ECE421: Electronics for Instrumentation
MEP382: Design of Applied Measurement Systems
Lecture #1: Sensor Systems

April 14th 2014

Some slides are borrowed from Dr. Moahmed Elshiekh lectures

Outline

- What is a measurement system?
- Sensor and sensor types
- Characteristics of sensor
  - Static characteristics of sensors
  - Dynamic characteristics of sensors

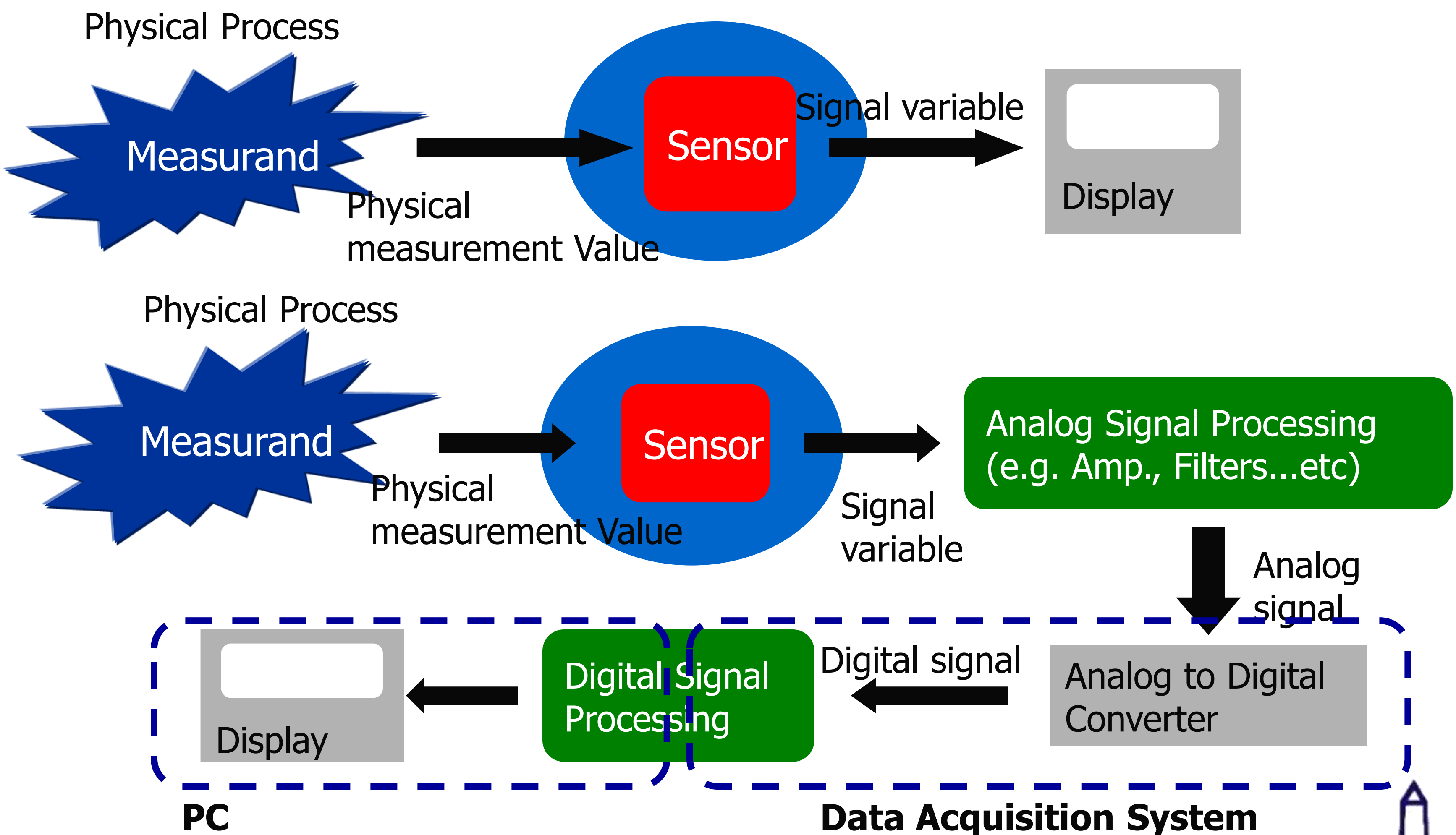
What is a measurement system?

- Measurements of physical variables (Mesurands) are needed for monitoring and control purposes.
- Typical mesurands are:
  - Position, velocity, acceleration.
  - Force, torque, strain, pressure.
  - Temperature.
  - Humidity.
  - Flow rate.

What is a measurement system?

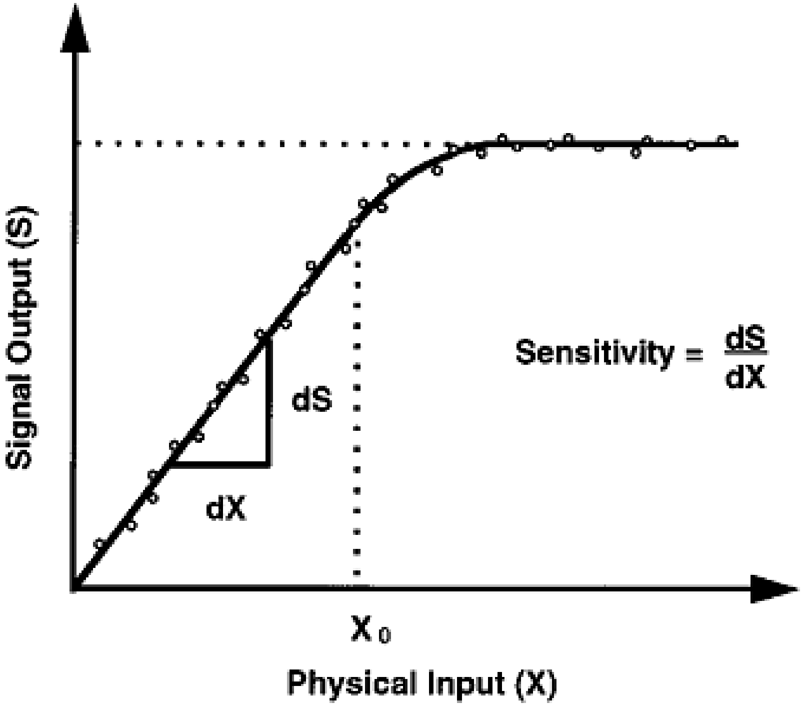
- Measurement system concept:
  - The change in the measured physical value (measurand) is converted (transduced) into a change in the property of a sensor (resistance, capacitance, magnetic, coupling …).
  - The change in the sensor's property is translated into a low-power-level electrical signal, i.e. voltage, current, frequency.
  - The low-power sensor signal is then amplified, conditioned, and transmitted to a device for processing, display, or closed loop control system.

What is a measurement system?



Examples of physical/signal variables:

Common physical variables	Typical signal variables
Force	Voltage
Length	Displacement
Temperature	Current
Acceleration	Force
Velocity	Pressure
Pressure	Light
Frequency	Frequency
Capacity	
Resistance	
Time	
…	



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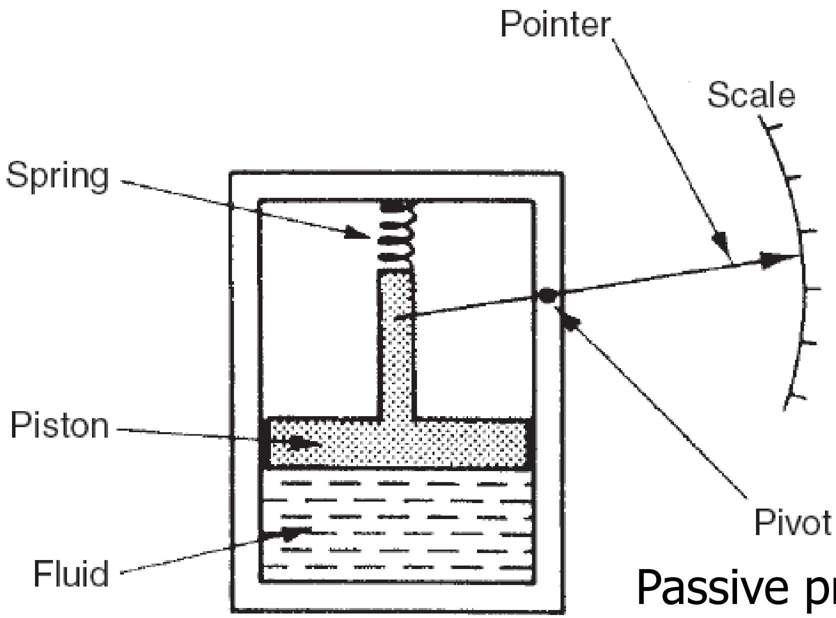
Types of sensors

- Sensors are considered as transducers that convert input energy of one form into output energy of another form.
- In many cases, it converts the input energy from many forms into output energy in a form of electrical energy to be signal processed.
- Sensors could be mainly active/passive and analog/digital.

Types of sensors: Passive

- Do not add energy as part of the measurement process.
- The output power is almost entirely provided by the measured signal without an external power supply.
- Example: pressure gages

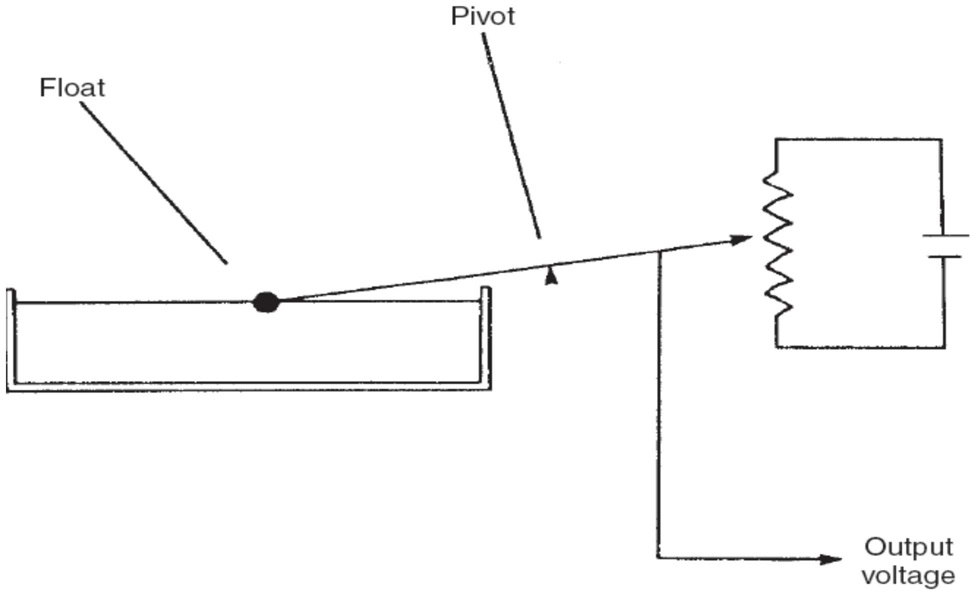


Passive pressure gauge.

Types of sensors: Active

- Require an external source of power that provides the majority of the output power of the signal
- In other words, external energy is added to the measurement environment as part of the measurement process.
- **Better resolution** control by the adjustment of the magnitude of the external energy input.

Active level sensor.



Types of sensors: Analog/Digital

- Analog sensors produce a signal which is continuous over time and proportional to the measurand.
- Example: bulb thermometer.

- Digital sensors provide a signal that is a direct digital representation of the measurand. Digital sensors are basically binary ("on" or "off") devices.
- Example: A revolutionary counter.

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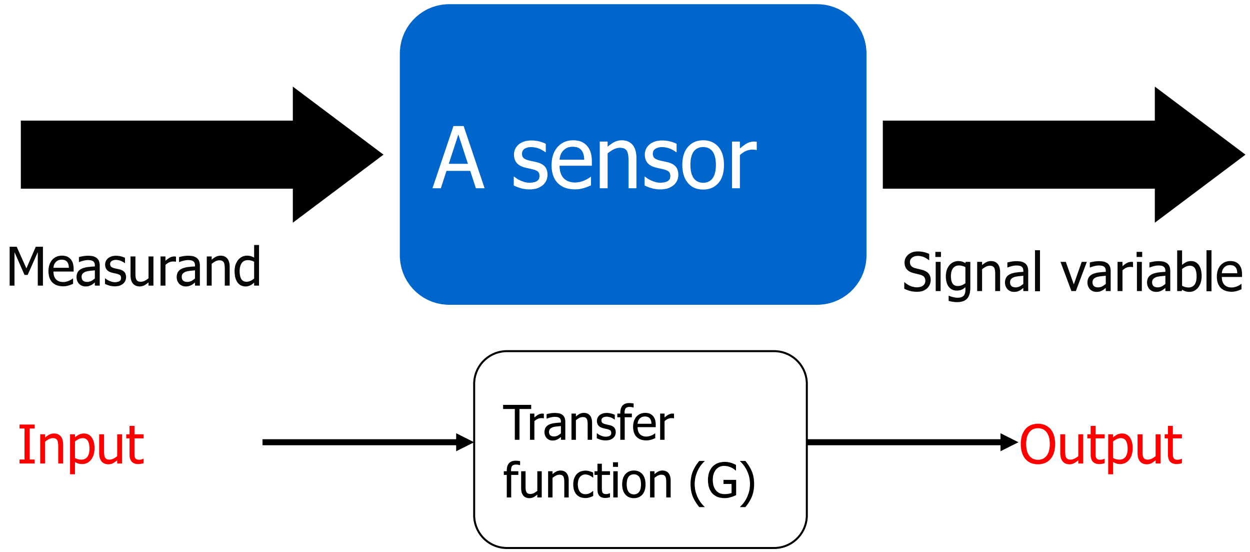
Characteristics of sensor

- Static characteristics of the sensor are its properties when all its dynamics settle down (steady state):
  - Sensitivity, offset & bias, span & dynamic range, saturation & dead zone, hysteresis & backlash, and nonlinearity.
- Dynamic characteristics of the sensor describe the sensor's transient properties and how it transiently responds to changes in measurands:
  - The reason for dynamic characteristics is the presence of energy-storing elements, masses, springs, inductances, capacitances.

Characteristic of sensor



Transfer function (G) = $G_{static} \times G_{dynamic}$

(Transfer characteristics)

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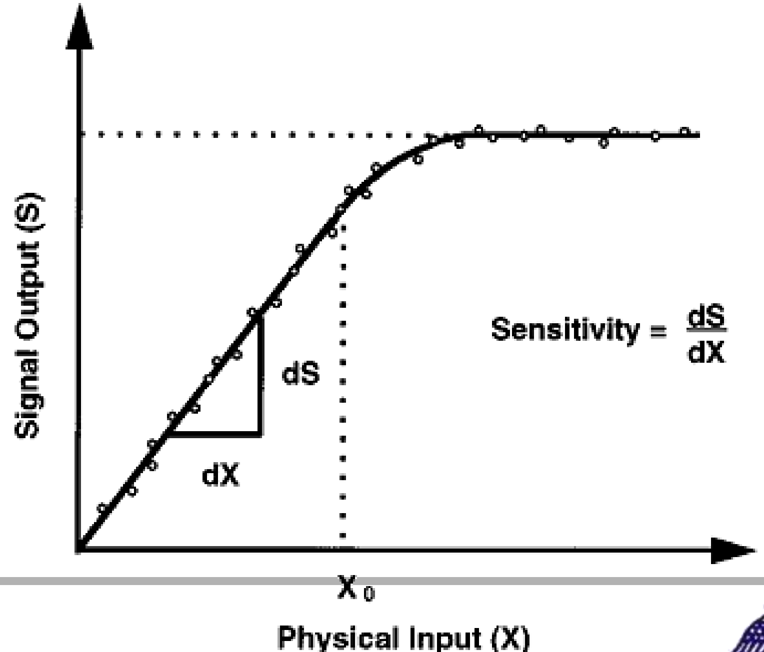
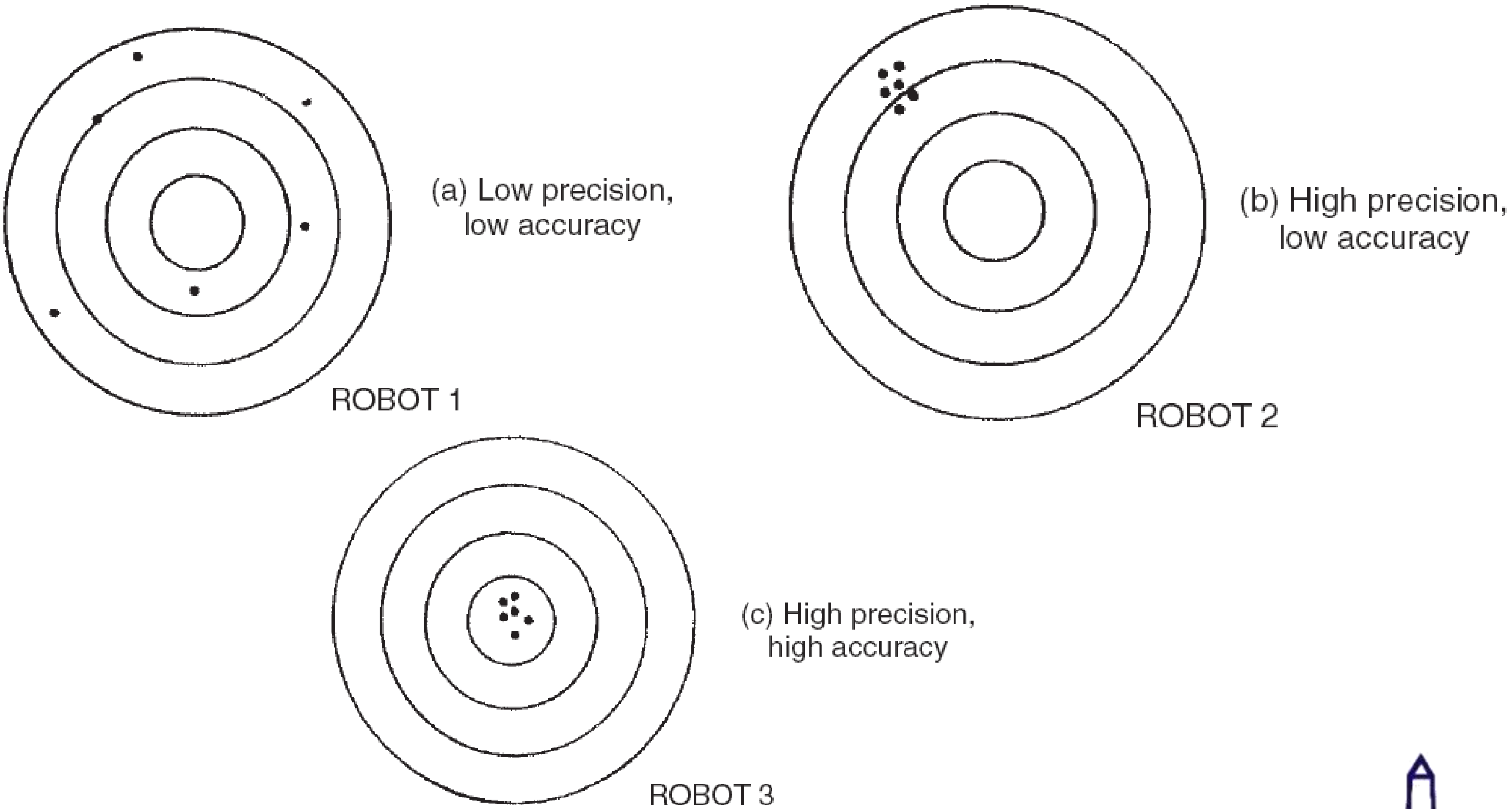
Static Characteristics: Sensitivity

- The sensitivity of measurement system is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount.
- Sensitivity is also named amplification factor or gain (if greater than one) and attenuation (if less than one).
- Measured in the linear/nonlinear region of the curve.

Sensitivity $= {}^{dS}/_{dx}$

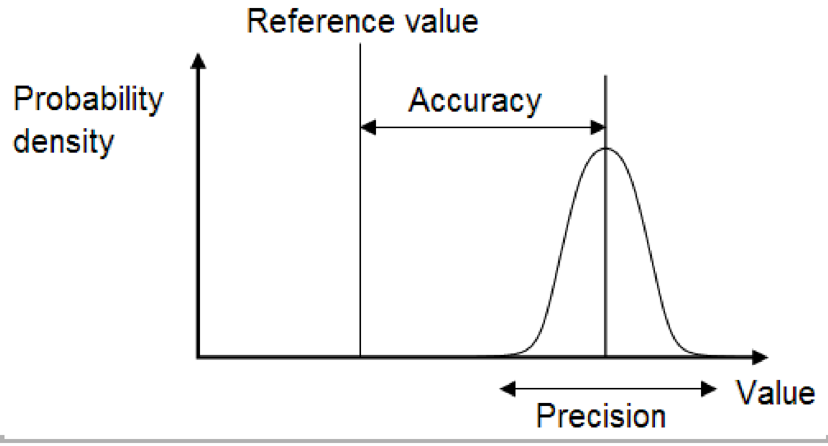


Accuracy vs. Precision



Static Characteristics: Definitions

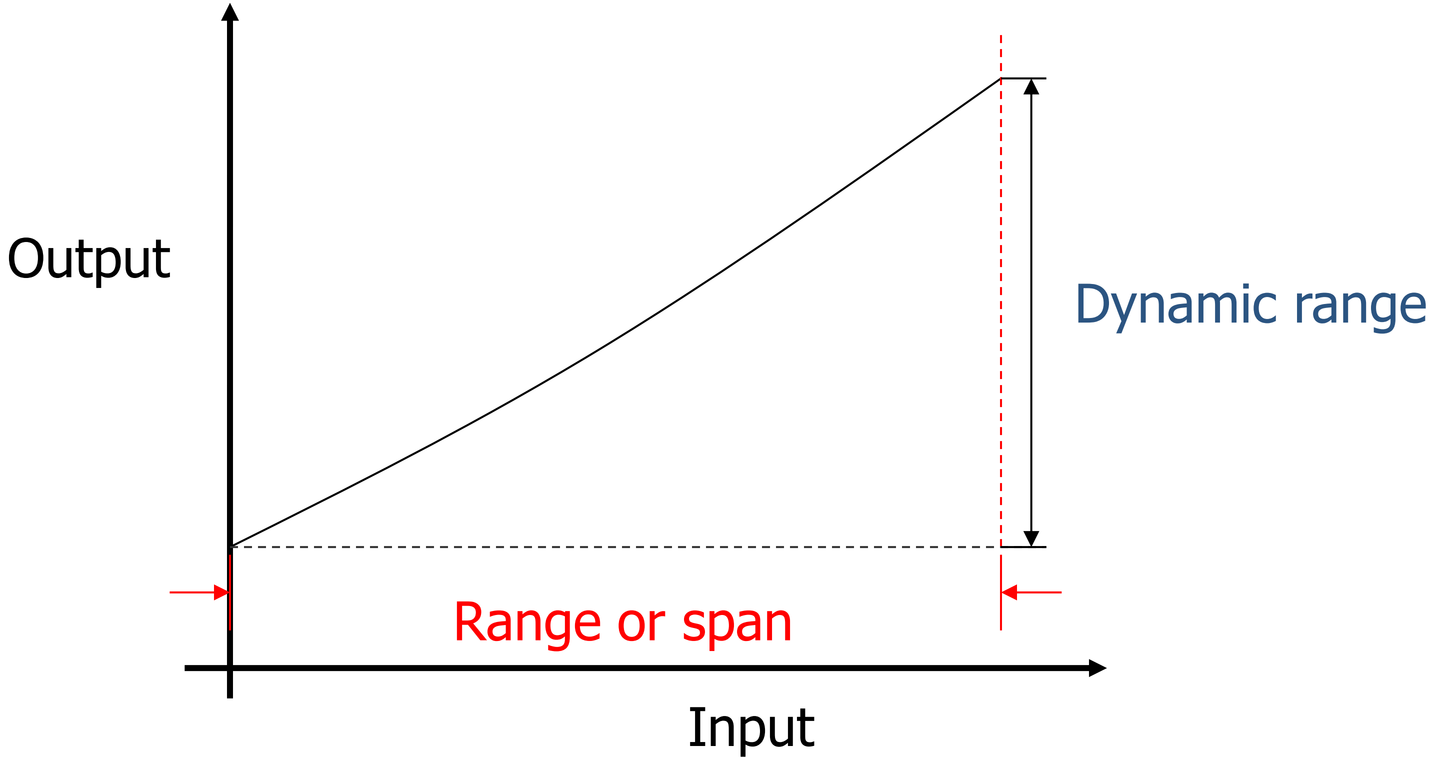
- **Accuracy:**
  - The *accuracy* of an instrument is a measure of how close the output reading of the instrument is correct.
  - Usually indicated in terms of *inaccuracy.*
- **Precision:**
  - Precision is a term that describes an instrument’s degree of freedom from random errors.
  - Can be improved by *recalibration.*



Static Characteristics: Definitions (2)

- **Repeatability:**
  - Describes the closeness of output readings when the same input, from same item and using same instrument, is applied repetitively over a *short period of time*, with the *same* measurement conditions.
- **Reproducibility:**
  - Describes the closeness of output readings for the same input when there are *changes* in the method of measurement.
- **Resolution:**
  - The minimum change in the input measurand that produces an observable change in the instrument output.

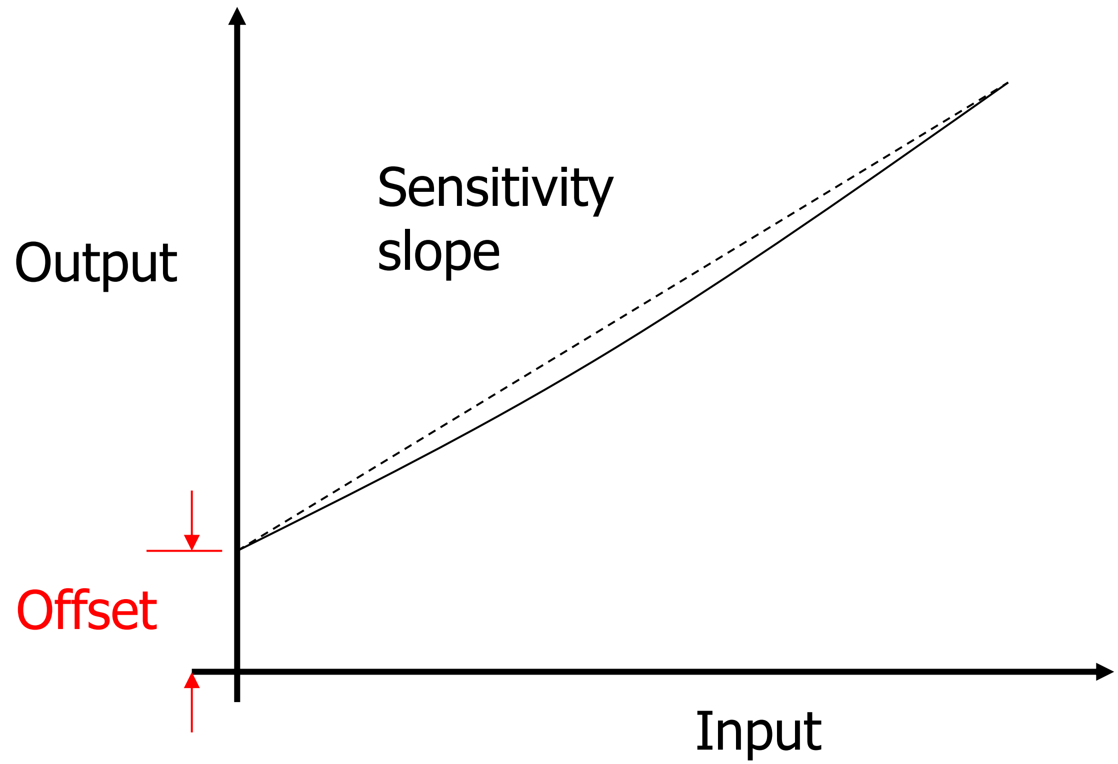
Static Characteristics: Dynamic Range



- Dynamic range: is the maximum and minimum value range within the input range (or input span).

Static Characteristics: Offset & Bias

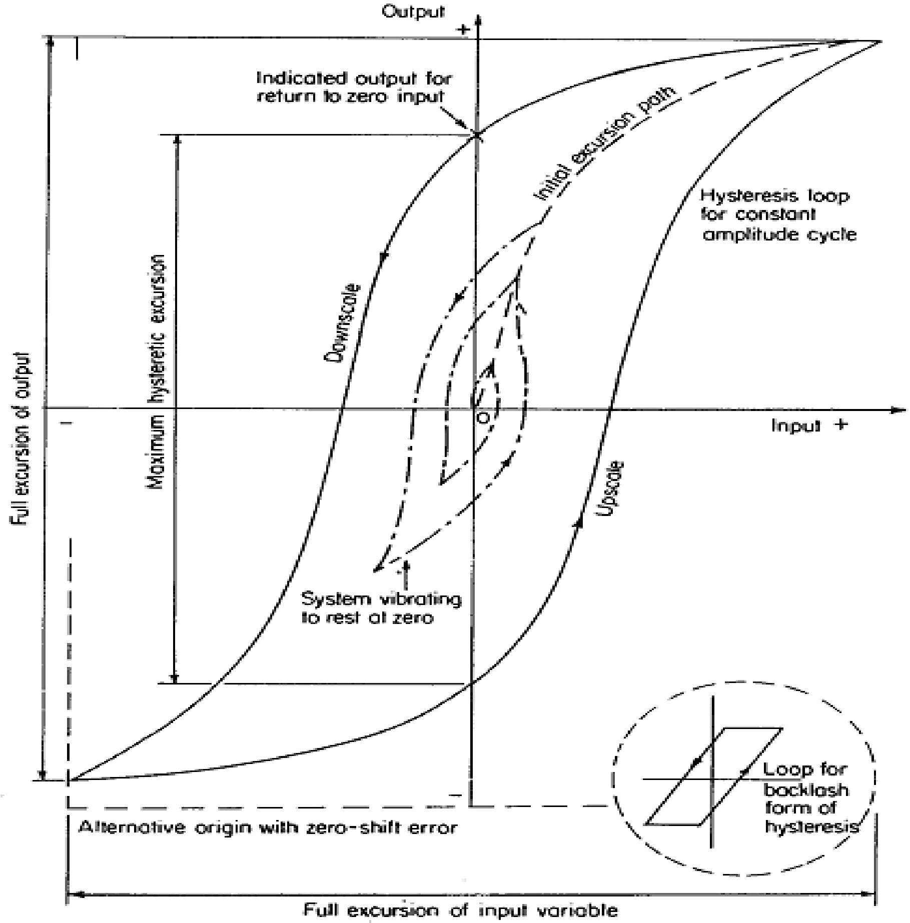
- Offset: is the output reading of the sensor without any input value.
- Bias: is a value which intentionally added to the sensor's output.



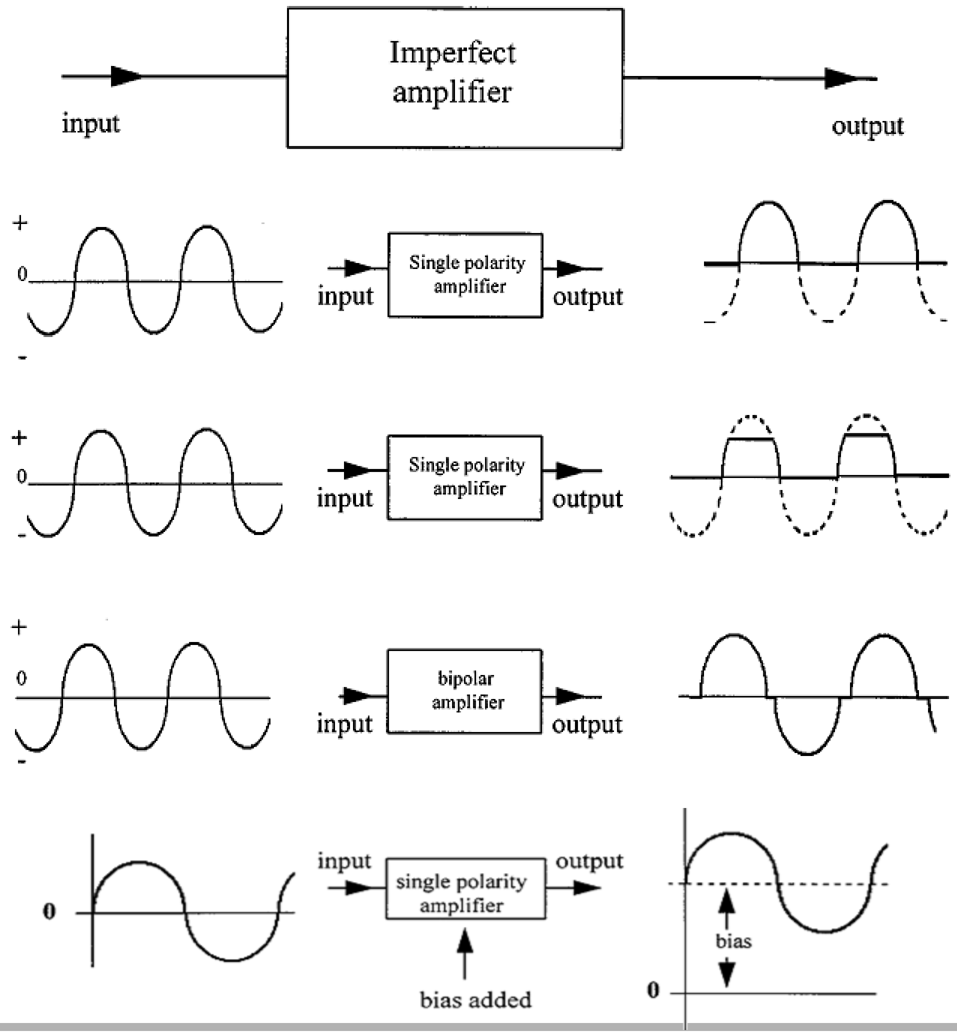
Static Characteristics: Hysteresis and Backlash

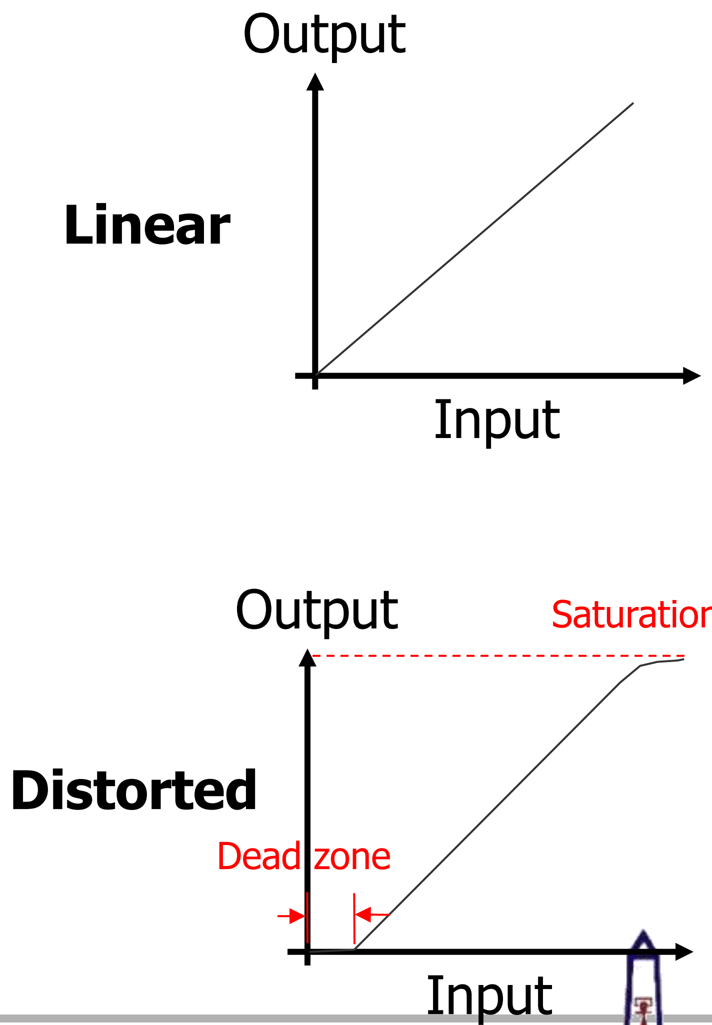
- **Hysteresis:** when the value of output is affected by the direction of the change of the input.

- **Backlash:** when the output has sudden changes with the input



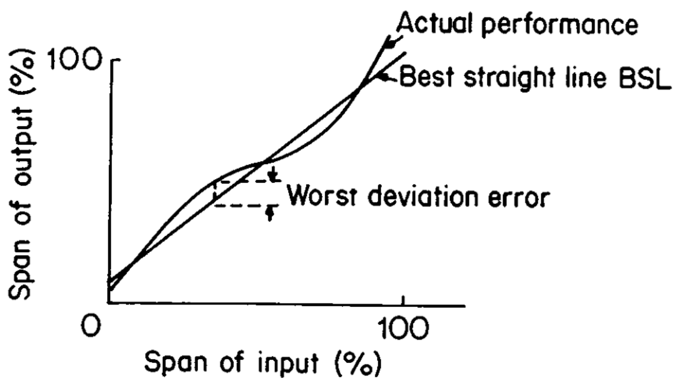
Static Characteristics: Saturation and dead-zone

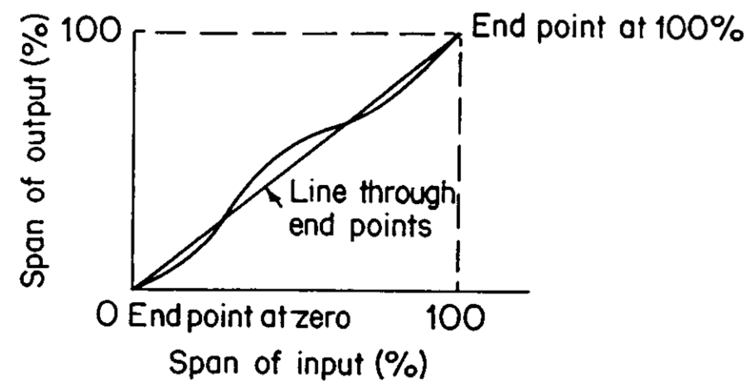


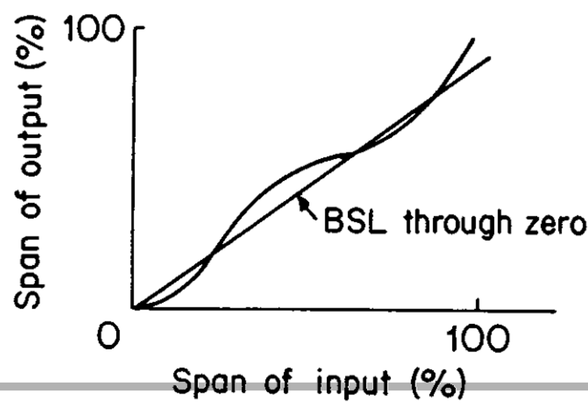


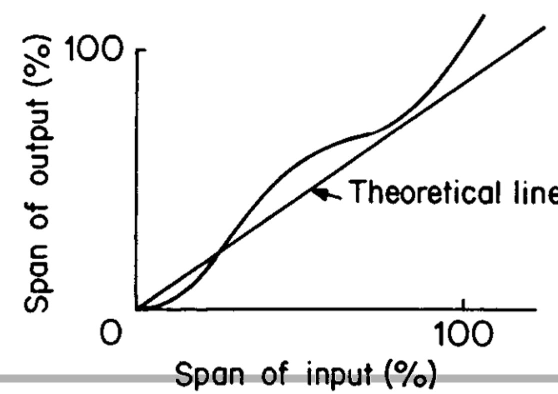
Static Characteristics: Nonlinearity

- Linearity: it is the general term used to describe how close the actual response is compared with the straight-line approximation.









Static Characteristics of Sensors: Nonlinearity

- For nonlinear systems, linearization can be done using Taylor's series:

Taylor series of a function *f(x)* around point (*a*) is:

$$f(x) = f(a) + \frac{f'(a)}{1!}(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \cdots$$

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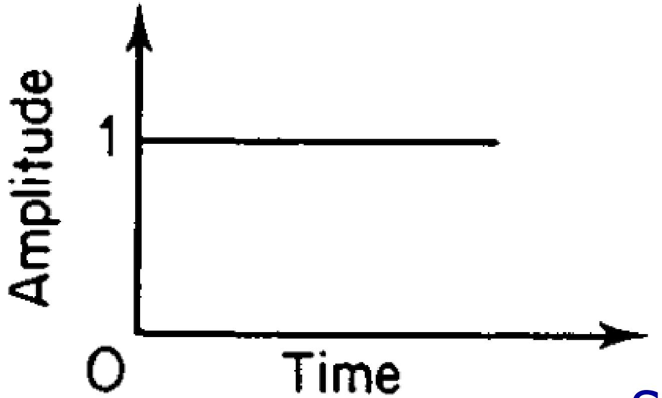
Dynamic Characteristics of Sensors:

- The dynamic characteristics of a measuring instrument describe its behavior between the time a measured quantity changes value and the time when its output attains a steady value in response.
- The behaviour of the sensor is described using a time-varying differential equation:

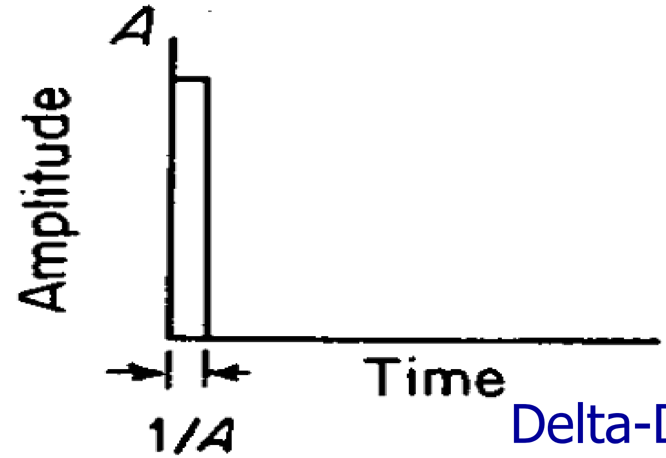
$$a_n \frac{d^n q_0}{dt^n} + a_{n-1} \frac{d^{n-1} q_0}{dt^{n-1}} + \cdots + a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$

- The solution depends on the order of the characteristic equation and the variation of q_i with time.
- Laplace transform is a very good tool for characteristic equation solution if it a linear differential equation.

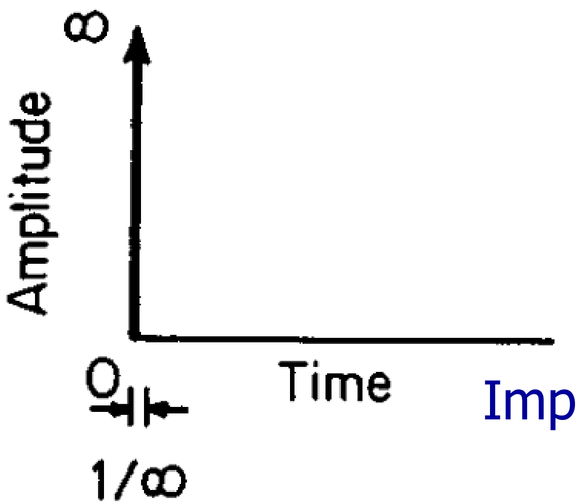
Dynamic Characteristics: Important inputs



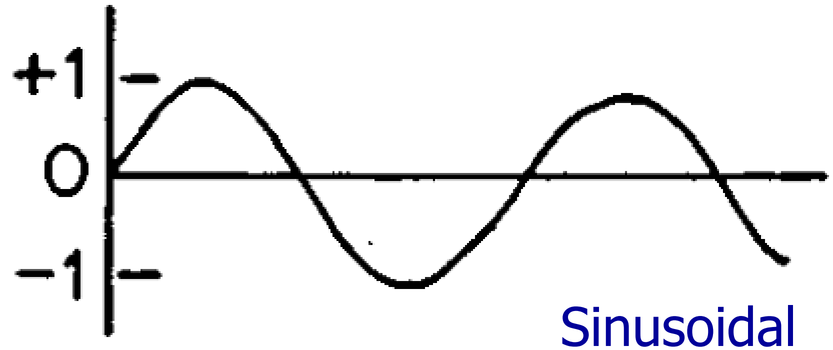
Step



Delta-Dirac



Impulse



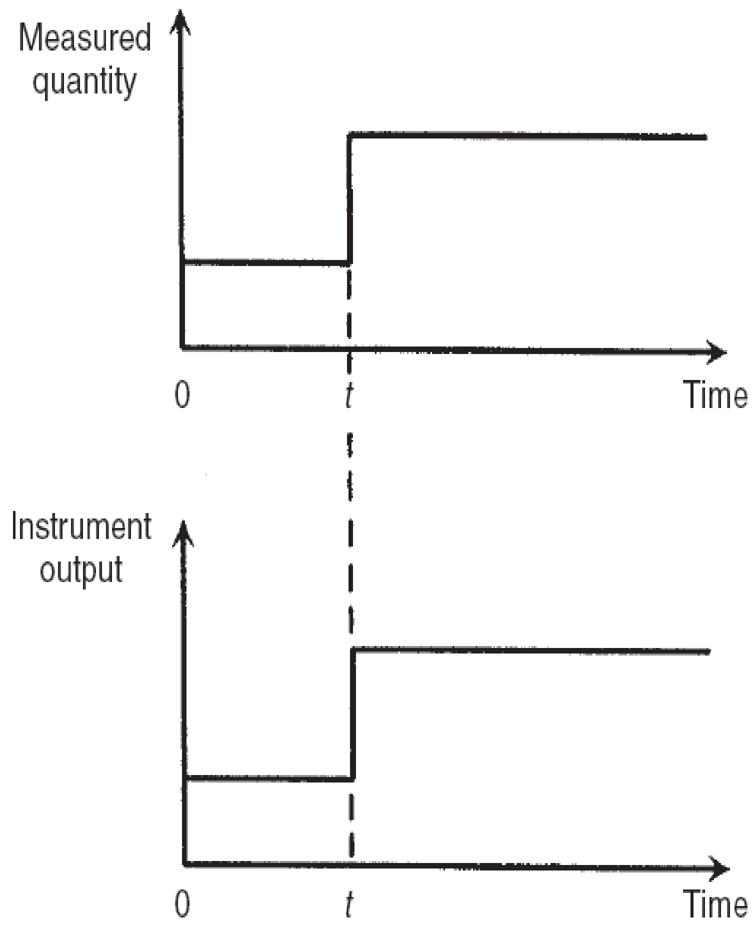
Sinusoidal

Dynamic Characteristics: System response

Order	Characteristic Equation	Transfer function (Y(s)/X(s))
0	$a_o y$	$1/a_o$
1^{st}	$a_1\, dy/dt + a_o y$	$1/(\tau s+1)$
2^{nd}	$a_2\, d^2y/dt^2 + a_1\, dy/dt + a_o y$	$1/(\tau_1 s+1)\,(\tau_2 s+1)$
n^{th}	$a_n\, d^ny/dt^n + a_{n-1}\, dy^{n-1}/dt^{n-1} + \ldots + a_o y$	$1/(\tau_1 s+1)\,(\tau_2 s+1)\ldots(\tau_n s+1)$

Dynamic Characteristics: Zero-order system

Following a step change in the measured quantity at time t, the instrument output moves immediately to a new value at the same time instant t



$$q_o = k\, q_i$$

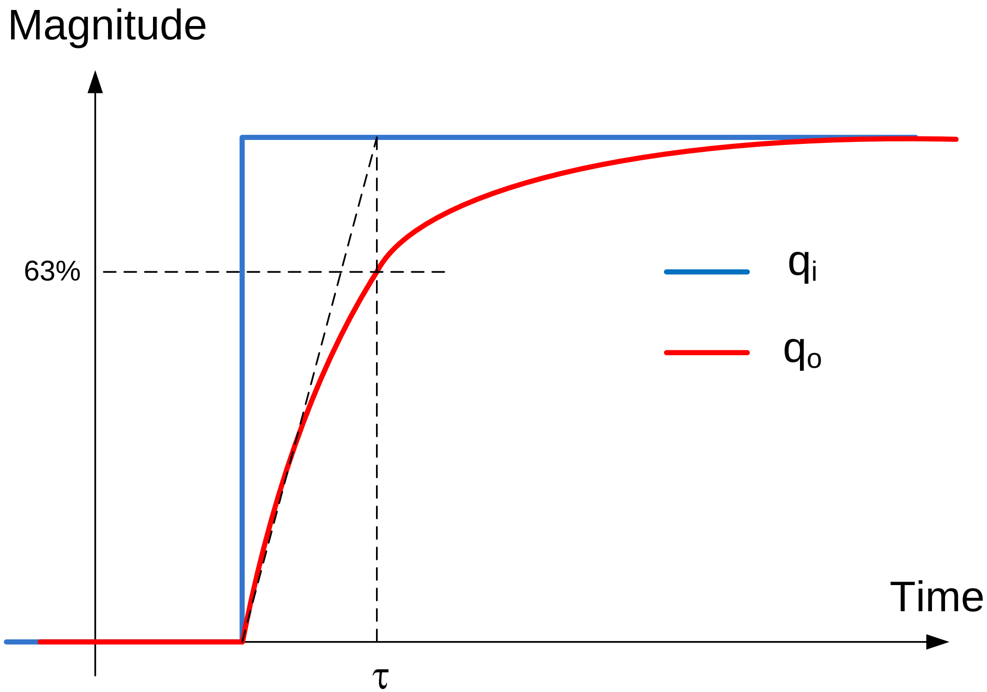
No energy storage elements.

Example: A potentiometer measuring distance/motion

Dynamic Characteristics: First-order system

$$a_1 \frac{dq_o}{dt} + a_o q_o = b_o q_i$$

$$q_o = \frac{k \cdot q_i}{1 + \tau \cdot D}$$



where:

- k = static senstivity = b_o/a_o
- τ = time constant = a_1/a_o

Example: Liquid glass thermometer

One energy storage elements.

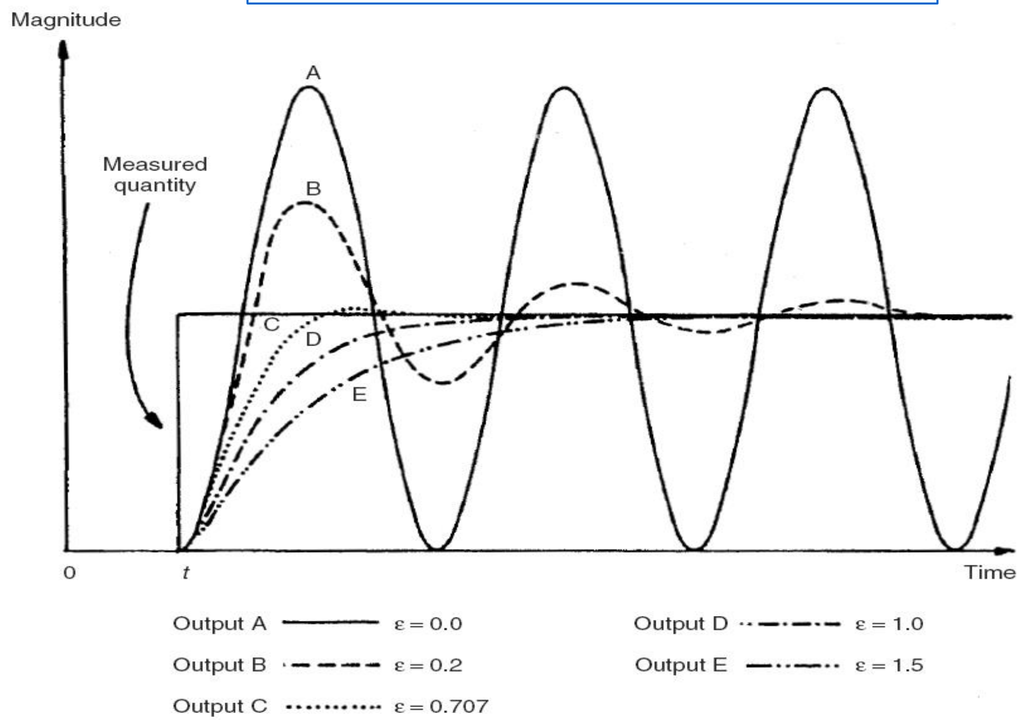
Dynamic Characteristics: Second-order system

$$a_2 \frac{d^2 q_o}{dt^2} + a_1 \frac{dq_o}{dt} + a_o q_o = b_o q_i$$

$$q_o = \frac{k \cdot \omega_n^2 \cdot q_i}{D^2 + 2\zeta\omega_n D + \omega_n^2}$$

where:

- $k = b_o/a_o$
- $\omega_n = \sqrt{(a_o/a_2)}$
- $\zeta = a_1/[2\sqrt{(a_o a_2)}]$



- Example: Inertial Sensors

Two energy storage elements.