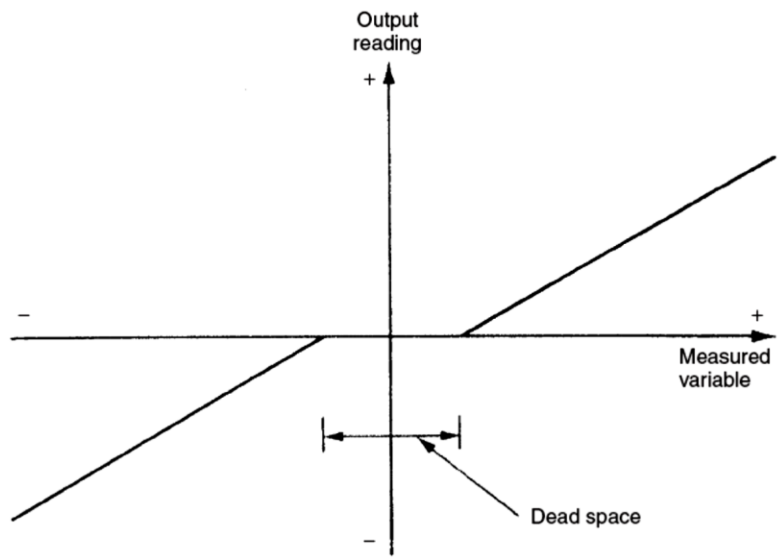


Fig.10: Threshold or Dead Space

12- **Stability:** It is the ability of an instrument to retain its performance throughout is specified operating life.

13- **Tolerance**: The maximum allowable error in the measurement is specified in terms of some value, which called tolerance.

14- **Bias:** The constant error that exists over the full range of measurement of an instrument is called bias.

Such a bias can be completely eliminated by calibration. The zero error is an example of bias which can be removed by calibration.

Dynamic characteristics

Measurement outcomes are rarely static over time. They will possess a dynamic component that must be understood for correct interpretation of the results. For example, a trace made on an ink pen chart recorder will be subject to the speed at which the pen can follow the input signal changes.

Instruments rarely respond to the instantaneous changes in the measured variables. Their response is slow or sluggish due to mass, thermal capacitance, electrical capacitance, inductance etc. sometimes, even the instrument has to wait for some time until, the response occurs. These type of instruments are normally used for the measurement of quantities that fluctuate with time. The behavior of such a system, whereas the input varies from instant to instant, the output also varies from instant to instant is called as dynamic response of the system. Hence, the dynamic behavior of the system is also important as the static behavior.

The dynamic inputs are of two types: 1. Transient 2. Steady state periodic. Transient response is defined as that part of the response, which goes to zero as the time becomes large. The steady state response is the response that has a definite periodic cycle. The variations in the input that are used practically to achieve dynamic behavior are I. Step input:-The input is subjected to a finite and instantaneous change. E.g.: closing of switch. II. Ramp input: - The input linearly changes with respect to time. III. Parabolic input: - The input varies to the square of time. This represents constant acceleration. IV. Sinusoidal input: - The input changes in accordance with a sinusoidal function of constant amplitude.

The dynamic characteristics of a measurement system are: 1) Speed of response 2) Fidelity 3) Lag 4) Dynamic error 5) Frequency response

1) **Speed of Response** It is defined as the rapidity with which an instrument responds to the changes in the measured quantity. It shows how active and fast the system is.

2) **Fidelity** it is defined as the degree to which a measurement system is capable of faithfully reproducing the changes in output depend on input, without any dynamic error.

3) **Lag**: Every system requires its own time to respond to the changes in input. This time is called as lag. It is defined as the retardation or delay, in the response of a system to the changes in the input. The lags are of two types:

1. Retardation lag: As soon as there is a change in the measured quantity, the measurement system begins to respond.
2. Time delay: The response of the measurement system starts after a dead time, once the input is applied. They cause dynamic error.

4) **Dynamic error**: It is the difference between the true value of the quantity that is to be measured, changing with time and the measured value, if no static error is assumed.

5) **Frequency response:** Dynamic characteristics refer to the response of an instrument to continuously changing input. The dynamic response of an instrument to an input signal is typically modeled in terms of zero, first or second order linear differential equations.

1- Zero-order instrument

The simplest model for measurement systems is a zero order differential equation.

$y = kx$

Where k is called the static sensitivity.

An instrument can be modeled as a zero order instrument when its dynamic is very fast compared to the variation in its input signal.

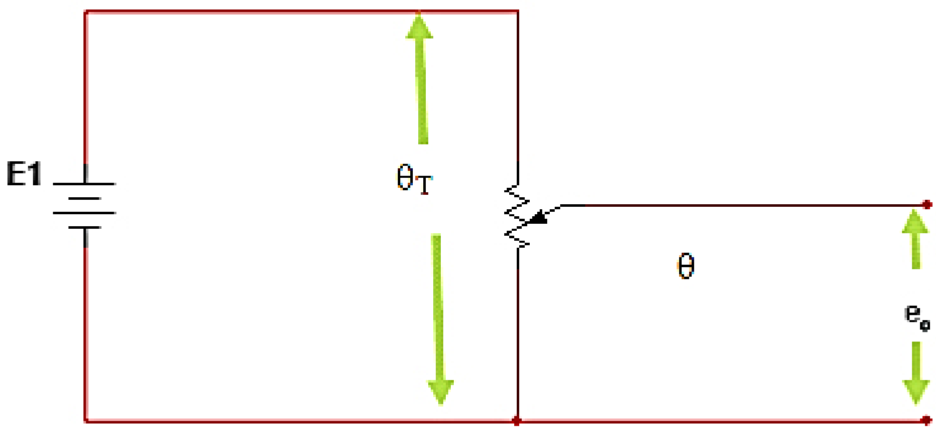


Figure 11: Zero-order circuitry

A potentiometer is the example of a zero order instrument.

$$\theta = \frac{\theta}{\theta_T} E = k\theta \quad (3)$$

Where k = E/ θ_T = volts/radian

2- First order instrument

Transducer that contains a single storage element can be modeled to be of first order. Therefore, the dynamic characteristics of a first order instrument is given by

tý + y = kx

t is called the time constant of the system and it always has the dimension of time. The mercury in the glass thermometer is an example of a first order instrument while the thermocouple in thermo-well is an example of a first order sensor.

1- First order instrument response to a step input

The response of a first order instrument to a step input is given by

$$Y(T) = kX_s[1 - e^{-\frac{t}{T}}] \qquad (4)$$

T is the time constant.

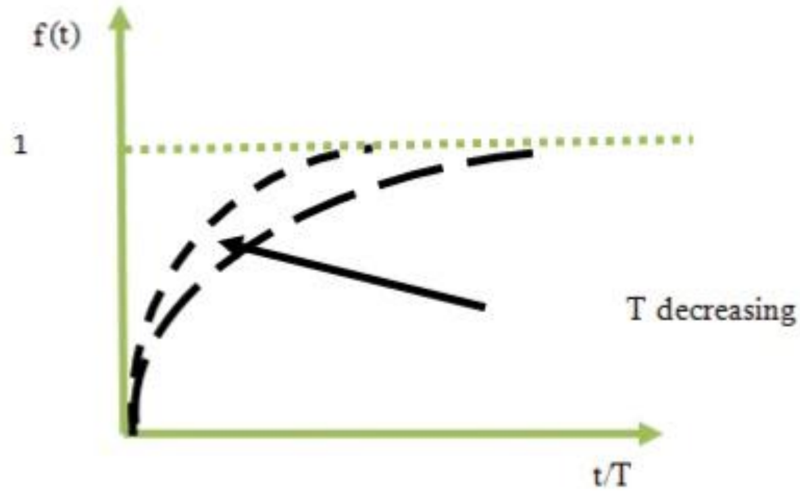


Figure 12: Response of a first order element to a unit step

2- First order instrument response to a sinusoidal input

The response of a first order instrument to a sinusoidal input explained as shown below.

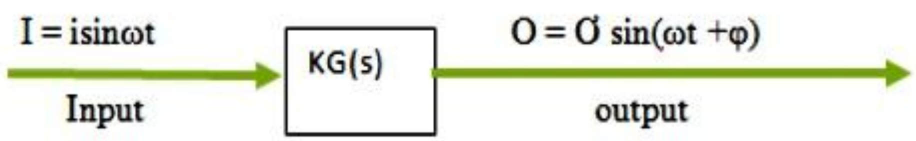


Figure 13: First order instrument response

3- Frequency response of an element with linear dynamics

Frequency response of an element with linear dynamics is governed by the equation:

$$y = \frac{KX_s}{\sqrt{1+\omega^2\tau^2}} \sin(\omega t - \emptyset) = A\sin(\omega t - \emptyset) \qquad (5)$$

Where

$$A = \frac{KX_s}{\sqrt{1+\omega^2\tau^2}} \quad (6)$$

"A" represents the amplitude of the steady state response and Ø is the phase shift of output response with respect to sinusoidal input.

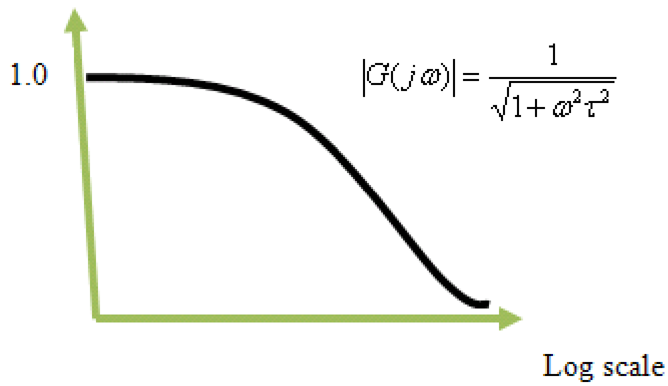


Figure 14: Frequency response of an element with linear input

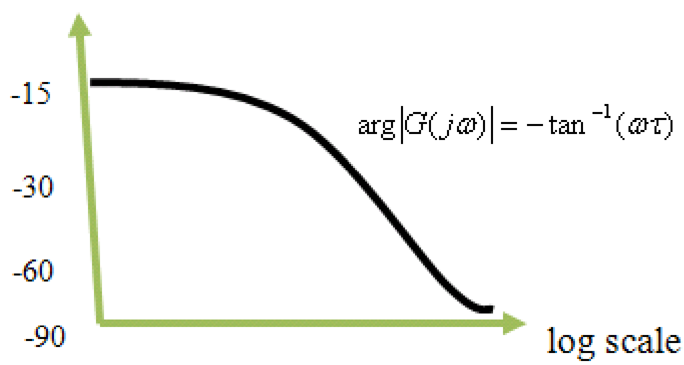


Figure 15: Frequency response characteristics of first order element

3- Second order instrument

The second order sensor is modeled by a second order differential equation. Accelerometers, diaphragm pressure transducers, mercury in glass manometers are few examples of second order system.

The second order instrument dynamic characteristics is given by:

$$\frac{\ddot{y}}{\omega^2 n} + 2\frac{\xi}{\omega n}\dot{y} + y = Kx \qquad (7)$$

or

$$s^2 + 2\zeta\omega s + \omega^2 = 0 \qquad (8)$$

Let us apply an input signal and see how the output looks like.

Case 1: ξ >1, over damped systems (real unrepeated roots)

The normalized output will be expressed as

$$\frac{y}{KXs} = 1 - \frac{\xi + \sqrt{(\xi^2 - 1)}}{2\sqrt{(\xi^2 - 1)}} e^{(-\xi + \sqrt{(\xi^2 - 1)}} \omega_n t + \frac{\xi - \sqrt{(\xi^2 - 1)}}{2\sqrt{(\xi^2 - 1)}} e^{(-\xi - \sqrt{(\xi^2 - 1)}} \omega_n t \qquad (9)$$

Case 2: ξ =1, critically damped system (real repeated roots)

$$\frac{Y}{KXs} = 1 - (+\omega_n t) e^{-\omega_n t} \qquad (10)$$

Case 3: 0< ξ <1, under-damped system (complex conjugate roots)

$$\frac{y}{KXs} = 1 - \frac{e^{-\xi \omega_n t}}{\sqrt{(1 - \xi^2)}} \sin(\sqrt{(1 - \xi^2)}\, \omega_n t + \varphi) \qquad (11)$$

Where $\varphi = \sin^{-1}\sqrt{(1 - \xi^2)}$

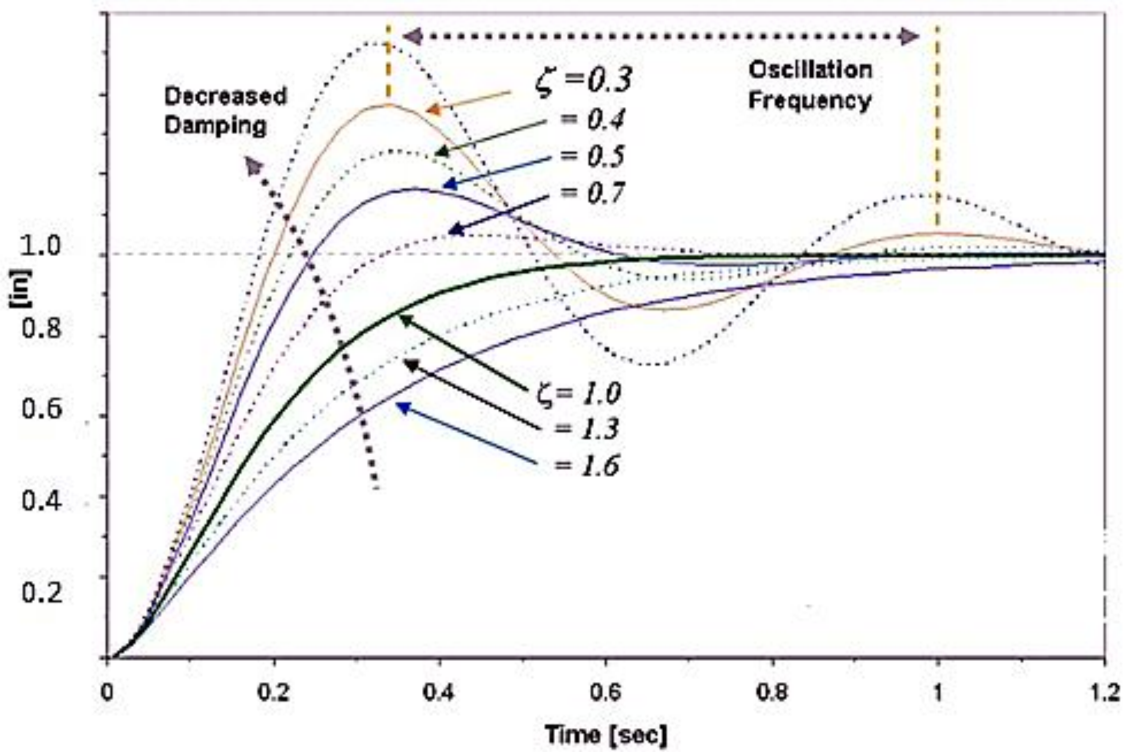


Figure 16: Amplitude versus time responses of a second order element

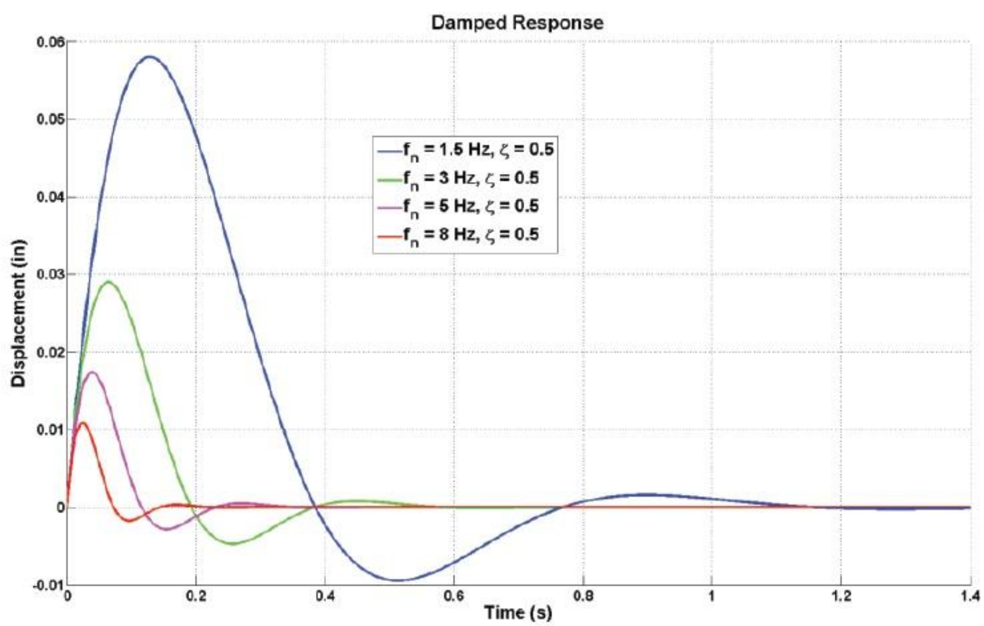


Figure 17: Amplitude versus time responses of a second order element [ζ= constant]

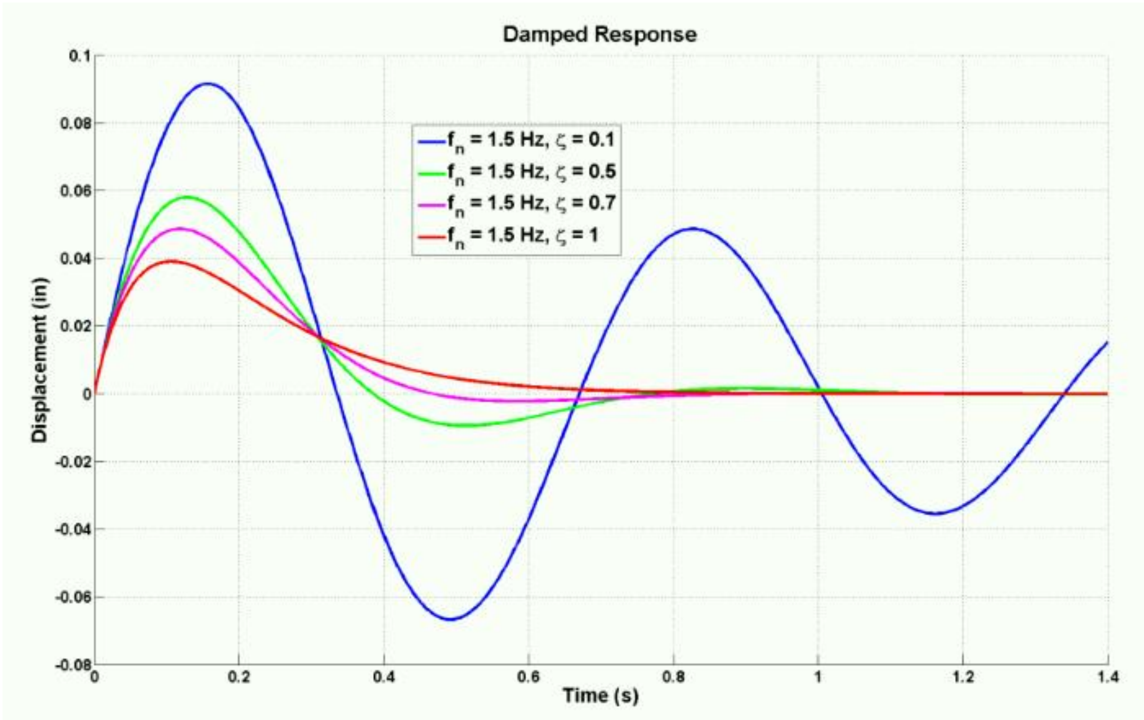


Figure 18: Amplitude versus time responses of a second order element f_n=constant

(i) Undamped system: $\xi = 0$ or $c = 0$

(ii) Underdamped system: $0 < \xi < 1$ or $0 < c < 2\sqrt{mk}$

(iii) Critically-damped system: $\xi = 1$ or $c = 2\sqrt{mk}$

(iv) Over-damped system: $\xi > 1$ or $c > 2\sqrt{mk}$

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