European Scientific Journal March 2014 edition vol.10, No.9 ISSN: 1857 – 7881 (Print) e - ISSN 1857- 7431

MEASUREMENT SYSTEMS: CHARACTERISTICS AND MODELS

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Abstract

In this paper, the major static characteristic parameters for sensors and instruments are defined and explained. Also, the process of calibration and subsequent characterization of errors are illustrated. Moreover, we describe the response and models of first and second order instrument to step and sinusoidal inputs.

Keywords: Static characteristic , sensors, first order, second order

1. Introduction

All measurement systems can be thought of being made of one or more of these blocks of Figure1. At the input we have the input element to be measured, temperature, displacement, .etc. that affecting the sensing element. Actually, sensing element is the process of continuous energy conversion from one form depending on what we want to measure, e.g, from mechanical form, optical form to finally electrical form, and then the electrical form get finally transform further to digital form before the output. The signal at the sensing element is in the form of voltage and current. The real pressure or real temperature which it exist at the sensing element, then the sensing element brings it generally to some sort of electrical form or electrical parameters like resistors, capacitor changes or in the form of voltage and current which have be further manipulated by electrical circuit called signal conditioning element.(sometimes amplifier or conversion from resistor to voltage). Then further signal processing goes on to remove noise and make it linear or something like that. Some of it can be analog and some of it can be digital. Finally, it goes to the data presentation element where data is utilized so it can be recorded, or can be displayed or can be controlled.

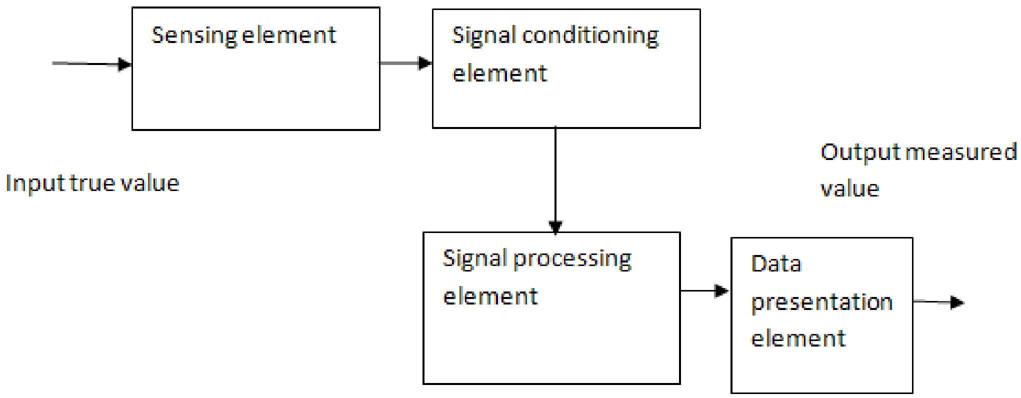


Figure 1: General structure of measurement system

Here is the weight measurement system as an example. The input is the true weight which is sensed by a mechanical member that called load cell. The load cell converts the input (weight) to the strain that sensed by another member called strain gauge. The latter converts it to a resistance form then we feed it to the electrical circuit called wheat-stone. The wheat-stone converts the resistance to a low voltage level. The low voltage goes to the amplifier. Finally, the amplified signal passes to the digital signal processing and from there to a microcontroller where some digital processing is done. Finally, the data may be displayed along with a unit. Here is how real measurement system looks like. It is basically cascaded of several blocks including the sensor, signal conditioning, plus some computer elements.

Sensing is actually extremely important in automation from various points of view:

a. Product quality control, because quality control is actually accessed by a sensor element.
b. Manufacturing process control. All the process control are closed feedback control. So the critical element is the feedback element. The performance of the control system is critical to the sensor.

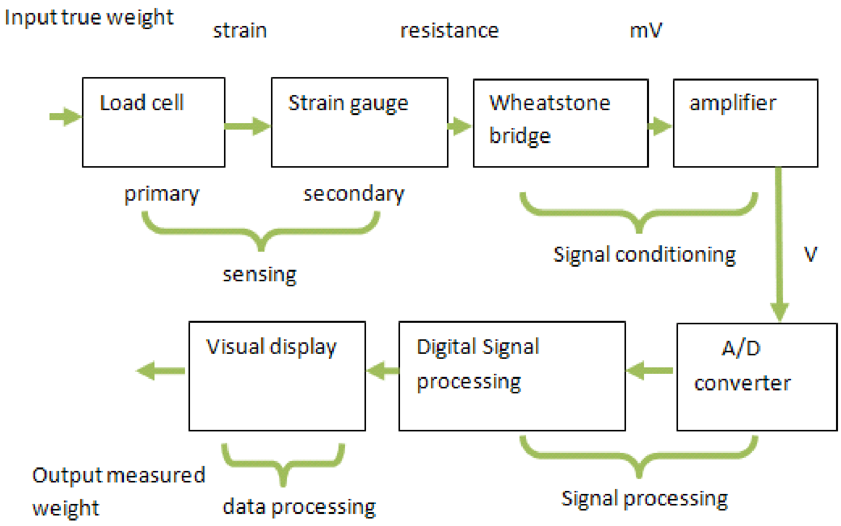


Figure 2: Weight measurement system

c. Process monitoring and supervision.
All these can be done plus providing energy efficient, obtaining set-point, for all these we need sensors.

d. Manufacturing automation, this how the manufacturing automation systems can be put together using programmable logic controllers. Then you find that they use various kinds of sensors. So sensors are extremely important in automation. They will give a value or information about physical quantity we need to know how to characterize the behavior of this device called a sensor in instrument, we need to understand instrument characteristics.

The performance characteristics may be broadly divided into two types, namely, 'statistics' and 'dynamic' characteristics. Static characteristics where the performance criteria for the measurement of quantities that remain constant. Or vary only quite slowly. Dynamic characteristics on the other hand, shows the relationship between the system input and output when the measured quantity is varying rapidly.

1.1-Calibration

The procedure that involves a comparison of the particular instrument with either a primary standard or a secondary standard with a higher accuracy than the instrument to be calibrated.

From Figure 3, the measurand 1 is considered to be the true value, while the measurand 2 is not only from the sensor instrument under calibration but it can be a result of other factors. It may be a result of temperature. For example, in the case of the weight measurement, the strain gauge,(the resistance change) is not only a function of the weight, it also a function of temperature. Because every resistance has some temperature coefficient.

There are some noise can be induced from a power supply or from some power lines especially in the industry environment, there are plenty of noise sources. This signal (noise) can affect the measurement. When you want to characterize the instrument, you have to characterize it to respond these kinds on inputs.

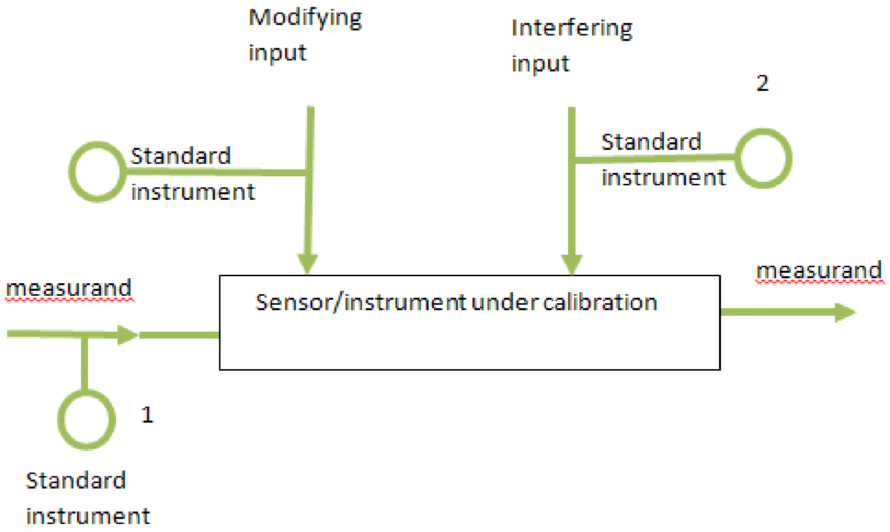


Figure 3: Calibration of an instrument

Essentially, we try to measure the measurand, the output of the instrument, and the modifying input like the temperature. Then we establish the characteristics of the instrument. Since the instrument must happen constructed to be unaffected by modifying input, so the most important thing is to see how the instrument characteristics depend on the measurand.

There are different standards of instrument. The instrument can be calibrated against laboratory standard. The laboratory standard instrument can also be calibrated from time to time against other standard like the secondary standard which is special instrument that exists in some testing houses. So from time to time you should send the instrument to test houses and get calibrated. On the other hand, the guest house instruments again have to be calibrated against very accurate national standards. So in this way you have what can be called change of standards of increasing accuracy and add different levels you always calibrate according with respected instrument.

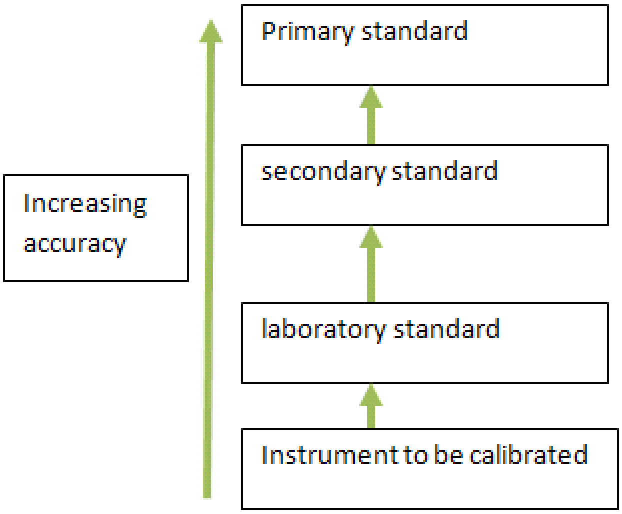


Figure 4: increasing accuracy with different levels of standards

1.2- Span

If in a measurement instrument the highest point of calibration is x2 units and the lowest point is x1 units, then the instrument range is x2 units and the instrument span is x2-x1.

1.3- Accuracy

One of the most important parameter called accuracy. Usually, "accuracy is expressed as accurate to within x percent" of reading/span. It means that true value within ±x percent of instrument reading/span at all calibration points of the scale. When a temperature transducer with an error of ±1% of reading indicates 100^{o}C, then the true temperature is between 99^{o}C and 101^{o}C.

1.4- Linearity

The calibration curve of a real instrument is typically not a exactly straight line. But still is very useful to imagine the system real one. It is very easily to interpret the true value. If you have an instrument sensitivity 10mV/^{o}C, and if it gives 25mV signal, then you know that the temperature is 2.5 ^{o}C. So you can get just by dividing by a number. From that point of view, it is very attractive to express the characteristics of a linear one, but it is not line. Therefore, why you mention a line which can be used for inducing the true value from a reading. For ease of use, it is desirable that the reading of an instrument is considered Linearly related to the quantity being measured. The linearity specification indicates the deviation of the Calibration curve from a good fit straight line of it.

How do you obtain the straight line? It can be obtained in various ways: (non-)linear method; this method is defined as the maximum deviation of an output reading from the good fit straight line and may be expressed as a percentage of full scale or reading.

The true characteristics of the instrument is indicated by the curve shown in Figure5. So we can approximate it by the straight line. Therefore, the true value will be within two limits shown in Figure 5.

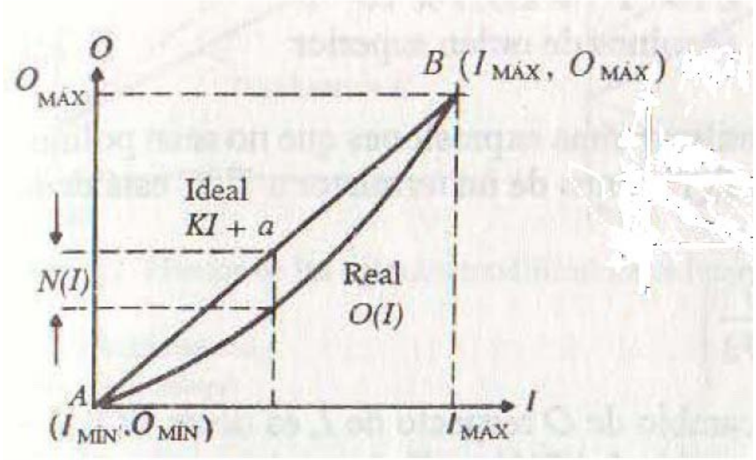


Figure 5: Non-linear method for obtaining a straight line

Actually linearity specification is only linear specification in the sense that it indicates deviation from linearity.

1.5- Sensitivity

The slope of an static calibration curve evaluated at an input value is the static sensitivity.

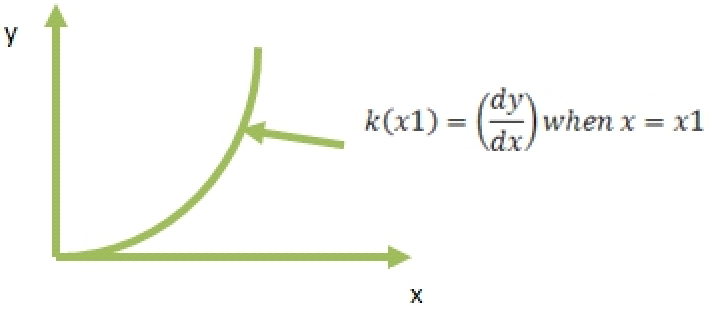


Figure 6: The slope of an static calibration curve

If you have a calibration curve, then you get a straight line. In case you have a linear characteristic, then you will have a single sensitivity. However, if you have a very non-linear one, sometime you do various things. In the case of three sensitivity figure, one sensitivity figure you apply along the line A, another sensitivity figure you apply at the region B which is the average slope of the line , and a third sensitivity figure you apply at the range of C.

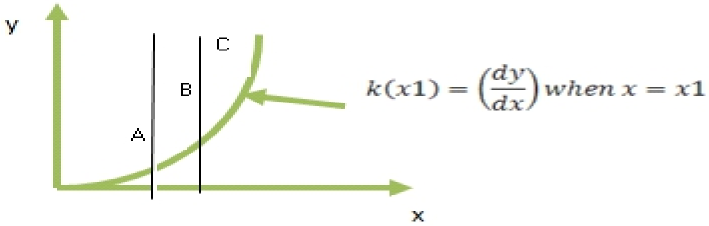


Figure7: Non-linear calibration characteristics curve

1.6- Repeatability or Precision

The repeatability of an instrument is the degree of closeness with which a measurable quantity may be repeatedly measured. It is defined as the maximum measure of variation in the measured data for a particular input value given by standard deviation δ.

1.7- Resolution

The measurement resolution of an instrument defines the smallest change in measured quantity that causes a detectable change in its output. For example, in a temperature transducer, if 0.2 ^{o}C is the smallest temperature change that observed, then the measurement resolution is 0.2 ^{o}C.

1.8- Dead Zone

Dead zone is the largest value of a measured variable for which the instrument output stays zero. It occurs due to factors such as static friction in a mechanical measurement system.

1.9- Hysteresis

Hysteresis error refers to the difference between responses to increasing and decreasing sequence of inputs. It can occur due to gear backlash in mechanism, magnetic hysteresis or due to elastic hysteresis.

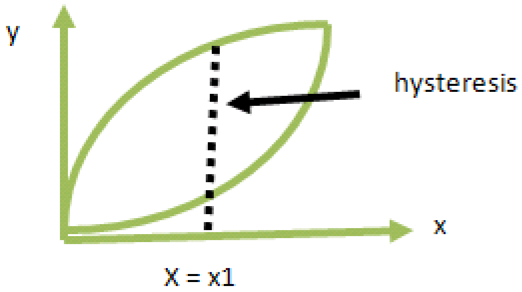


Figure 8: hysteresis

1.10- Bias/offset

It is the constant component of error that may be assumed to exist over the full range.

1.11- Sensitivity/Gain error

It is the component of error which is assumed to be proportional to the reading.

1.12- Correction

Instruments often provide facilities to correct for these error using signal conditioning circuitry.

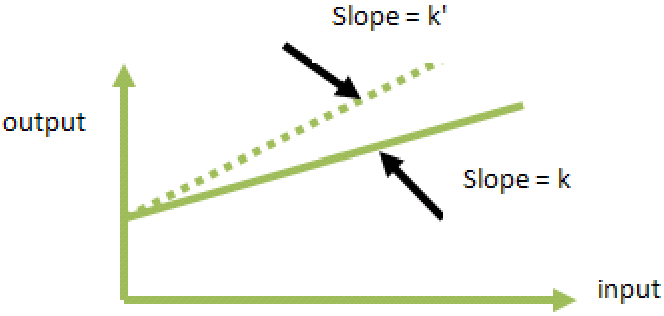


Figure 9: Bias and Gain error

1.13- Drift

The calibration of an instrument is usually performed under controlled conditions. As variations occur in these conditions and also with passage of time, the instrument characteristics change. Usually, typical factors for which drift is characterized are temperature and time.

2.0- Dynamic Characteristics

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.

2.1- Zero-order instrument

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

$$y = k_x$$

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.

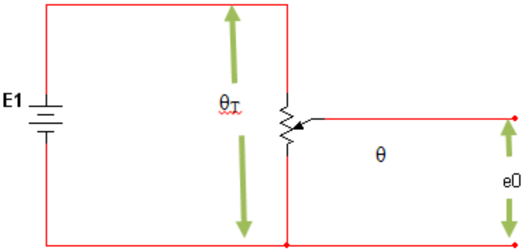


Figure 10: Zero-order circuitry

A potentiometer is the example of a zero order instrument.

$$e_0 = \frac{\theta}{\theta_T} E = k\theta$$

where $k = E/\theta_T$ = volts/radian

2.2- 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

$$t\acute{y} + y = kx$$

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.

2.2.1- First order instrument response to a step input

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

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

T is the time constant.

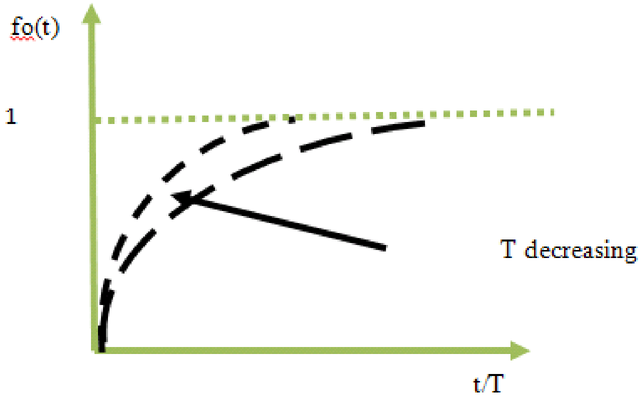
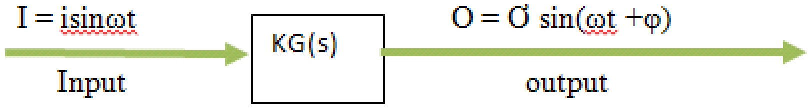


Figure 11: Response of a first order element to a unit step

2.2.2- First order instrument response to a sinusoidal input

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



2.2.3- Frequency response of an element with linear dynamics

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

$$y = \frac{KXs}{\sqrt{1+\omega^2\tau^2}}\sin(\omega t - \varphi) = A\sin(\omega t - \varphi)$$

Where $A = KXs\frac{KXs}{\sqrt{1+\omega^2\tau^2}}$

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

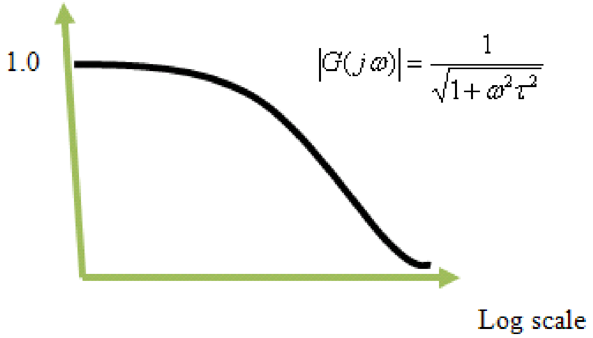


Figure 12: Frequency response of an element with linear input

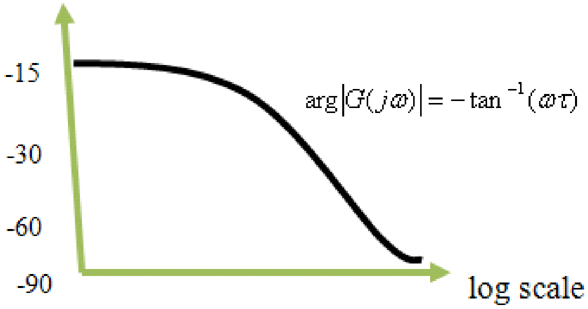


Figure 13: Frequency response characteristics of first order element

Depending on some physical reasons, we can also have second order instrument.

2.3- 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

$$\frac{\ddot{y}}{\omega^2 n} + 2\frac{\xi}{\omega n}\dot{y} + y = Kx\,.$$

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

Case 1: $\xi > 1$, over damped systems (real unrepeated roots)

The normalized output will be expressed as

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

Case 2: $\xi = 1$, critically damped system (real repeated roots)

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

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

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

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

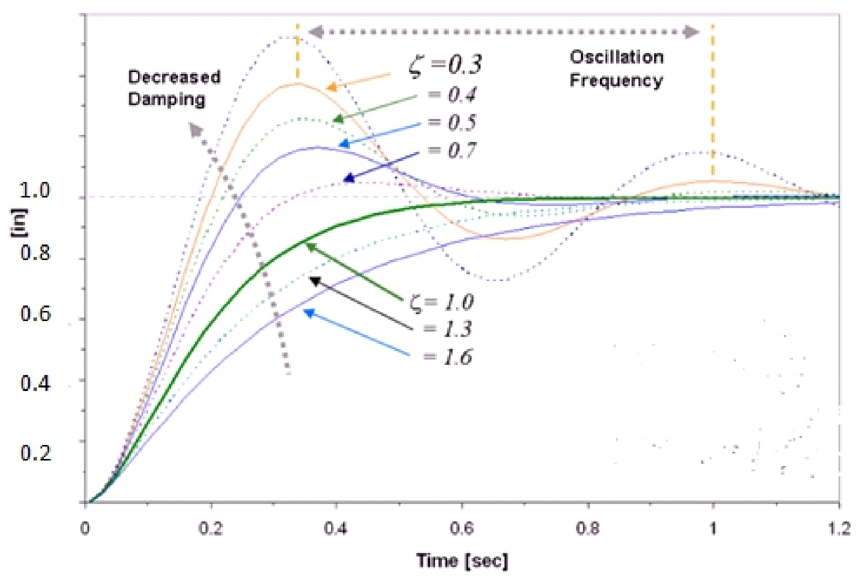


Figure 14: Amplitude versus time responses of a second order element

2.3.1- Second order instrument with a sinusoidal input

The equation is

$$x = x_s \sin \omega t$$

$$\frac{y/k}{x_s} = \frac{\sin(\omega t+\varphi)}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\frac{4\xi^2\omega^2}{\omega_n^2}}}$$

Phase shift $\varphi = \tan^{-1}\left(\frac{2\xi}{\frac{\omega}{\omega_n}-\frac{\omega_n}{\omega}}\right)$

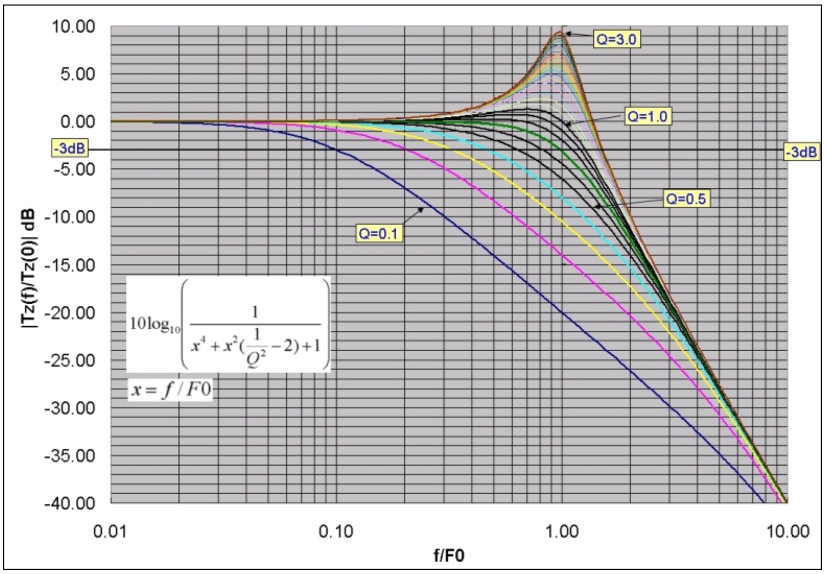


Figure 15: Phase shift responses of a second order element

3.0- Conclusion

In this article, the fundamental static and dynamic characteristics and models of zero, first, and second order instrument were discussed supported with the appropriate figures.

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