BIRZEIT UNIVERSITY
Department of Mechanical and
Mechatronics Engineering

ENMC3361
Sensors and Instrumentation

Lecture #1

Ihab Abu Ajamieh, PhD.

Introduction

Course details

Instructor: *Asst. Prof*. Ihab Abu Ajamieh.

Email: iabuajamieh@birzeit.edu

Time: Tue 10:00 – 11:15 Aggad 307

Thu 10:00 – 11:15 Aggad 307

Office hours: You can email me.

Lectures format: will include theory and some class discussion

Introduction

Course description:

- This course focuses on methods of sensing, physical principles of sensors operations and practical designs.
- It covers the selection of best suited sensors for a specified problem regarding range, accuracy, dynamic behavior, environment requirements etc...

Introduction

Course description:

- Introduction to Measurement.
- Instrument Types (passive, active, analog, digital…etc.).
- Performance Characteristics (static and dynamic).
- Errors Measurement.
- Calibration of Measuring Sensors and Instruments.
- Measurement Noise and Signal Processing (filter design, ADC/DAC, amplifier…etc.).
- Electrical Indicating and Test Instruments.
- Variable Conversion Elements (dc and ac bridge circuit…etc.).
- Signal Transmission, display, recording and presentation of Measurement Data.
- Measurement Reliability and Safety Systems.
- Measurement Sensors and Instruments (Capacitive and resistive, strain gauge, optical, magnetic… etc.).
- Sensors Based Physical Variable Measurement.
- System Analogy and System Conversion Form.

Introduction

Course outline:

1. **Grade:**
   - Project: 35 %
   - *Assignments: 15 %* ????
   - Mid Exam: 20 %
   - Final Exam: 30 %

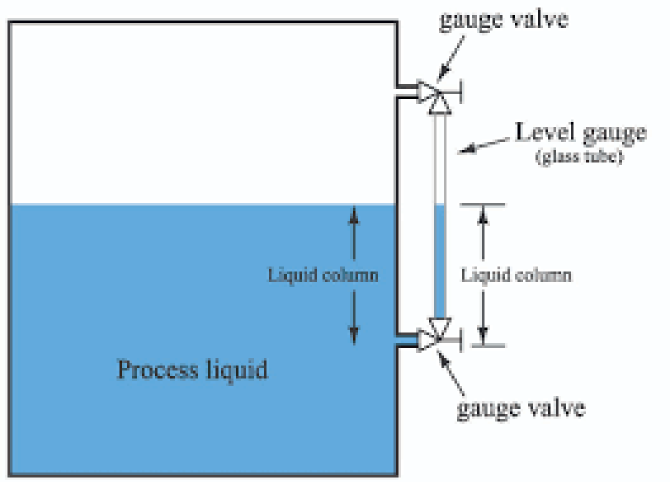
2. **Project:**
   - Free to choose your group.
   - Groups are free to choose projects.

3. **Course timetable:**

   Available in the course syllabus.

Introduction

Project:



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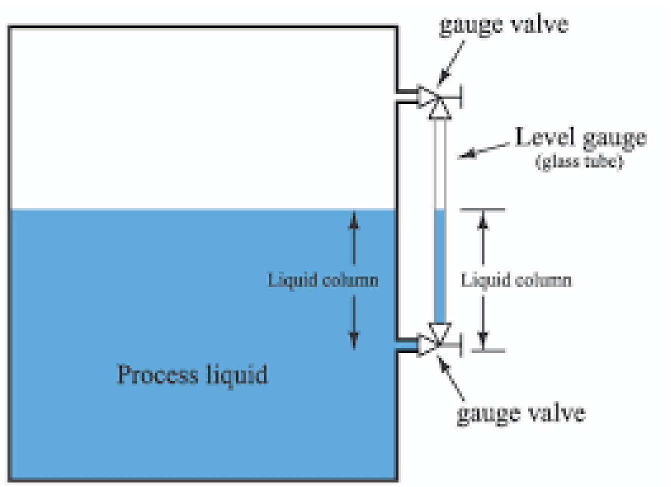

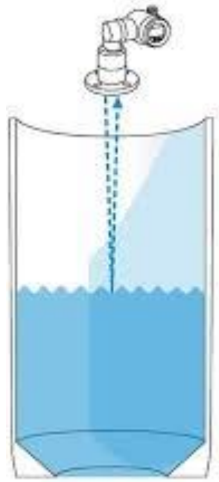

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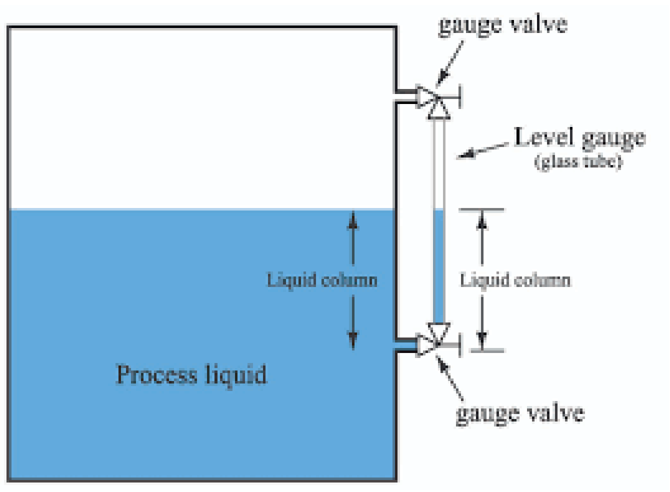

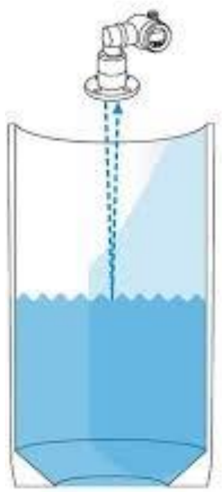

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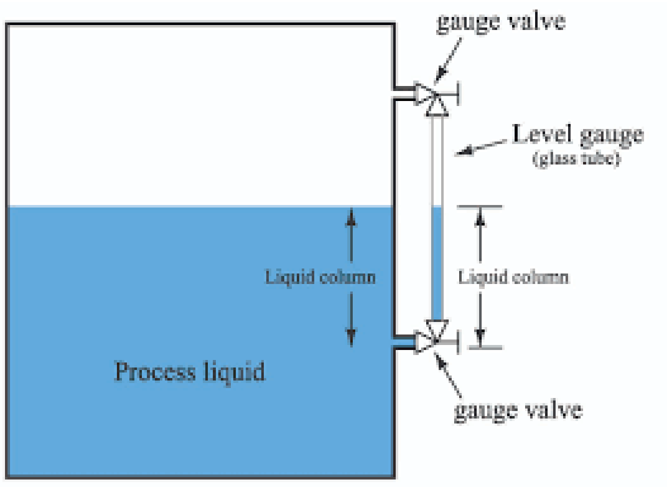

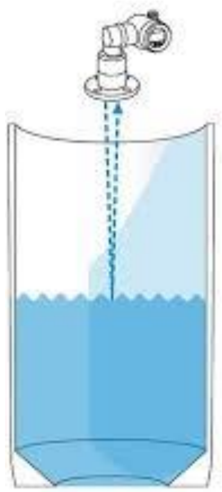

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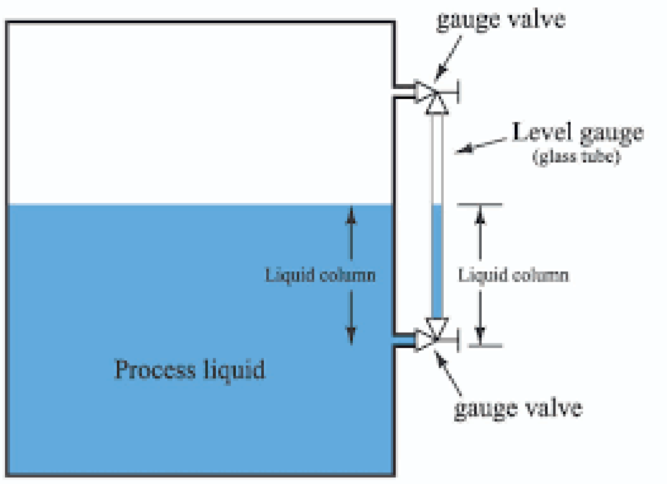

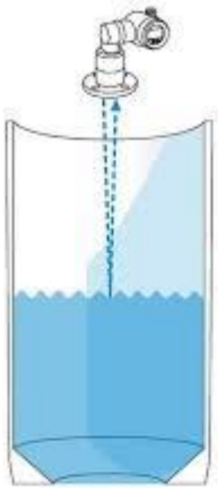

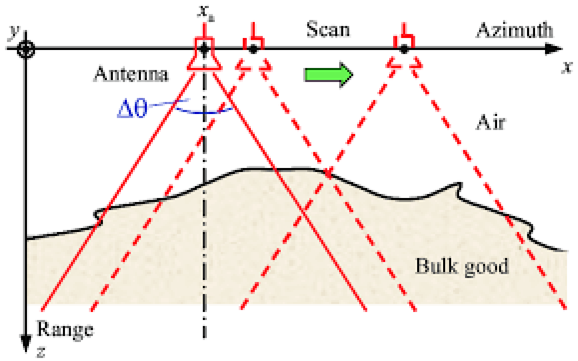

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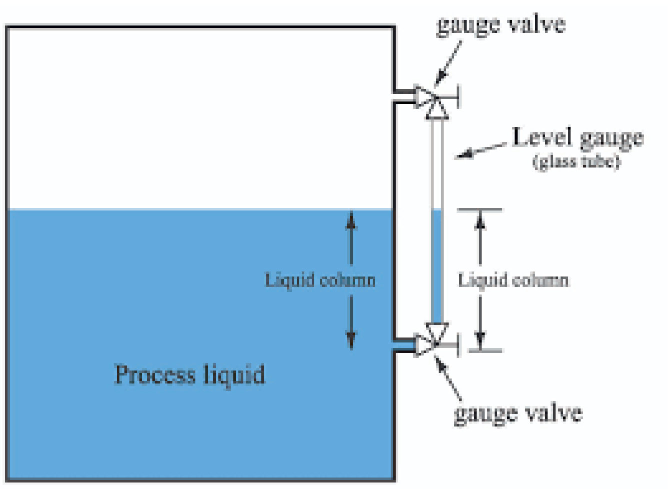

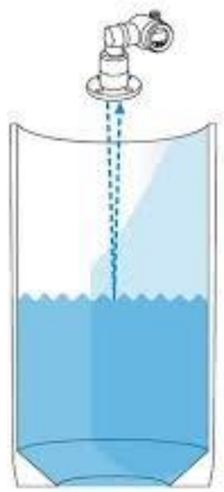

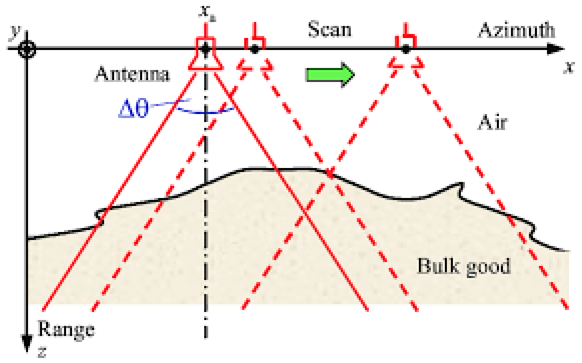

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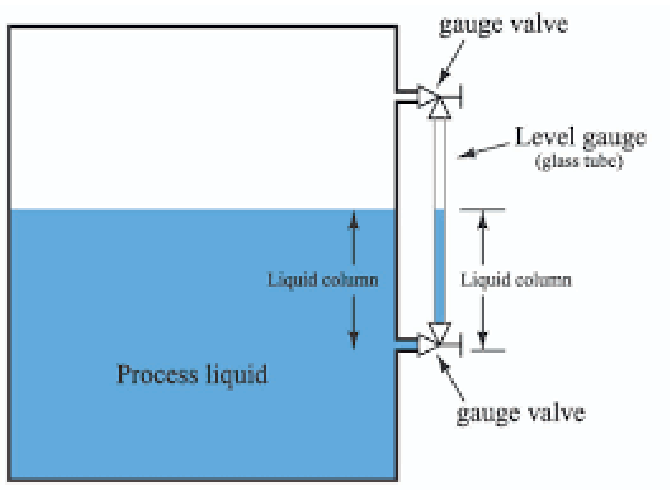

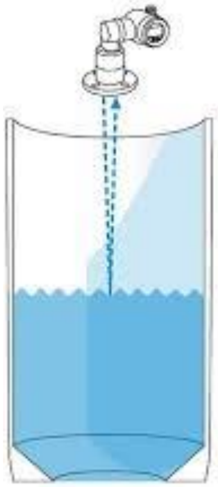

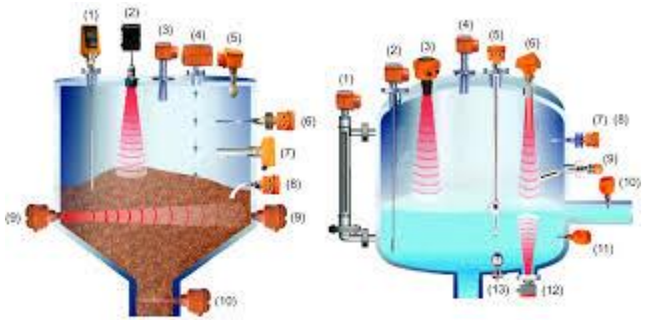

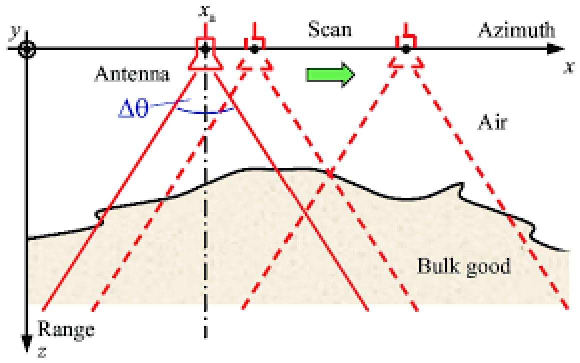

Introduction

Purpose of the Course:

Usually knowledge of sensors and how to design a sensor network is left as an on-the-job training.

The trend in the industry is that new employees are expected to contribute and work from the first day!

Introduction

Purpose of the Course:

This course will provide you with a fundamental knowledge about different sensing technologies and their implementation.

1. **Be Familiar with different types of sensors:**

   Recognize and explain at a basic level fundamental physical principle of sensing, including electro-chemical, Electromagnetic, photoelectric, thermoelectric, piezoelectric, and pyroelectric transduction effects.

2. **Be able to select appropriate sensors :**

   Based on measurement requirements for the engineering and research tasks

3. **Create calibration procedures.**

4. **Select and implement basic digital filters:**

   Based on sensor characteristics.

Introduction

Project:

1. Think about an application, or engineering task
2. Develop an implementation using at least two sensors, suitable for the suggested application scenario.
3. Choose any sensor type suitable to the application – No limit.

A lecture (after two weeks) will be about how to wright the project report.

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Sensors and Instrumentation

Lecture #2

Ihab Abu Ajamieh, PhD.

Introduction

Course details

Instructor: *Asst. Prof*. Ihab Abu Ajamieh.

Email: iabuajamieh@birzeit.edu

Introduction

Concepts:

What is an intelligent System?

- A system that would alter its behavior based on changes to its environment or internal changes.
- Can be simple such as a water tank on a toilet or as complex as an autonomous vehicle.

Major functions in engineering?

- Design of equipment and processes.
- Proper operation and maintenance of equipment and processes.

Both of these functions require measurements.

What is measurement?

An experiment that compares unknown quantity with a standard of the same quantity and consists of:

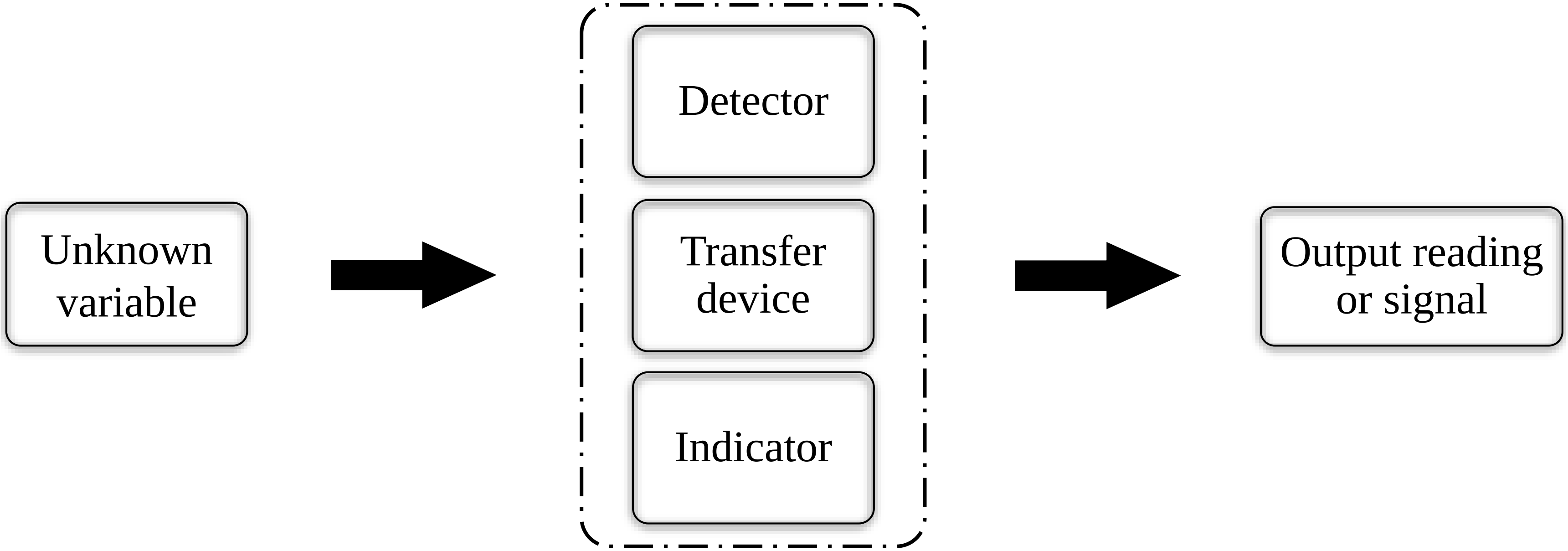
- An observable variable.
- A sensor generates a signal.

It converts a physical parameter to a meaningful numbers.

Instruments

Concepts:

Measuring Instrument



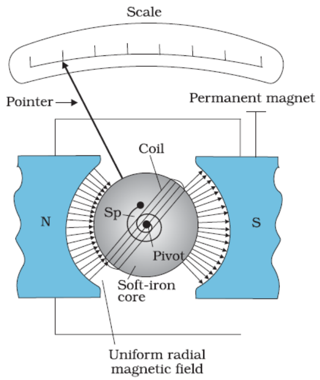
Instruments

Concepts:

Measuring Instrument

- Absolute Instruments — No Calibration required
- Secondary Instruments — Calibration required
  - Operation Mode
    - Analog
    - Digital

Tangent Galvanometer



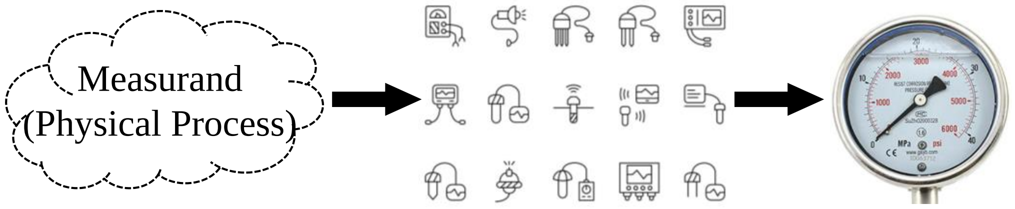
$$B = \frac{\mu_o\, n\, I}{2a} \quad \text{But:} \quad B = B_h \tan\theta$$

$$\rightarrow B_h \tan\theta = \frac{\mu_o\, n\, I}{2a}$$

Definitions

➢ **Sensor:** (Mostly in Europe)

A device that responds to stimuli (or an input) by generating processable outputs (*generally an electrical signal*).

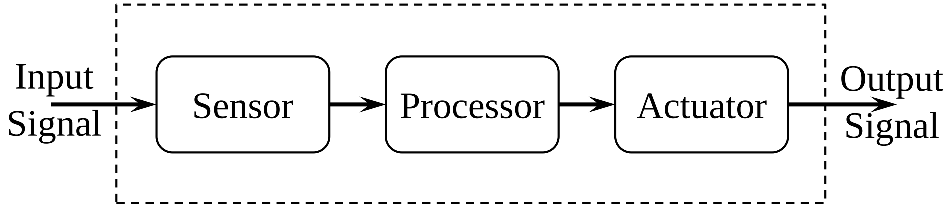


➢ **Transducer:** (Mostly in North America)

- A device that converts a signal from one physical form to a corresponding signal having a different physical form.
- Energy converter or modifier.
- It is a sensor and actuator.

Sensor (Input transducer) - Microphone
Actuator (output transducer) - Speaker.

Physical form: *mechanical, thermal, magnetic, electric, optical, chemical…*

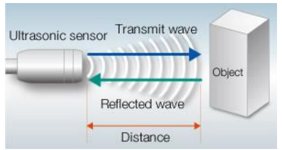


Sensors

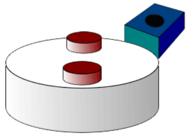
Examples:

contact → switch

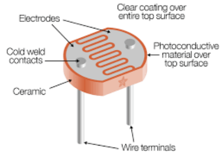
distance → ultrasound, radar, infra red



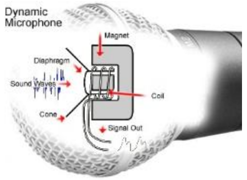
magnetic field → compass, hall effect



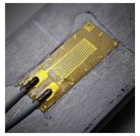
light level → photo cells, cameras



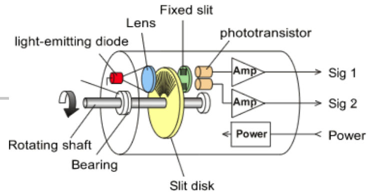
sound level → microphones



strain → strain gauges

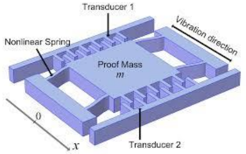


rotation → encoders, switch, potentiometer

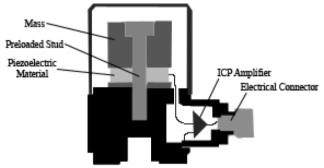


temperature → thermometer

Gravity → inclinometers



acceleration → accelerometers



flames → UV detector

Sensor Types

Power wise:

Passive

- Does not need any additional energy source
- Directly generates an electric signal in response to an external stimulus.
- The input stimulus energy is converted by the sensor into the output signal.
- Most of passive sensors are direct sensors as we defined them earlier.
- **Examples**: Thermocouple, Photodiode, and piezoelectric sensor.

Active

- Requires external power for its operation, which is called an excitation signal.
- The signal is modified by the sensor to produce the output signal.
- **Examples**: Temperature sensitive resistor - Thermistor.
  - It does not generate any electric signal.
  - But by passing an electric current through it (excitation signal).
  - Its resistance can be measured by detecting variations in current and/or voltage across the thermistor.
- **Other Examples:** Scanning electron microscopes, radar, GPS, blood pressure sensor, X-ray, infrared and seismic

Sensor Types

Application wise:

Mechanical Sensors:

A change in a device or material as a result of an input that causes mechanical deformation of that device or material.

Examples: *Accelerometer, Strain gauge, Pressure, Force, Displacement, …etc*.

Semiconductor Sensors:

Semiconductor sensors are low in cost, reliable, low in power consumption, long operational lifespan, and small form factor.

Examples: *Gas sensors, Temperature sensors, Magnetic sensors, Optical sensors, Displacement, …etc*.

Electrochemical Sensors:

Electrochemical sensor works on the principle of measuring an electrical parameter of the sample of interest. It composes of a sensing electrode, a reference electrode, and a counter electrode, all are placed in contact with a liquid or a solid electrolyte.

Examples: *pH, conductivity, dissolved ions, dissolved gases sensors (at low-temperature <140 °C).*

Measuring of exhaust gases and molten metals (at high temperatures >500 °C).

Biosensors:

Biosensors use biochemical mechanisms to identify an analyte of interest in chemical, environmental (air, soil, and water), and biological samples (blood, saliva, and urine). When an analyte comes into contact with the immobilized biological material, the sensor produces a measurable output, such as a current, change in mass, or a change in color.

Sensor Types

Mode of operation:

Analog signal:

. signals that vary in a continuous fashion and take an infinite number of values in any given range.

Digital signal:

signals that vary in discrete steps and thus take only finite different values in a given range.

Sensors

Concepts:

Sensing is the most difficult task for any “intelligent systems”

What is so difficult about sensing?

- We expect a sensor to provide an absolute truth – unachievable.
- Can you say with 100% certainty what the temperature of the room is?
- Sensors have noise, calibration error, drift, malfunctions, etc.

Sensing

Concepts:

- Sensing is the most difficult task for any “intelligent systems”
- The sensing process proceeds in the following steps:

Input Signal Physical Phenomenon → Sensor → Signal conditioning → Digitization → Noise Filter → Convert to measured parameter → Data Analytics → Used as a feedback in a loop

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Sensors and Instrumentation

Lecture #3

Ihab Abu Ajamieh, PhD.

Closing

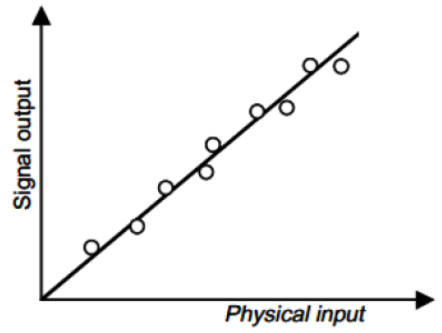
Terminology:

Measured or measurand:

Any physical object quantity or property that can be measured.

Sensor Calibration:

Presenting a fully defined relationship that receives the input stimulus and computes the output signal along the desirable range. This relationship is called the transfer function.



Transducer:

Device that converts one form of energy to another.

Sensor:

Electronic transducer that converts physical quantity into an electrical signal.

Actuator:

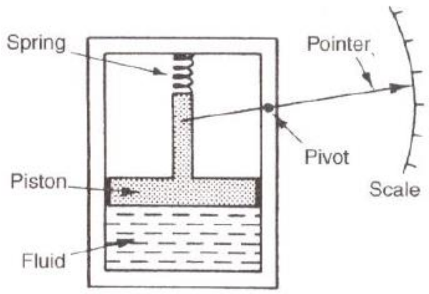
Electronic transducer that converts electrical energy into mechanical energy

Sensor Types

Power wise:

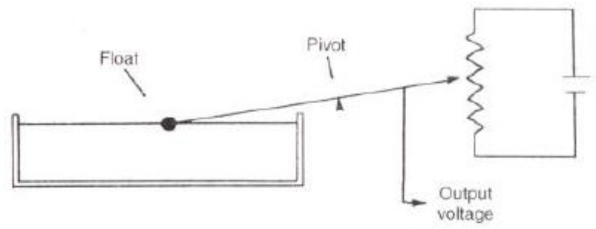
Passive

Examples: Thermocouple, Photodiode, and piezoelectric sensor, pressure-measuring device



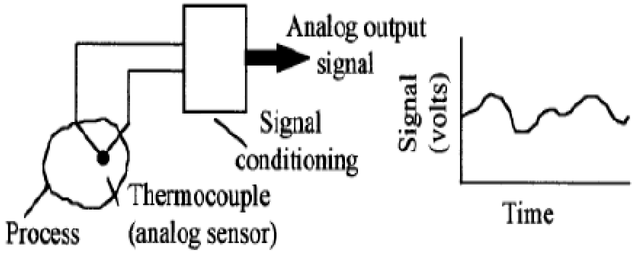
Active

Examples: radar, GPS, Float-type petrol tank level indicator



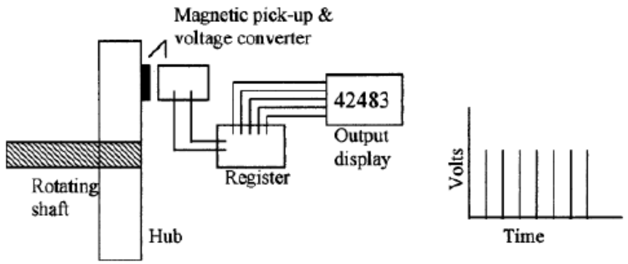
Analog

Examples: pressure gauge deflection-type, thermocouple.



Digital

Examples: Revolution counter, Encoder.



Sensing

Sensor Characteristics:

Input Signal Physical Phenomenon → Sensor → Signal conditioning → Digitization → Noise Filter → Convert to measured parameter → Data Analytics → Used as a feedback in a loop

- To be able to design all these processing steps it is necessary to understand the behavior of the sensing system
- This behavior patterns can be categorized as either static or dynamic characteristics of the sensing system

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Minimum Detectable signal
- Sensitivity
- Linearity
- Selectivity
- Hysteresis
- Response and recovery time

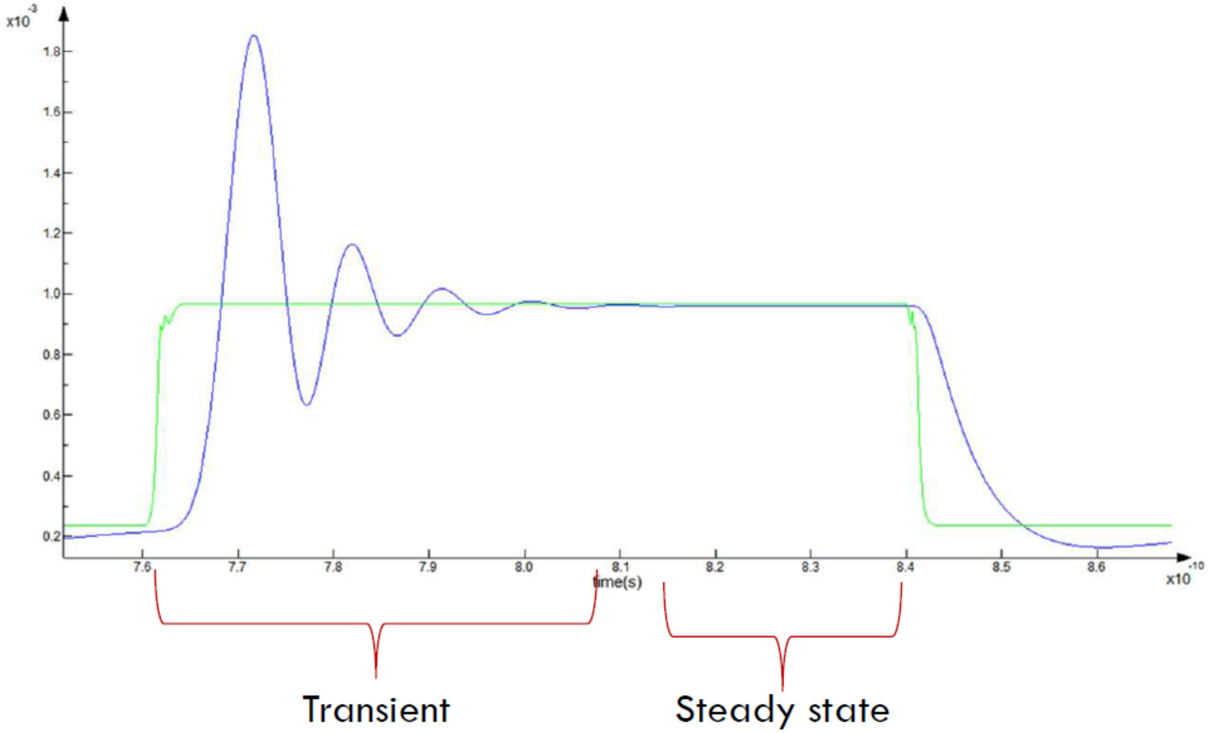
Dynamic Characteristics

- Rise time
- Peak overshoot
- Time to first peak
- Settling time
- Damping ratio

Sensor Characteristics

Static Characteristics:

➢ Static characteristics are those that can be measured after all transient have been stabilized to their final or steady state values.



Static Characteristics

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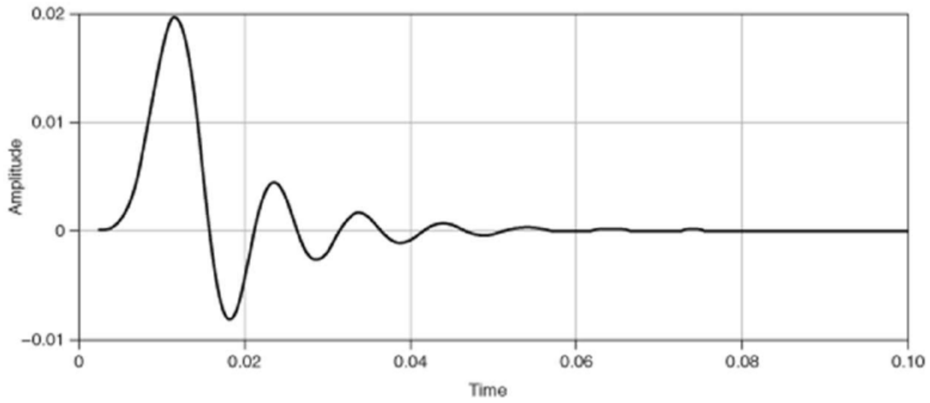
Sensor Characteristics

Dynamic Characteristics:

- Dynamic characteristics describes the sensing system's transient properties in the presence of changing measurand (variable input).
- The reason for dynamic characteristics is the presence of energy-storing elements:
  - Inertial: masses, inductances.
  - Capacitances: electrical, thermal
- Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:



Dynamic Characteristics

- Rise time
- Peak overshoot
- Time to first peak
- Settling time
- Damping ratio

Sensor Characteristics

Static Characteristics:

Accuracy:

- Accuracy of a sensing system represents the correctness of its output in comparison to the actual value of a measurand.

- To assess the accuracy, either the system is benchmarked against a standard measurand or the output is compared with a measurement system with a superior accuracy.

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Minimum Detectable signal
- Sensitivity
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- Selectivity
- Hysteresis
- Response and recovery time

Sensor Characteristics

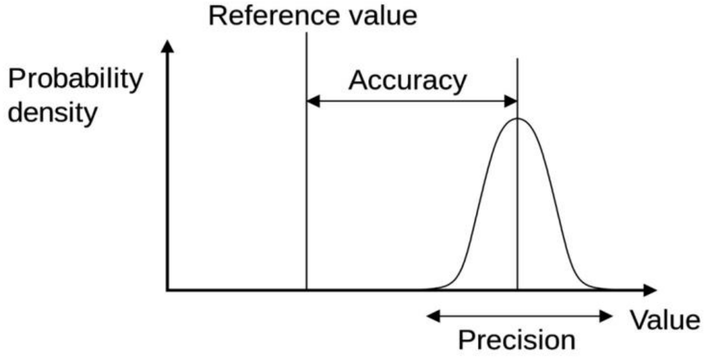
Static Characteristics:

Accuracy:

- Using this definition it is unclear if the accuracy is the mean error (systematic error) or the combination of random and systematic error
- To assess the accuracy, either the system is benchmarked against a standard measurand or the output is compared with a measurement system with a superior accuracy.

$$Accuracy_1 = X_T - Average\ (X_1\text{-}X_n)$$

$$Accuracy_2 = [X_T - Average\ (X_1\text{-}X_n)]+3\sigma$$



- In sensor data sheet the accuracy is usually represented as a % of Full Scale (FS) but can also be absolute value.

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Minimum Detectable signal
- Sensitivity
- Linearity
- Selectivity
- Hysteresis
- Response and recovery time

Sensor Characteristics

Static Characteristics:

Accuracy:

➢ What is the actual accuracy of the this mass flow meter under the following conditions?

- Temperature 25C above calibration point.
- Pressure at 15 PSI above calibration point.

Answer:
The pressure and temperature coefficients have a uniform distribution. This will mean that the errors from the T and P coefficients would be simply added.

$$E=1\% + 0.05*25 + 0.01*15 = 2.4\%$$

Accuracy
Standard: +/- 1.0% of full scale including linearity under calibration conditions
(+/- 2.0% of full scale for 180M from 201 to 300 slpm)
High Accuracy Calibration: +/-0.5% of reading + 0.3% of full scale at calibration conditions

Dial-A-Gas
+/- 1.0% of full scale in all 10 standard gases

Repeatability
+/- 0.2% of full scale

Temperature Coefficient
+/- 0.025% of full scale per °F (0.05% of full scale per °C), or better

Pressure Coefficient
+/- 0.01% of full scale per psi (0.15% of full scale per bar), or better

Static Characteristics

- Accuracy
- Trueness
- Precession
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- Range
- Resolution
- Minimum Detectable signal
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The End

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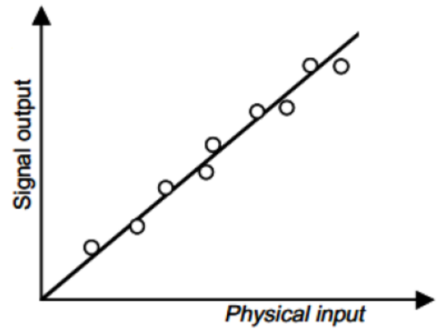

Transducer:

Device that converts one form of energy to another.

Sensor:

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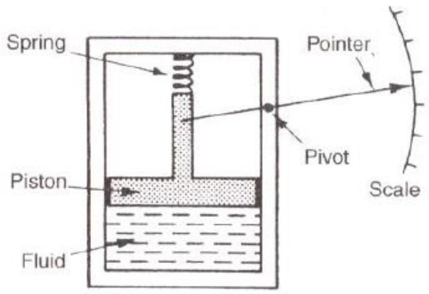
Sensor Types

Power wise:

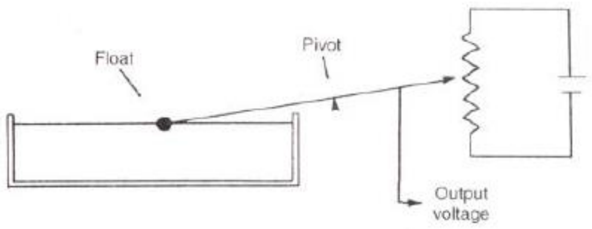
Passive

Examples: Thermocouple, Photodiode, and piezoelectric sensor, pressure-measuring device



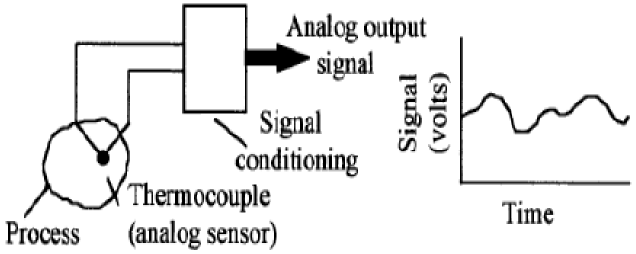
Active

Examples: radar, GPS, Float-type petrol tank level indicator



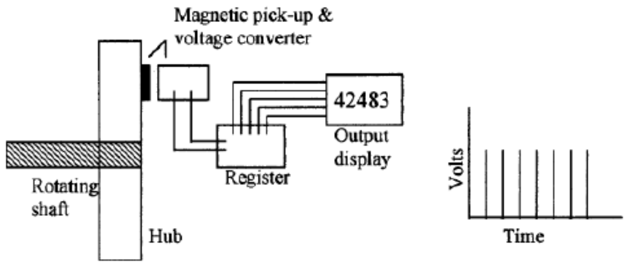
Analog

Examples: pressure gauge deflection-type, thermocouple.



Digital

Examples: Revolution counter, Encoder.



Sensing

Input Quantities:

Desired Inputs:

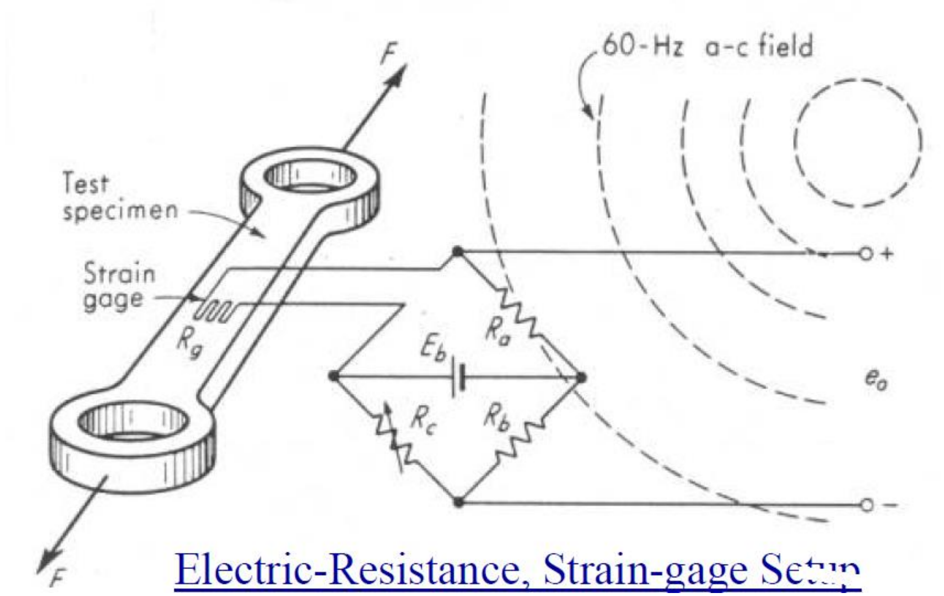
These are quantities that the instrument is specifically intended to measure.

Interfering Inputs:

These are quantities to which the instrument is unintentionally sensitive.

Modifying Inputs:

These are quantities that cause a change in the input-output relation for the desired and interfering inputs.



Electric-Resistance, Strain-gage Setup

Desired Inputs: Strain
Interfering Inputs: 60 Hz magnetic field, gage temperature
Modifying Inputs: Temperature, battery voltage.

Sensing

Input Quantities:

Desired Inputs:

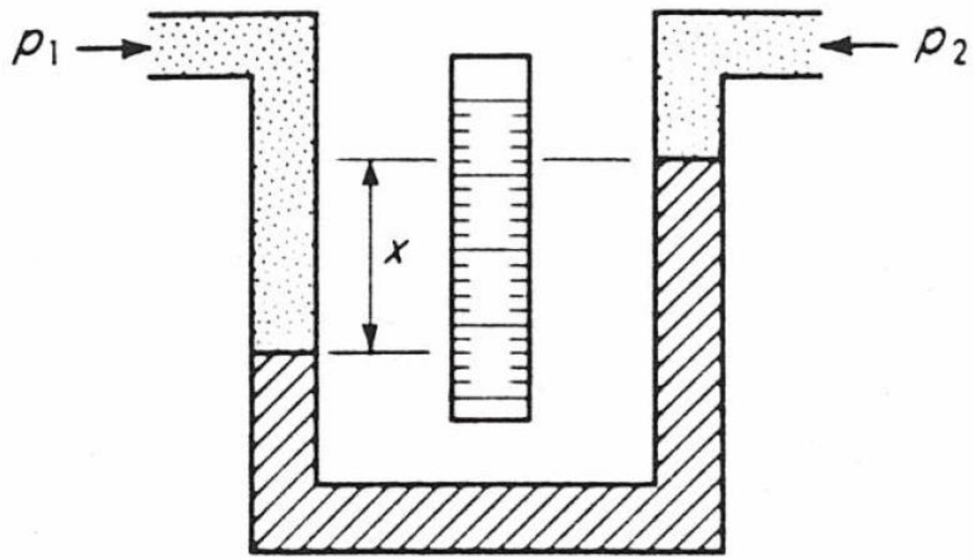
These are quantities that the instrument is specifically intended to measure.

Interfering Inputs:

These are quantities to which the instrument is unintentionally sensitive.

Modifying Inputs:

These are quantities that cause a change in the input-output relation for the desired and interfering inputs.



Desired Inputs: P1 and P2

Interfering Inputs: Acceleration, tilt angle.

Modifying Inputs: Temperature, gravity, tilt angle.

Sensing

Correcting the Interfering and Modifying Inputs:

Inherent Sensitivity:

- The sensing element design should inherently be sensitive to the desired input only.
- This approach requires that the interfering and modifying forces (inputs) be made as nearly zero as possible, to minimize their effect.

High Gain feedback:

These are quantities to which the instrument is unintentionally sensitive.

Corrections of the calculated output:

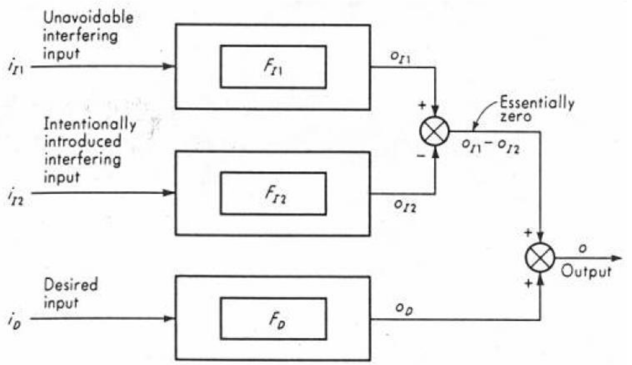
Estimate the magnitude of the interfering and modifying inputs to calculate a correction to the output.

Signal filtering:

Add filters.

Opposing Input:

Add interfering and modifying inputs intentionally, to cancel the unavoidable others.



Sensing

Sensor Characteristics:

Input Signal Physical Phenomenon → Sensor → Signal conditioning → Digitization → Noise Filter → Convert to measured parameter → Data Analytics → Used as a feedback in a loop

- ➢ To be able to design all these processing steps it is necessary to understand the behavior of the sensing system
- ➢ This behavior patterns can be categorized as either static or dynamic characteristics of the sensing system

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Minimum Detectable signal
- Sensitivity
- Linearity
- Selectivity
- Hysteresis
- Response and recovery time

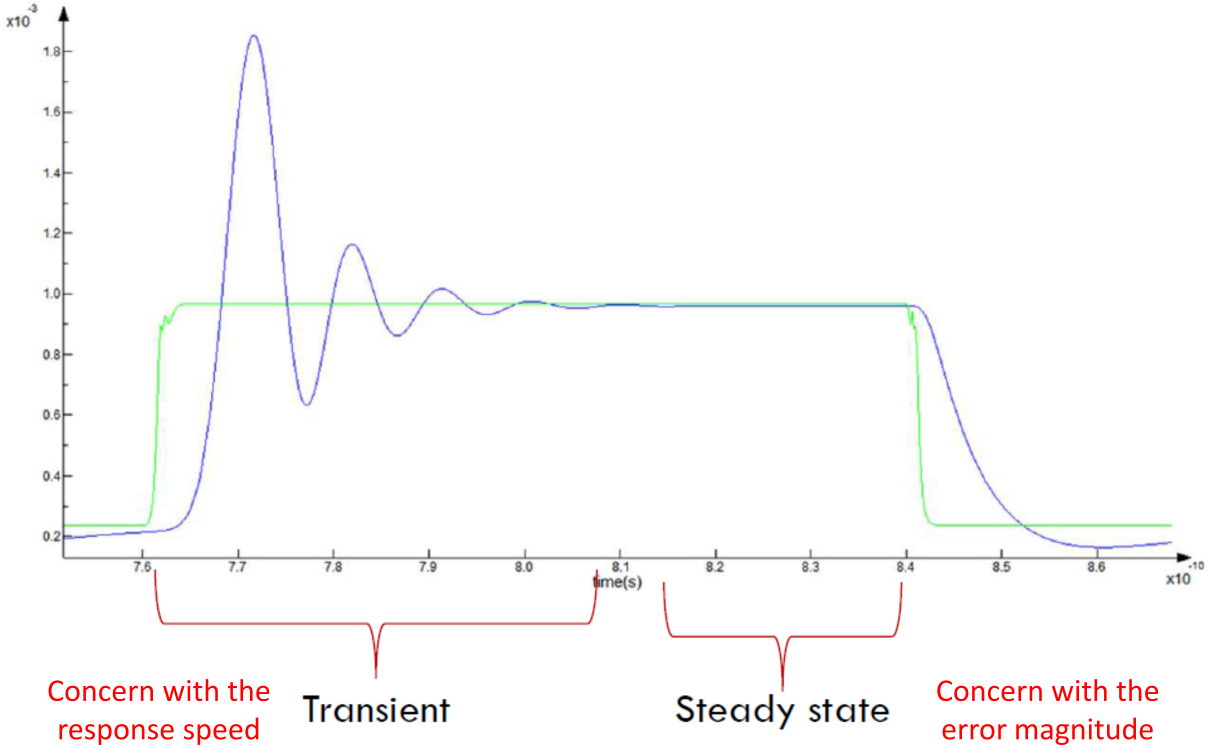
Dynamic Characteristics

- Rise time
- Peak overshoot
- Time to first peak
- Settling time
- Damping ratio

Sensor Characteristics

Static Characteristics:

- Static characteristics are those that can be measured after all transient have been stabilized to their final or steady state values.



Static Characteristics

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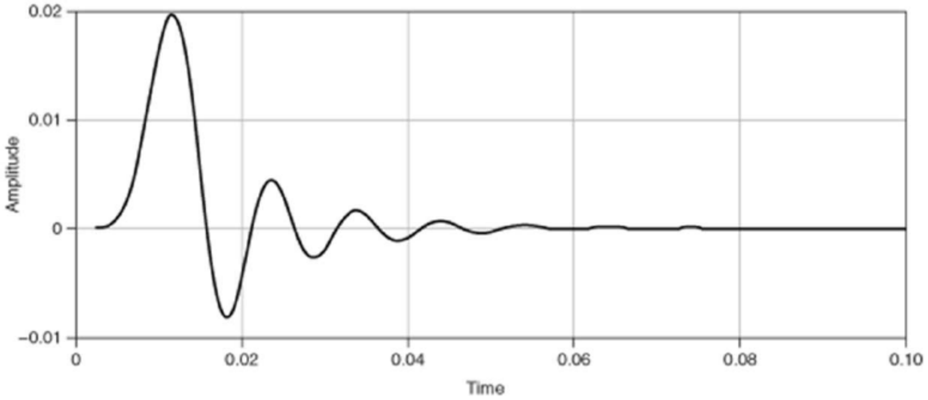
Sensor Characteristics

Dynamic Characteristics:

- ➢ Dynamic characteristics describes the sensing system's transient properties in the presence of changing measurand (variable input).
- ➢ The reason for dynamic characteristics is the presence of energy-storing elements:
  - Inertial: masses, inductances.
  - Capacitances: electrical, thermal
- ➢ Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms.

Dynamic Characteristics

- Rise time
- Peak overshoot
- Time to first peak
- Settling time
- Damping ratio



Sensor Characteristics

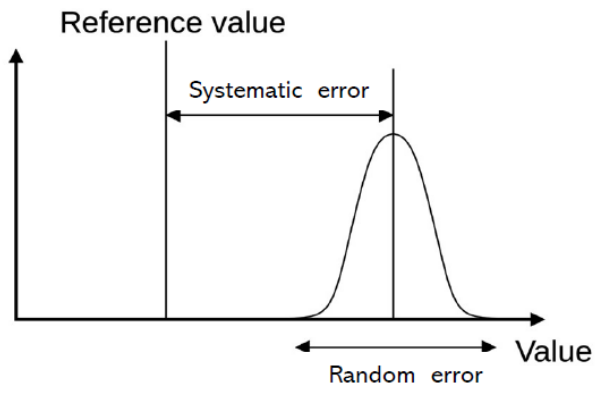
Static Characteristics:

Accuracy:

- Accuracy of a sensing system represents the correctness of its output in comparison to the actual value of a measurand.

  OR/ How much the sensing system gives results close to the True Value of the measurand.

- To assess the accuracy, either the system is benchmarked against a standard measurand or the output is compared with a measurement system with a superior accuracy.



Static Characteristics

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Sensor Characteristics

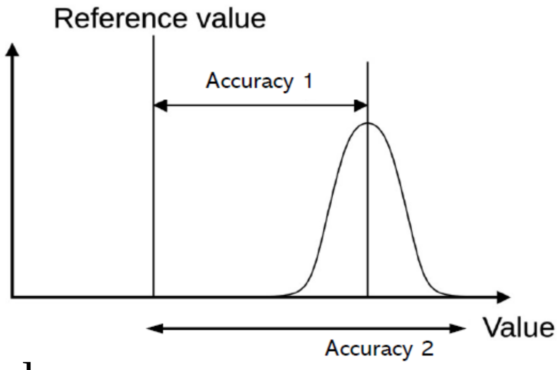
Static Characteristics:

Accuracy:

- ➢ Using this definition it is unclear if the accuracy is the mean error (systematic error) or the combination of random and systematic error
- ➢ To assess the accuracy, either the system is benchmarked against a standard measurand or the output is compared with a measurement system with a superior accuracy.

$$Accuracy_1 = X_T - Average\ (X_1\text{-}X_n)$$

$$Accuracy_2 = [X_T - Average\ (X_1\text{-}X_n)] + 3\sigma$$



- ➢ In sensor data sheet the accuracy is usually represented as a % of Full Scale (FS) but can also be absolute value.

Static Characteristics

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Sensor Characteristics

Static Characteristics:

Accuracy:

➢ What is the actual accuracy of the this mass flow meter under the following conditions?

- Temperature **25C** above calibration point.
- Pressure at **15 Psi** above calibration point.

Answer:
The pressure and temperature coefficients are assumed to have a uniform distribution. Then the errors from the T and P coefficients would be simply added.

E = 1% + (0.05*25) + (0.01*15) = 2.4%

Accuracy
Standard: +/- 1.0% of full scale including linearity under calibration conditions
(+/- 2.0% of full scale for 180M from 201 to 300 slpm)
High Accuracy Calibration: +/-0.5% of reading + 0.3% of full scale at calibration conditions

Dial-A-Gas
+/- 1.0% of full scale in all 10 standard gases

Repeatability
+/- 0.2% of full scale

Temperature Coefficient
+/- 0.025% of full scale per °F (0.05% of full scale per °C), or better

Pressure Coefficient
+/- 0.01% of full scale per psi (0.15% of full scale per bar), or better

Sensor Characteristics

Static Characteristics:

Accuracy:

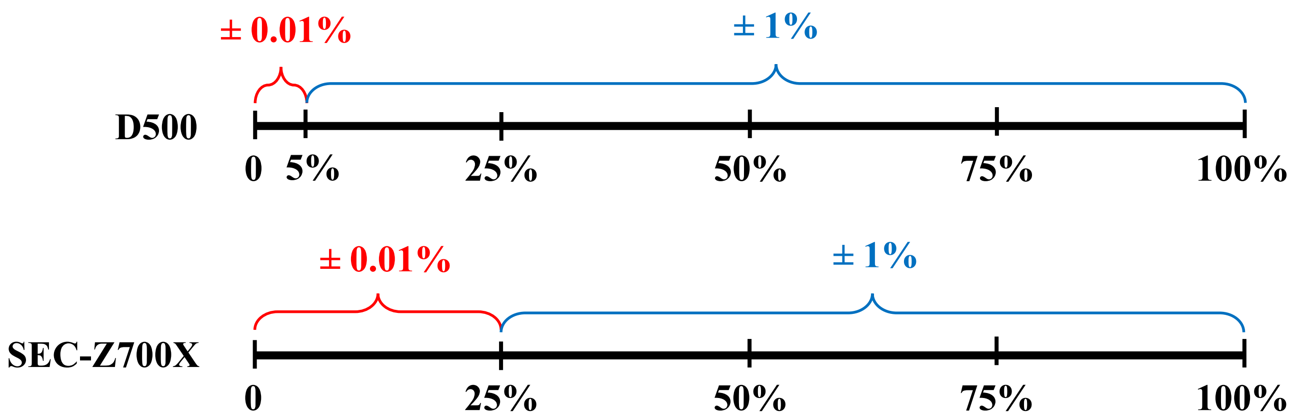
➢ Which mass flow controller is more accurate?

Answer:

- ➢ **0 - 5% identical**
- ➢ **5 - 25% SEC-Z700X is better**
- ➢ **25 - 100% identical**

Then: SEC-Z700X is recommended

Model	D500	SEC-Z700X
Sensor Type	Pressure Based	Thermal
Accuracy	±1%S.P (>5% F.S.) ±0.01 F.S. (<5% F.S.)	±1%S.P (>25% F.S.) ±0.01 F.S. (<25% F.S.)



Static Characteristics

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ENMC3361

Sensors and Instrumentation

Lecture #4

Ihab Abu Ajamieh, PhD.

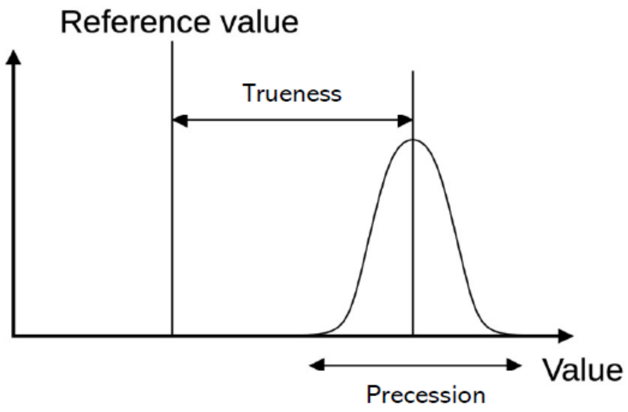
Sensor Characteristics

Static Characteristics:

Trueness:

- It is a new term for the accuracy of a sensing system.
- Trueness is the average error between multiple readings and the reference (X_T).

$$\text{Trueness} = X_T - \text{Average}\,(X_1\text{-}X_n)$$



Static Characteristics

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Sensor Characteristics

Static Characteristics:

Trueness:

➢ It should be noted that the data sheet of most sensors will

➢ This value is determined in ideal conditions without any environmental factors, cross sensitivity, and any other factors that can affect the accuracy/trueness of a sensor

MEASUREMENT PERFORMANCE CHARACTERISTICS

Measurement Range	0 to 20 ppm
Lower Detection Limit	<0.1 ppm
Resolution	<0.1 ppm
Accuracy	< ± 2 % of reading
Response Time T90	< 30 seconds
Power-On Stabilization Time	60 minutes recommended

Static Characteristics

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Sensor Characteristics

Static Characteristics:

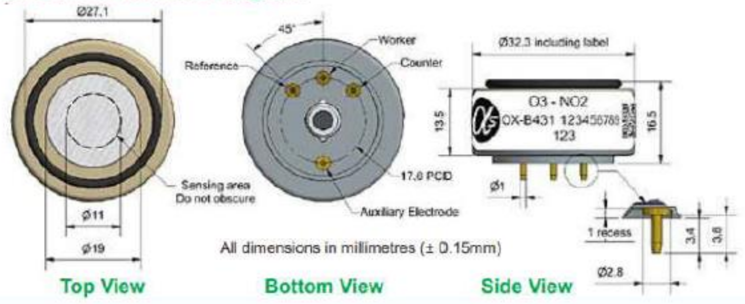
Trueness:

What is the trueness of this sensor?

Answer:

Given no other information and assuming perfect calibration, the linearity can be used as the trueness (0.5 ppm or 2.5%)

Figure 1 OX-B431 Schematic Diagram



Specification O_3 Sensing

PERFORMANCE

Sensitivity	nA/ppm at 1ppm O_3	-225 to -750
Response time	t_{90} (s) from zero to 1ppm O_3	< 80
Zero current	nA in zero air at 20°C	-80 to +80
Noise*	±2 standard deviations (ppb equivalent)	15
Range	ppm O_3 limit of performance warranty	20
Linearity	ppm error at full scale, linear at zero and 20ppm O_3	< ±0.5
Overgas limit	maximum ppm for stable response to gas pulse	50

* Tested with Alphasense AFE low noise circuit

Static Characteristics

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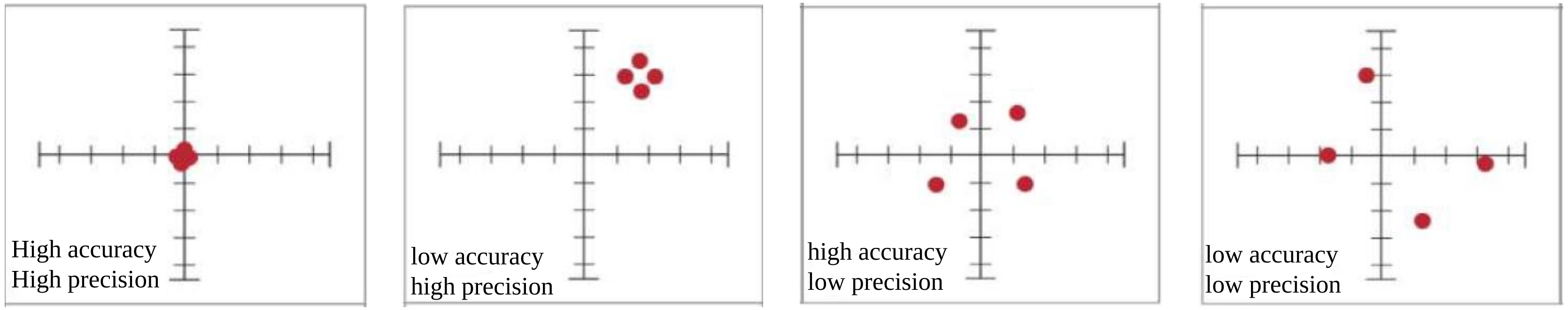
Sensor Characteristics

Static Characteristics:

Precision:

- ➢ Precision represents capacity of a sensing system to give the same reading when repetitively measuring the same measurand under the same conditions.
- ➢ Improving trueness requires better calibration (modeling between output signal and measurand) but improving precision usually requires signal processing (e.g. averaging)..



Static Characteristics

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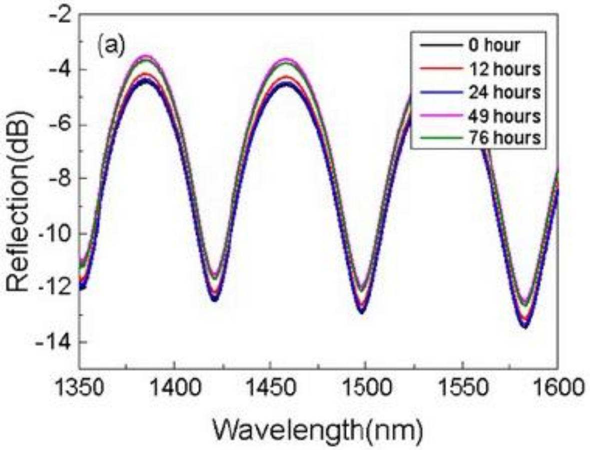
- Response and recovery time

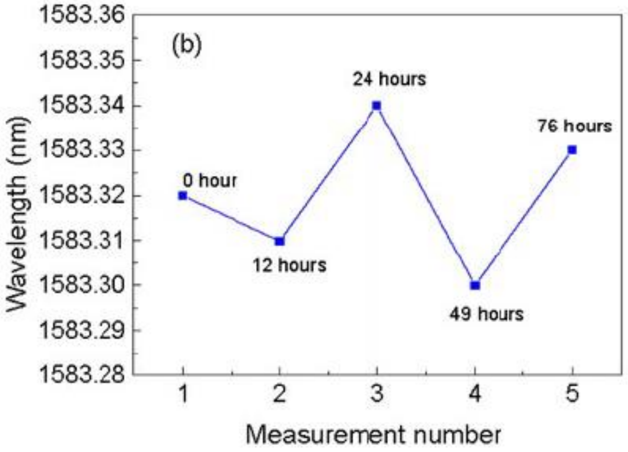
Sensor Characteristics

Static Characteristics:

Repeatability:

- repeatability is the ability of the sensing system to produce the same responses for the same input under the same operating and environmental conditions.
- For short time measurements, repeatability is related closely to the precision.
- Long-term repeatability will provide an indication of sensor drift over time.





Static Characteristics

- Accuracy
- Trueness
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- Range
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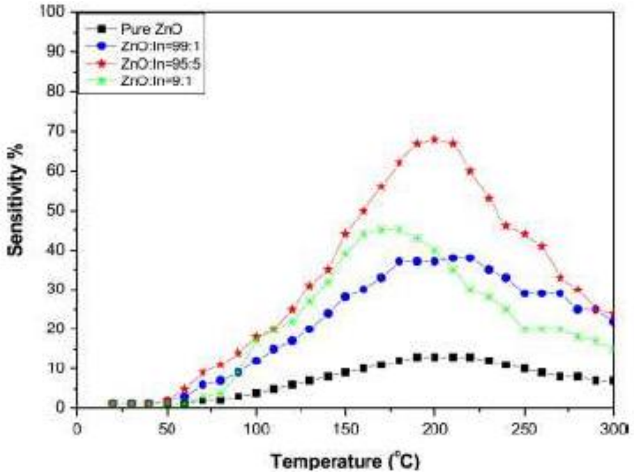
- Hysteresis
- Response and recovery time

Sensor Characteristics

Static Characteristics:

Reproducibility:

- Reproducibility is the ability of the sensing system to produce the same responses after measurement conditions have been altered.
- Some sensors may have excellent accuracy (or trueness) and precision but each time an environmental factor changes the calibration changes. Therefore, the sensor is not reproducible.



Static Characteristics
- Accuracy
- Trueness
- Precession
- Repeatability
- Range
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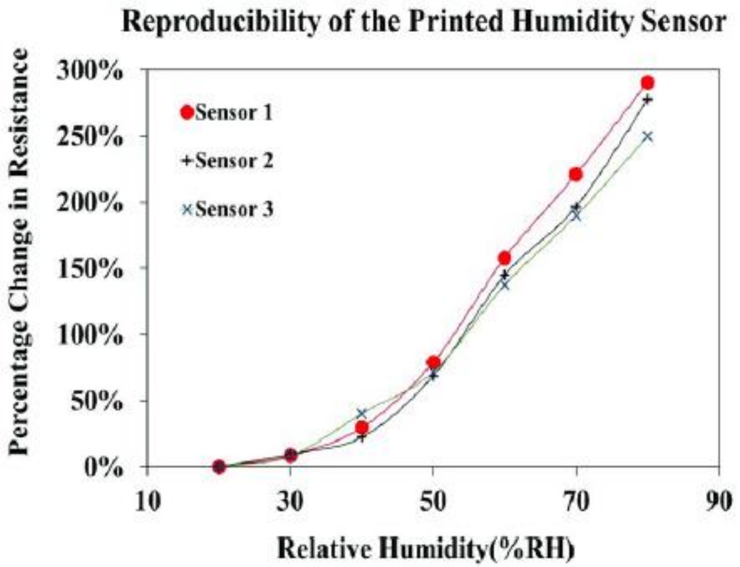
Sensor Characteristics

Static Characteristics:

Reproducibility:

➢ Reproductivity may also refer to the results obtained using identical sensors from same or different manufacturing batches.



Static Characteristics

- Accuracy
- Trueness
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- Range
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- Selectivity
- Hysteresis
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The End of Lecture #4

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Department of Mechanical and
Mechatronics Engineering

ENMC3361
Sensors and Instrumentation

Lecture #5

Ihab Abu Ajamieh, PhD.

Sensor Characteristics

Static Characteristics:

Range:

- ➢ The range of the sensor is the maximum and minimum values of applied parameter that can be measured.
- ➢ There may be another range defined in the datasheet which is the overload range.
- ➢ Overload describes the range before the sensor is permanently damaged

CO/C-1000
Carbon Monoxide Gas Sensor in Compact Housing

Operation Principle	3-Electrode Electrochemical
Nominal Range	0 - 1000 ppm
Maximum Overload	2000 ppm
Inboard Filter	-
Output Signal	100 ± 20 nA/ppm
Resolution (Electronics dependent)	< 0.5 ppm
T90 Response Time	< 35 s
Typical Baseline Range (pure air, 20°C)	-2 ppm to 5 ppm
Maximum Zero Shift (+20°C to +40°C)	10 ppm
Repeatibility	< 2 % of signal
Output Linearity	Linear
Gain	-

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Minimum Detectable signal
- Sensitivity
- Selectivity
- Hysteresis
- Response and recovery time

Sensor Characteristics

Static Characteristics:

Range:

➢ The range of some sensors can be adjusted to the measurand range to increase the accuracy.

Model	CRITERION D500
Product Features	Range topping accuracy & repeatability. Widest dynamic control range of 0.2% to 100%. Self diagnostics. Programmable, pressure insensitive mass flow module
Sensor Type	Pressure-based
Accuracy	+/- 1% S.P. (>5% F.S.)
Power Supply	+/-15VDC / 24VDC *1
Control Interface	Analog (0 - 5 VDC) / Digital (RS-485 F-NET) DeviceNET™ EtherCAT®

Pressure Reading	Yes
Multi Gas/Multi Range	Multi Gas/Multi Range/ Multi Pressure
Self Diagnostics	Yes
Fitting	VCR, IGS
Seal Material	Metal
Valve Type	Piezo electric - Normally closed
Mounting	Mount-free
Full Scale Flow Rate	10 SCCM - 50 SLM
Temperature	15 - 45°C

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Minimum Detectable signal
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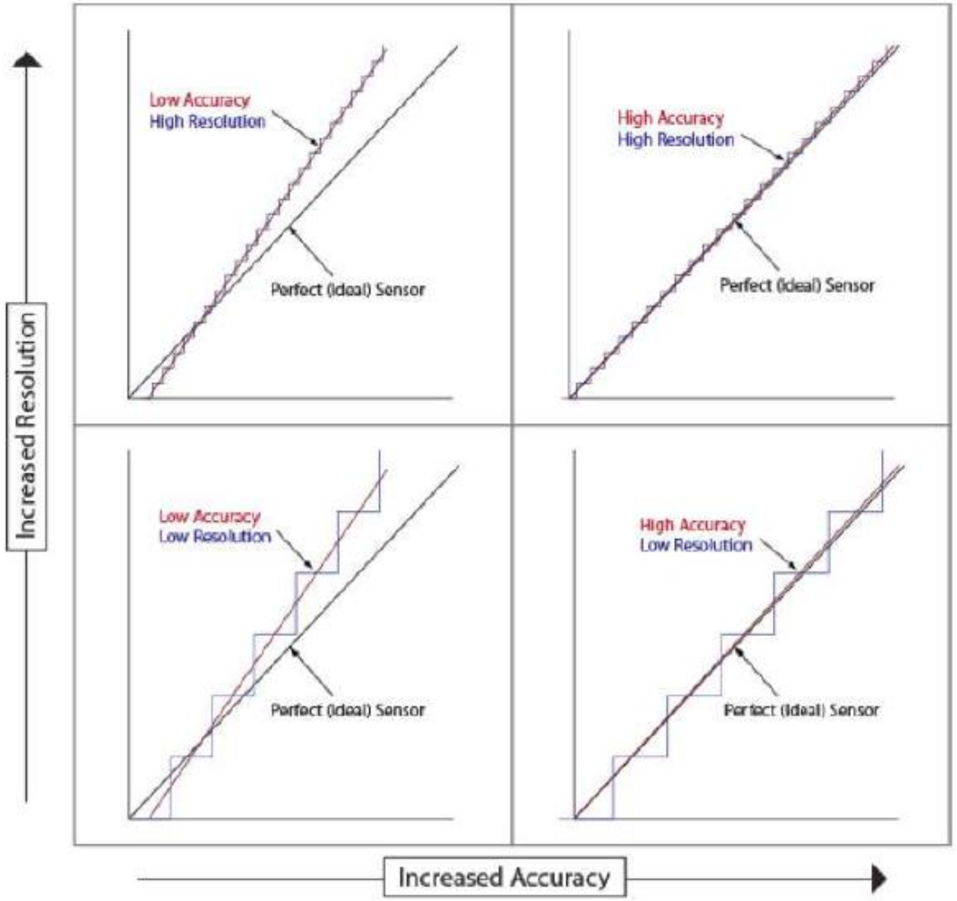
Sensor Characteristics

Static Characteristics:

Resolution:

- Resolution is the minimal change of the measurand that can produce a detectable increment in the output signal.



Static Characteristics

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Sensor Characteristics

Static Characteristics:

Resolution:

- Resolution is strongly limited by any noise in the signal.
- The resolution of the sensor is not the same as the resolution of the ADC system.
- This misconception often leads to sensor manufacturers claiming a much better resolution than the sensor is capable of.

Static Characteristics

- Accuracy
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BIRZEIT UNIVERSITY
Department of Mechanical and Mechatronics Engineering

Sensor Characteristics

Static Characteristics:

Resolution example:

- Max detection – 50 ppm
- Min Detection – 5 ppb
- Sensor output range 0.6 to 3.3V
- ADC - 14 bit 5V
- Sensor resolution 2 ppb

What is the resolution of the system?

Answer

- ADC resolution: 2^{14} = 16384 steps
- 5V/16384 steps = 0.000305 V/Step
- (3.3-0.6)/50000 = 0.000054 V/ppb
- ADC - 14 bit 5V
- 0.000305 V/step / 0.000054V/ppb = 5.65 ppb/step

Static Characteristics

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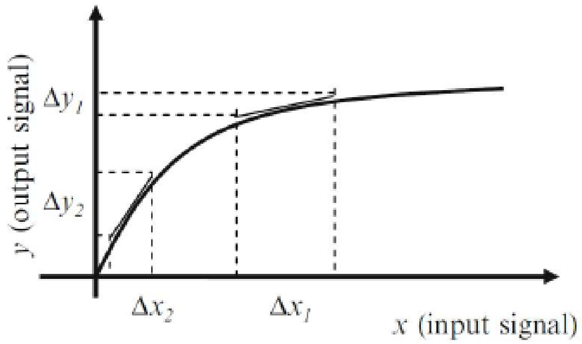
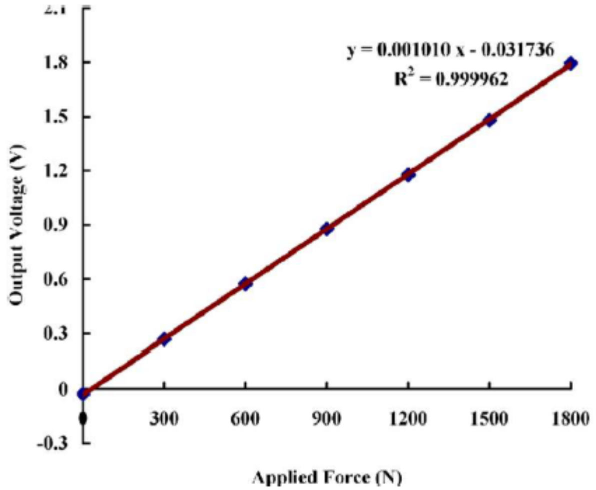
Sensor Characteristics

Static Characteristics:

Sensitivity:

- A sensor's sensitivity indicates how much the sensor's output changes when the input measurand changes.
- The sensitivity can be constant over the whole measurement range (linear response) or can be a function of many other parameters including the measurand.
- Sensitivity = df/dx ; for y=f(x)





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Sensor Characteristics

Static Characteristics:

Sensitivity:

- Sensor should output maximum 3.3V at 1 ppm.

What is the amplification required in a circuit with resistance 1 kΩ?

Specification O_3 Sensing

PERFORMANCE

Sensitivity	nA/ppm at 1ppm O_3	-225 to -750
Response time	t_{90} (s) from zero to 1ppm O_3	< 80
Zero current	nA in zero air at 20°C	-80 to +80
Noise*	±2 standard deviations (ppb equivalent)	15
Range	ppm O_3 limit of performance warranty	20
Linearity	ppm error at full scale, linear at zero and 20ppm O_3	< ±0.5
Overgas limit	maximum ppm for stable response to gas pulse	50

* Tested with Alphasense AFE low noise circuit

Answer

- $I*R = V \rightarrow$ 750 nA * 1 kΩ = 0.750 mv/ppm
- 3300/0.750 = 4400 amplification

Static Characteristics

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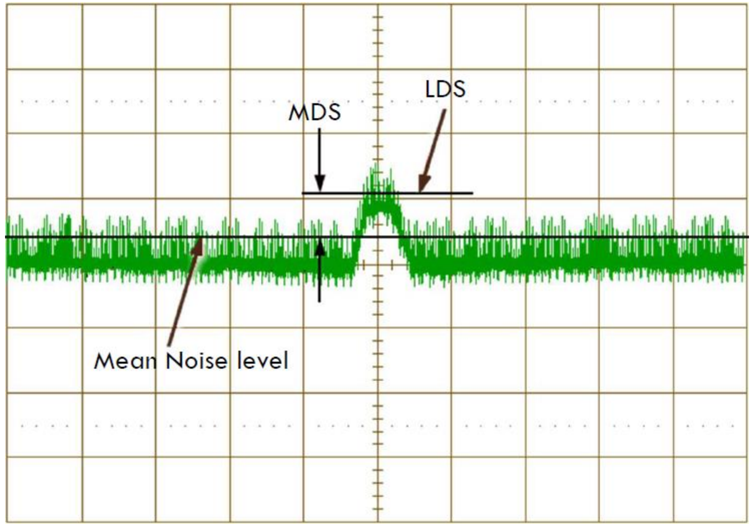
Sensor Characteristics

Static Characteristics:

Minimum Detectable Signal & Lowest Detectable Threshold:

- Minimum detectable signal (MDS) is the minimum signal increment that can be observed, when all interfering factors are considered.
- This is similar to resolution but also considers other factors such as environmental effects.
- When the signal increment is assessed from zero, the value is generally referred to as lowest detection limit (LDL).



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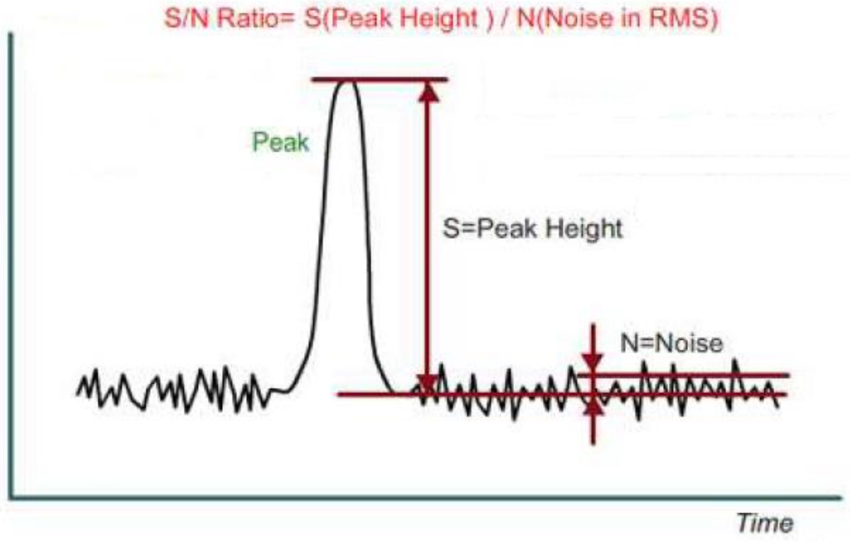
Sensor Characteristics

Static Characteristics:

Minimum Detectable Signal & Lowest Detectable Threshold:

- To calculate MDS, signal to noise ratio (SNR) is required.
- SNR is the ratio of a desired signal to the level of background noise.
- Usually defined in dB - Ratio of 1:1 (0 db)

$$\mathrm{SNR} = \frac{s^2}{\sigma_{\mathrm{N}}^2} \longrightarrow \mathrm{SNR} = \frac{\mu^2}{\sigma^2}$$



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Sensor Characteristics

Static Characteristics:

Minimum Detectable Signal & Lowest Detectable Threshold:

Specification O_3 Sensing

PERFORMANCE	Sensitivity	nA/ppm at 1ppm O_3	-225 to -750
	Response time	t_{90} (s) from zero to 1ppm O_3	< 80
	Zero current	nA in zero air at 20°C	-80 to +80
	Noise*	±2 standard deviations (ppb equivalent)	15
	Range	ppm O_3 limit of performance warranty	20
	Linearity	ppm error at full scale, linear at zero and 20ppm O_3	< ±0.5
	Overgas limit	maximum ppm for stable response to gas pulse	50
LIFETIME	Zero drift	ppb equivalent change/year in lab air	0 to 20
	Sensitivity drift	% change/year in lab air, monthly test	< -20 to -40
	Operating life	months until 50% original signal (24 month warranted)	> 24

* Tested with Alphasense AFE low noise circuit

SNR required is 10. What is the Minimum detectable signal?

Answer:

$$\mathrm{SNR} = \frac{s^2}{\sigma_N^2}$$

- ➢ SNR = 10 = $(\text{Signal})^2/(7.5)^2$
- ➢ Signal = Sqrt(10*56.25)
- ➢ Signal = 23.7 ppb

Static Characteristics

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Sensor Characteristics

Static Characteristics:

Selectivity:

- It is the sensing system's ability to measure a target measurand in the presence of other interferences.
- For example, a CO sensor (below) that responds to a range of other gases is considered not selective.
- Usually the selectivity is given in its opposite parameter, cross sensitivity.
- Cross sensitivity defines the response change of the sensor to change in influencing interference. This can be as a percentage or absolute reading of the measurand

Static Characteristics

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- Usually the selectivity is given in its opposite parameter, cross sensitivity.
- Cross sensitivity defines the response change of the sensor to change in influencing interference. This can be as a percentage or absolute reading of the measurand

Interfering Gas	Concentration [ppm]	Reading [ppm]
C_2H_4	10	14
CH_2O	5	15
Cl_2	20	-11
H_2	400	< 200
H_2S	500	1450
NO	50	13
NO_2	100	-64
O_3	130	> -500
SO_2	100	78

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Sensor Characteristics

Static Characteristics:

Selectivity:

- H2S sensor reading 7.5 ppm.
- SO2 sensor reading 39 ppm.
- How much H2S and SO2 gas are present?

H2S sensor

Interfering gas	Concentration	Reading
SO2	7	2

SO2 sensor

Interfering gas	Concentration	Reading
H2S	1	6

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Sensitivity
- Minimum Detectable signal
- Selectivity
- Hysteresis
- Response and recovery time

Answer:

- H2SR = 7.5 = H2SC + SO2C*2/7
- SO2R = 39 = SO2C + H2SC*6

→ H2S = 5.1 and SO2 = 8.4

The End of Lecture #5

ENMC3361
Sensors and Instrumentation

Lecture #6

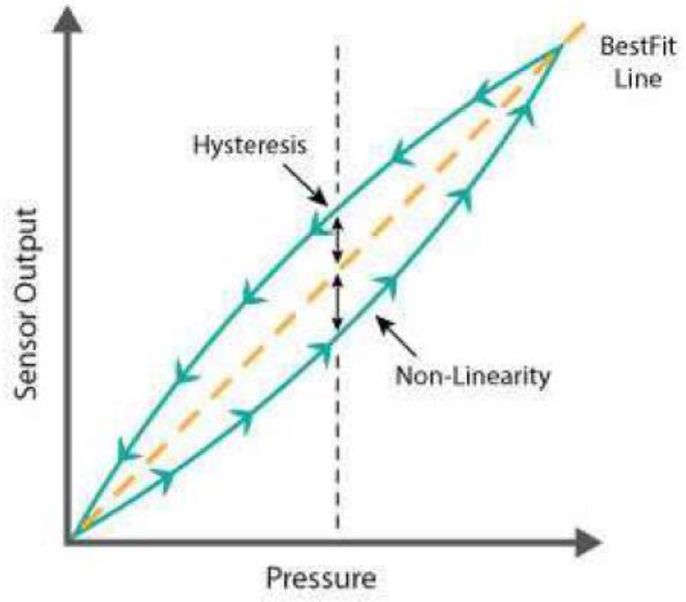
Ihab Abu Ajamieh, PhD.

Sensor Characteristics

Static Characteristics:

Hysteresis:

- ➢ An ideal sensor should be capable of following the changes of the input parameter regardless of which direction the change is made.
- ➢ Hysteresis is the measure of this property.
- ➢ A sensor with large hysteresis means that it matters from which direction the change is made.



Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Sensitivity
- Minimum Detectable signal
- Selectivity
- Hysteresis
- Response and recovery time

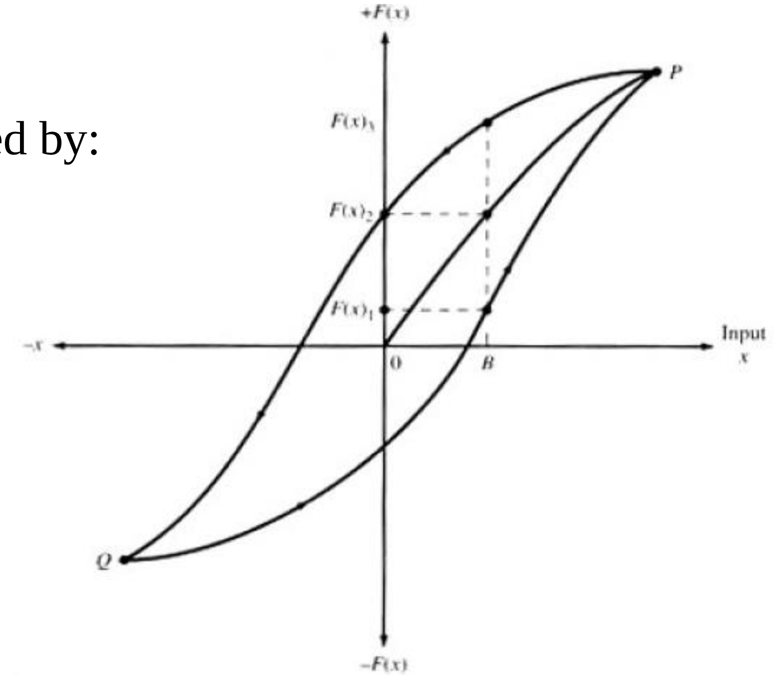
Sensor Characteristics

Static Characteristics:

Hysteresis:

- Approaching a fixed input value (point B) from a higher value (point P) will result in a different indication than approaching the same value from a lesser value (point Q or zero)..
- Therefore, input value B can be represented by:

  $F(x)_1$, $F(x)_2$, or $F(x)_3$.
- Calibration of a sensor is usually done depending on the application to use either of the 3 functions.



Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Sensitivity
- Minimum Detectable signal
- Selectivity
- Hysteresis
- Response and recovery time

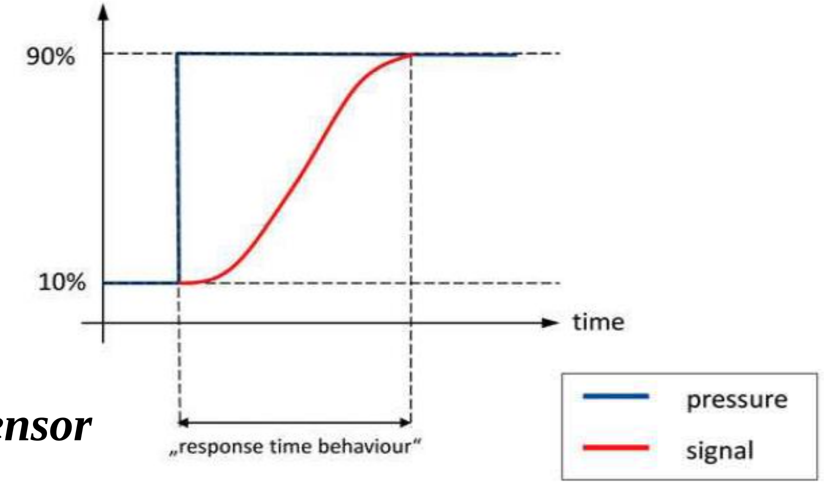
Sensor Characteristics

Static Characteristics:

Response Time:

- When a sensing system is exposed to a measurand, the time it requires to reach a stable value is the response time.
- It is generally expressed as the time at which the output reaches a certain percentage (for instance, 90%) of its final value, in response to a step change of the input.
- This time is provided as t_{95}

pressure sensor



Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Sensitivity
- Minimum Detectable signal
- Selectivity
- Hysteresis
- Response and recovery time

Sensor Characteristics

Static Characteristics:

Recovery Time:

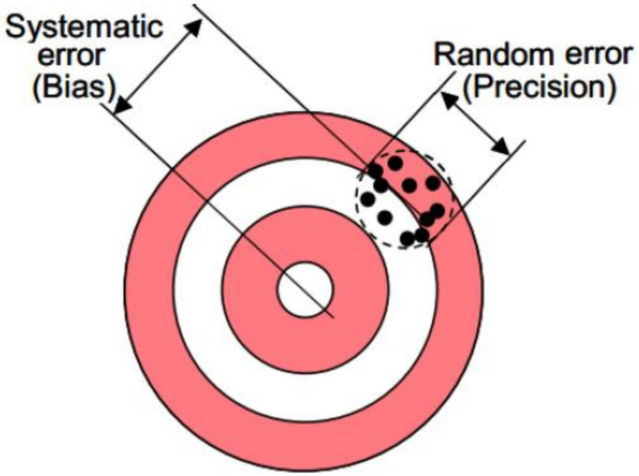
- The “recovery time” is defined conversely. Response and recovery time can often be affected by environmental conditions such as temperature and humidity.
- In a nano-fibre sensing application the response time is <10 ms while the recovery time is roughly 5 minutes for 10% FS exposure at room temperature.
- To reduce recovery time, the sensor can be kept at a higher temperature, which will increase response time, but at the same time reduce recovery time.

Static Characteristics

- Accuracy
- Trueness
- Precession
- Repeatability
- Range
- Resolution
- Sensitivity
- Minimum Detectable signal
- Selectivity
- Hysteresis
- Response and recovery time

Sensor Characteristics

Static Characteristics:



Accuracy and Errors:

Systematic error: Results from a variety of factors

- Interfering or modifying variables (i.e., temperature).
- Drift (i.e. changes in chemical structure or mechanical stresses).
- Human observers (i.e., parallax errors).

Systematic errors can be corrected with compensation methods (i.e. feedback, filtering).

Random error (noise): It is the signal that carries no information. Results from different sources:

- Repeatability of the measurand itself (i.e. height of a rough surface).
- Environmental noise (i.e., background noise picked by a microphone).

Sensor Characteristics

Dynamic Characteristics:

Dynamic response:

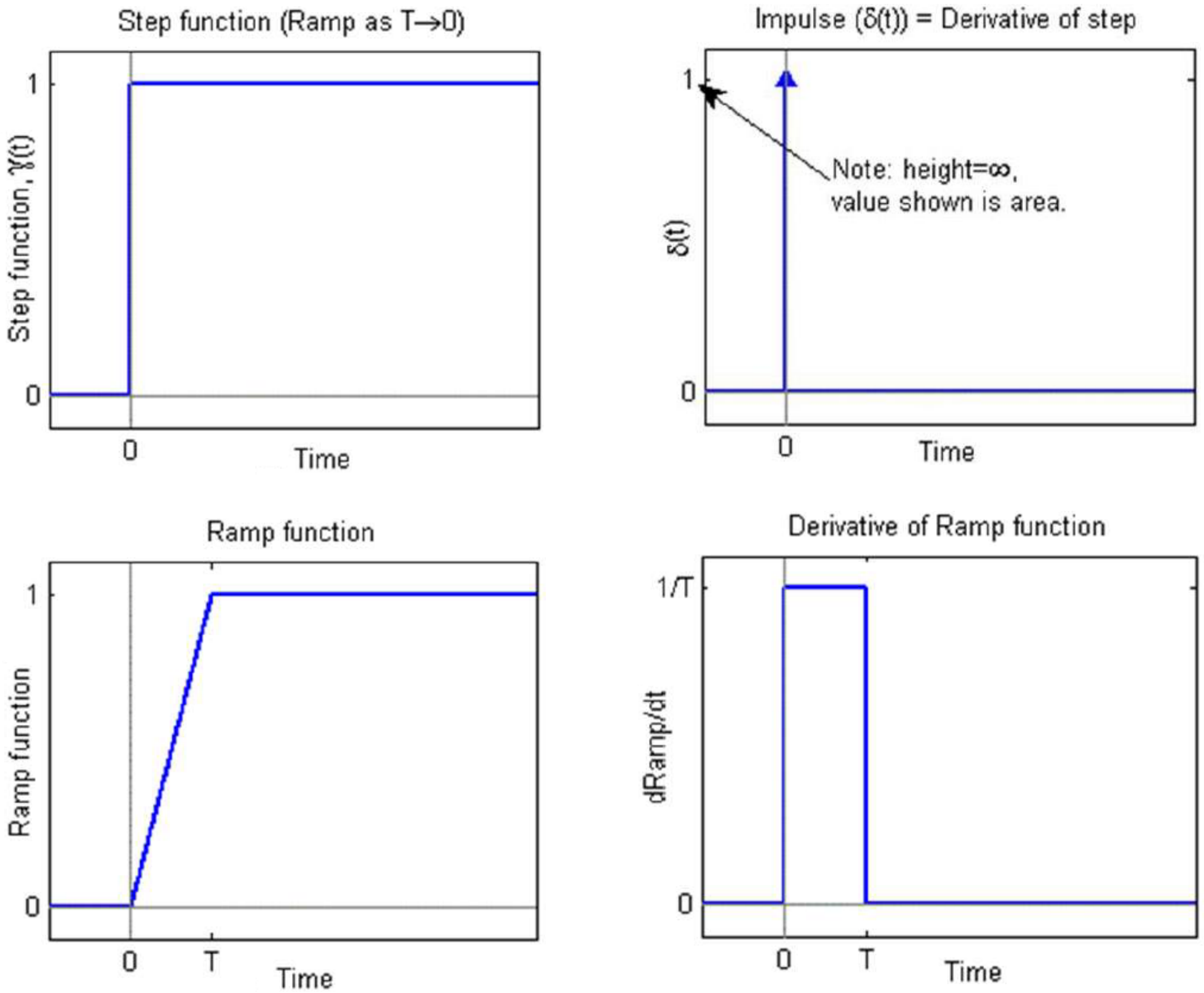
- Dynamic characteristics of a sensing system describe its behavior between the time a measured quantity changes value and the time when the instrument out put attains steady value in response
- The reason for the presence of dynamic characteristics is the existence of energy storing elements in a sensing system.
- They can be produced by electronic elements such as inductance and capacitance, mechanical elements such as vibration paths and mass, and/or thermal elements with heat capacity.

Sensor Characteristics

Dynamic Characteristics:

Dynamic response:

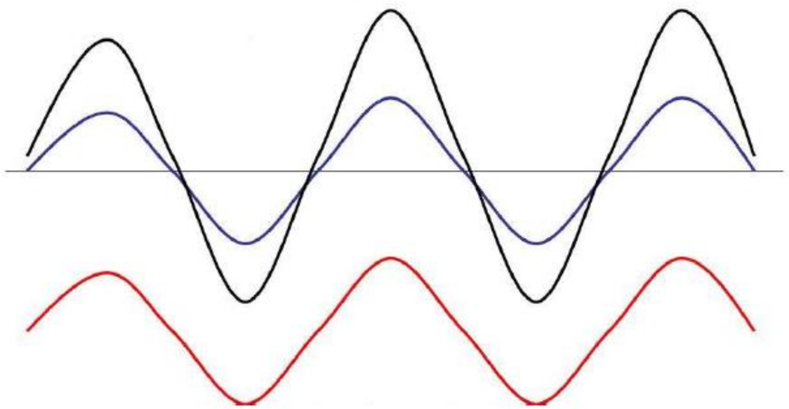
- Consequently, such a model can be utilized for analyzing the response to variable input waveforms such as impulse, step, ramp, sinusoidal, and white noise signals



Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:



- The simplest and most studied sensing systems are linear time invariant (LTI) systems.
- The properties of such systems do not change in time, Hence: ***time invariant***.
- It should also satisfy the properties of superposition. i.e. addition of two different inputs produces the addition of their individual outputs. Also scaling i.e. when input is amplified, the output is also amplified by the same amount.

  Hence: ***linear***.

Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:

- The relationship between the input and output of any LTI sensing system can be described as:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^{m-1} x(t)}{dt^{m-1}} + b_{m-1} \frac{d^{m-2} x(t)}{dt^{m-2}} + \cdots + b_2 \frac{dx(t)}{dt} + b_1 x(t) + b_0,$$

- where $x(t)$ is the measured (input signal).
- $y(t)$ is the output signal and
- $a_0, \ldots, a_n, b_0, \ldots, b_m$ are constants, which are defined by the system's parameters

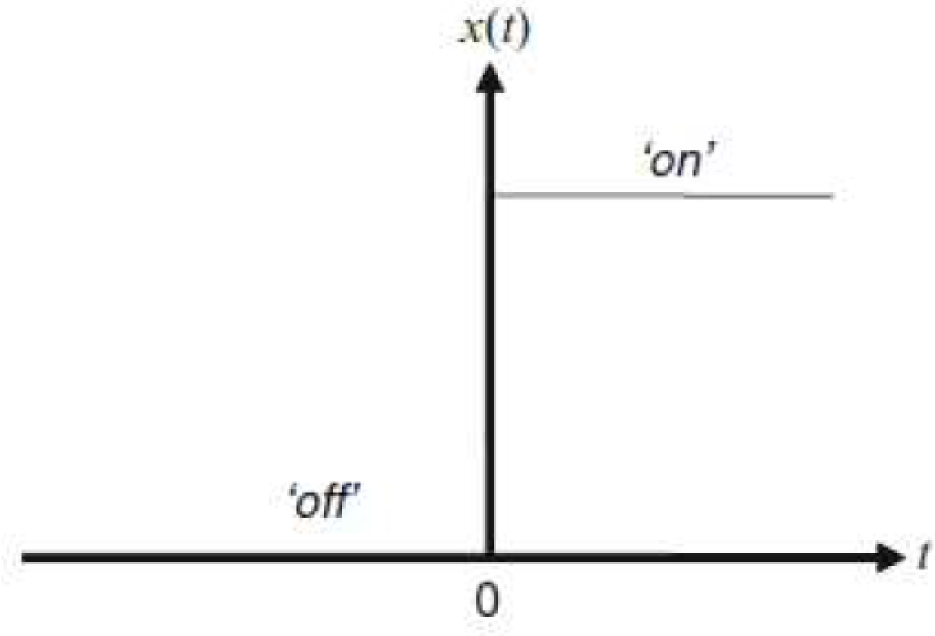
Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:

- $x(t)$ can have different forms such as impulse, step, sinusoidal, and exponential functions.

- As a simple example, $x(t)$ can be a step function.



Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:

- When the input signal is a step change, all derivatives of x(t) with respect to t are zero and equation of the LTI is reduced to:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = \cancel{b_m \frac{d^{m-1} x(t)}{dt^{m-1}}} + \cancel{b_{m-1} \frac{d^{m-2} x(t)}{dt^{m-2}}} + \cdots + \cancel{b_2 \frac{dx(t)}{dt}} + b_1 x(t) + b_0,$$

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_1$$

For $t > 0$

- b_0 is also considered zero in this case. If not zero, a baseline is added to the system response

Sensor Characteristics

Dynamic Characteristics:

Zero order system:

- A zero order system is that one in which a_1 to a_n are equal to zero.

$$a_n \frac{\cancel{d^n y(t)}}{\cancel{dt^n}} + a_{n-1} \frac{\cancel{d^{n-1} y(t)}}{\cancel{dt^{n-1}}} + \cdots + a_1 \frac{\cancel{dy(t)}}{\cancel{dt}} + a_0 y(t) = b_1, \Longrightarrow a_0 y(t) = b_1 \Longrightarrow y(t) = K$$

Where: $K = b_1 / a_0$ is the static sensitivity

- A perfect zero-order system can be considered if output shows without a delay in the response to the input signal.

Sensor Characteristics

Dynamic Characteristics:

Zero order system:

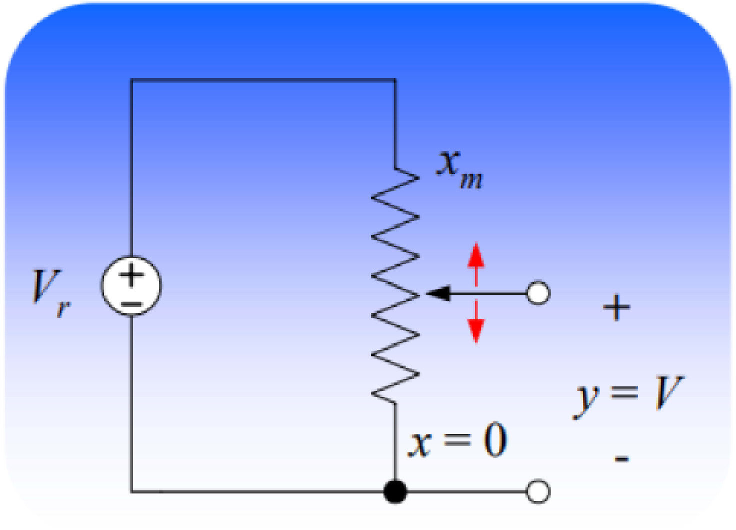
- A potentiometer, which measures motion (position sensor), is a good example of such instrument, where the output voltage changes instantaneously as the slider is displaced along the potentiometer track.

$$V = V_r \cdot \frac{x}{x_m}$$

Where: $K = V_r / x_m$

$0 \leq x \leq x_m$

And: V_r is a reference voltage



ENMC3361

Sensors and Instrumentation

Lecture #7

Ihab Abu Ajamieh, PhD.

Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:

- The relationship between the input and output of any LTI sensing system can be described as:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^{m-1} x(t)}{dt^{m-1}} + b_{m-1} \frac{d^{m-2} x(t)}{dt^{m-2}} + \cdots + b_2 \frac{dx(t)}{dt} + b_1 x(t) + b_0,$$

- where $x(t)$ is the input signal.
- $y(t)$ is the output signal and
- $a_0, \ldots, a_n, b_0, \ldots, b_m$ are constants, which are defined by the system's parameters

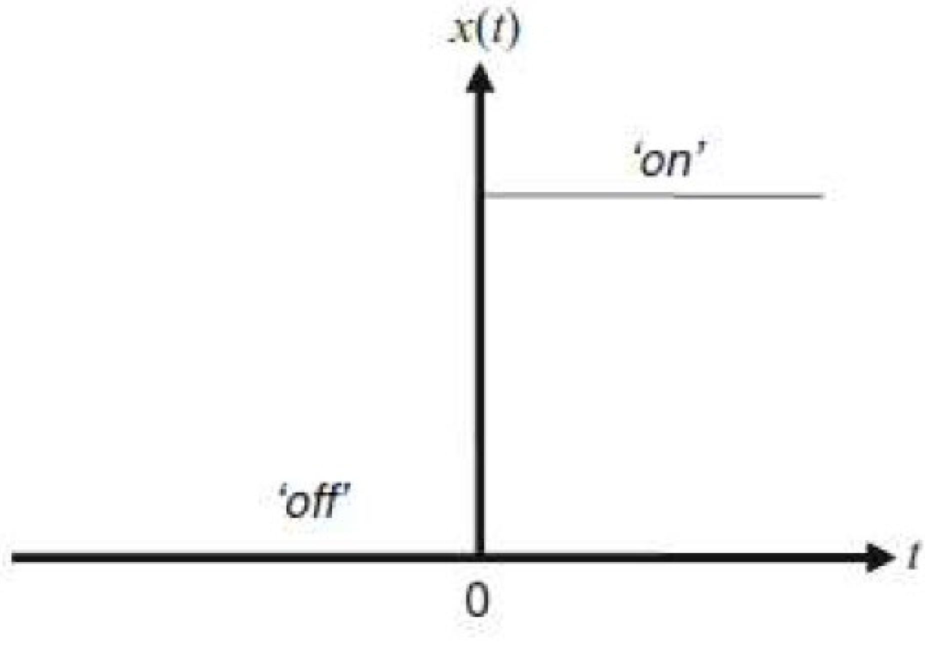
Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:

- $x(t)$ can have different forms such as impulse, step, sinusoidal, and exponential functions.

- As a simple example, $x(t)$ can be a step function.



Sensor Characteristics

Dynamic Characteristics:

Linear time invariant system:

- When the input signal is a step change, all derivatives of $x(t)$ with respect to t are zero and equation of the LTI is reduced to:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = \cancel{b_m \frac{d^{m-1} x(t)}{dt^{m-1}}} + \cancel{b_{m-1} \frac{d^{m-2} x(t)}{dt^{m-2}}} + \cdots + \cancel{b_2 \frac{dx(t)}{dt}} + b_1 x(t) + b_0,$$

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_1$$

For $t > 0$

- b_0 is also considered zero in this case. If not zero, a baseline is added to the system response

Sensor Characteristics

Dynamic Characteristics:

Zero order system:

- A zero order system is that one in which a_1 to a_n are equal to zero.

$$a_n \cancel{\frac{d^n y(t)}{dt^n}} + a_{n-1} \cancel{\frac{d^{n-1} y(t)}{dt^{n-1}}} + \cdots + a_1 \cancel{\frac{dy(t)}{dt}} + a_0 y(t) = b_1, \Longrightarrow a_0 y(t) = b_1 \Longrightarrow y(t) = K$$

Where: $K = b_1 / a_0$ is the static sensitivity

- A perfect zero-order system can be considered if output shows without a delay in the response to the input signal.

Sensor Characteristics

Dynamic Characteristics:

First order system: (contains one energy storing element)

- A first order system is that one in which a_2 to a_n are equal to zero. While $a_1 \neq 0$

$$a_n \cancel{\frac{d^n y(t)}{dt^n}} + a_{n-1} \cancel{\frac{d^{n-1} y(t)}{dt^{n-1}}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_1,$$

$$\Longrightarrow a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_1, \quad \Longrightarrow \frac{a_1}{a_0} \frac{dy(t)}{dt} + y(t) = \frac{b_1}{a_0}$$

$$\Longrightarrow \tau \frac{dy(t)}{dt} + y(t) = K.$$

Where:

- $K = b_1/a_0$ is the static sensitivity.
- $\tau = a_1/a_0$ is the time constant.

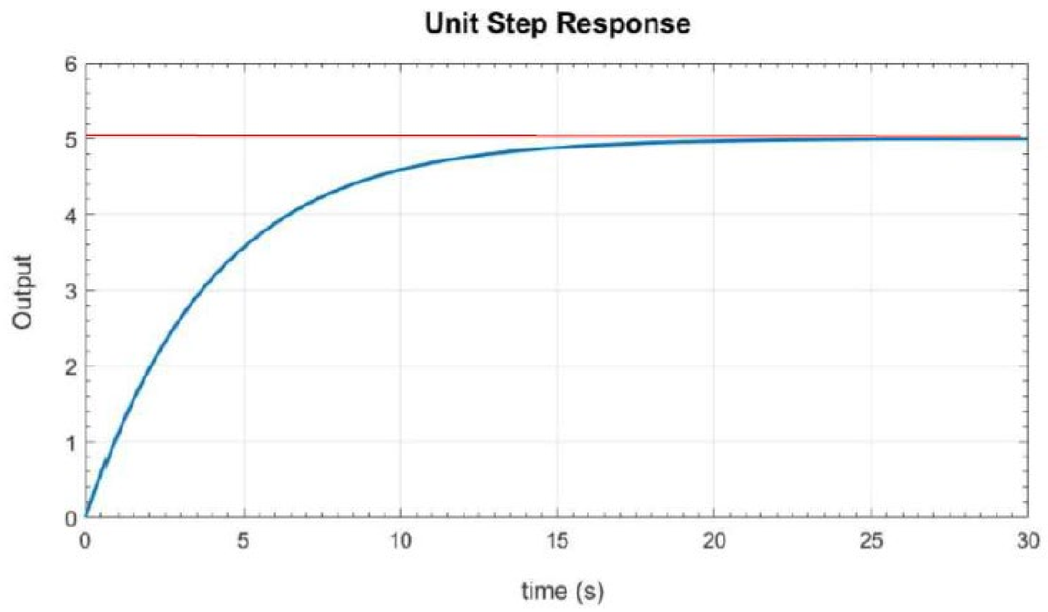
Sensor Characteristics

Dynamic Characteristics:

First order system: (contains one energy storing element**)**

- When solving the differential equation, the response to the step function x(t) is an exponential one.

$$\tau \frac{dy(t)}{dt} + y(t) = K.$$



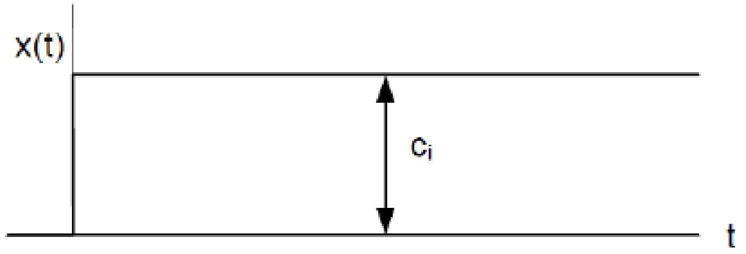
Sensor Characteristics

Dynamic Characteristics:

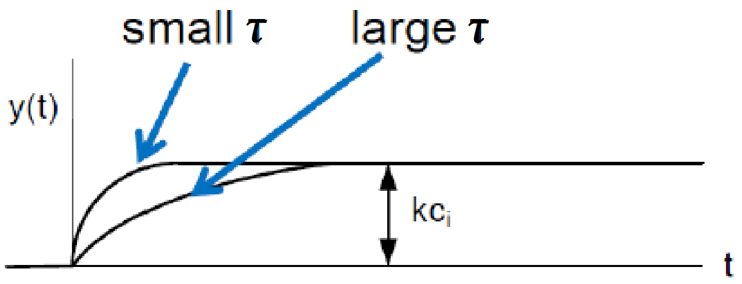
First order system: (contains one energy storing element**)**

- Static sensitivity (K): Is the amount of the output per unit input when the input is static (constant).
- Time constant (τ): Determines the lag of the output signal on a change in the input signal.
- The liquid-in-glass thermometer is a good example of a first order instrument.

$$\tau \frac{dy(t)}{dt} + y(t) = K.$$



step at input



response at output

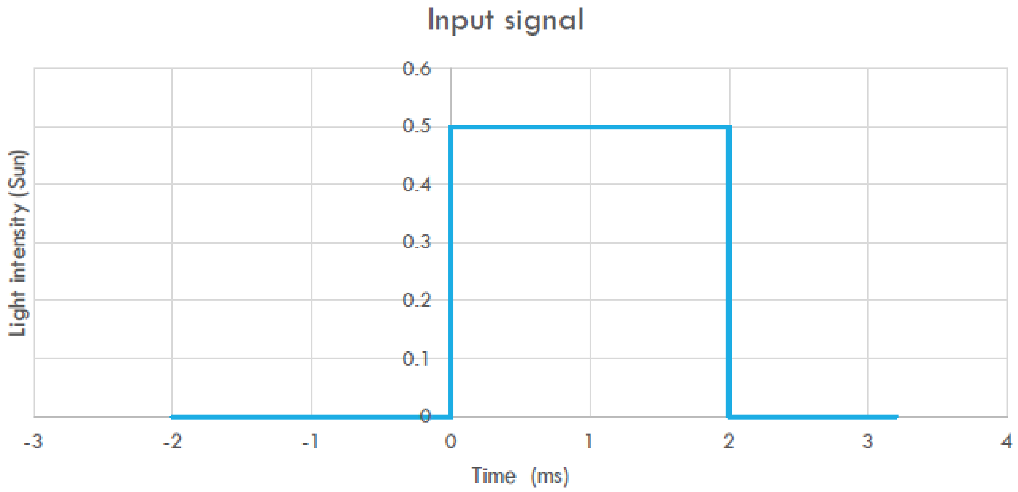
Sensor Characteristics

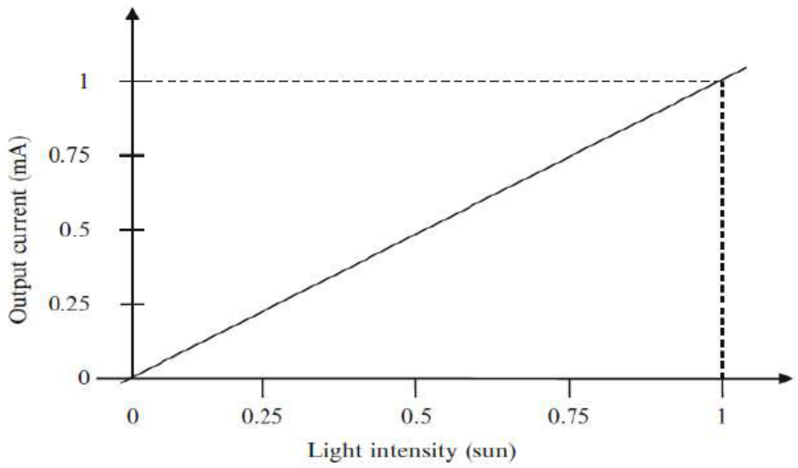
Dynamic Characteristics:

First order system: (contains one energy storing element**)**

Example: A photodiode sensor has a first-order response with $\tau = 1$ ms. The response of the sensor is linear with 0 mA when fully dark and 1 mA when under full sun (1 sun).

What is the output of the sensor?





Sensor Characteristics

Dynamic Characteristics:

First order system: (contains one energy storing element)

- For t < 0 the sensor has been kept in the dark for a long time so the output has reached steady state of 0 mA.
- For 0 < t < 2 the 0.5 sun becomes 0.5 mA
- Recall the 1st order system equation: $\tau \frac{dy(t)}{dt} + y(t) = K \quad \rightarrow \quad (1\,\text{ms})\frac{dy(t)}{dt} + y(t) = 0.5\,\text{mA}$

The solution is: $y(t) = y_h(t) + y_p(t)$

Where: $y_h(t) = A(e^{-t/1\ \text{ms}})$ And $y_p(t) = 0.5\ \text{mA}$

$$y(t) = A(e^{-t/1\ \text{ms}}) + 0.5\ \text{mA}.$$

At $t = 0 \rightarrow y(t) = 0 \qquad \therefore A = -0.5$

$$\boxed{\rightarrow \quad y(t) = 0.5\, mA \times (1 - e^{-t/1\, ms})}$$

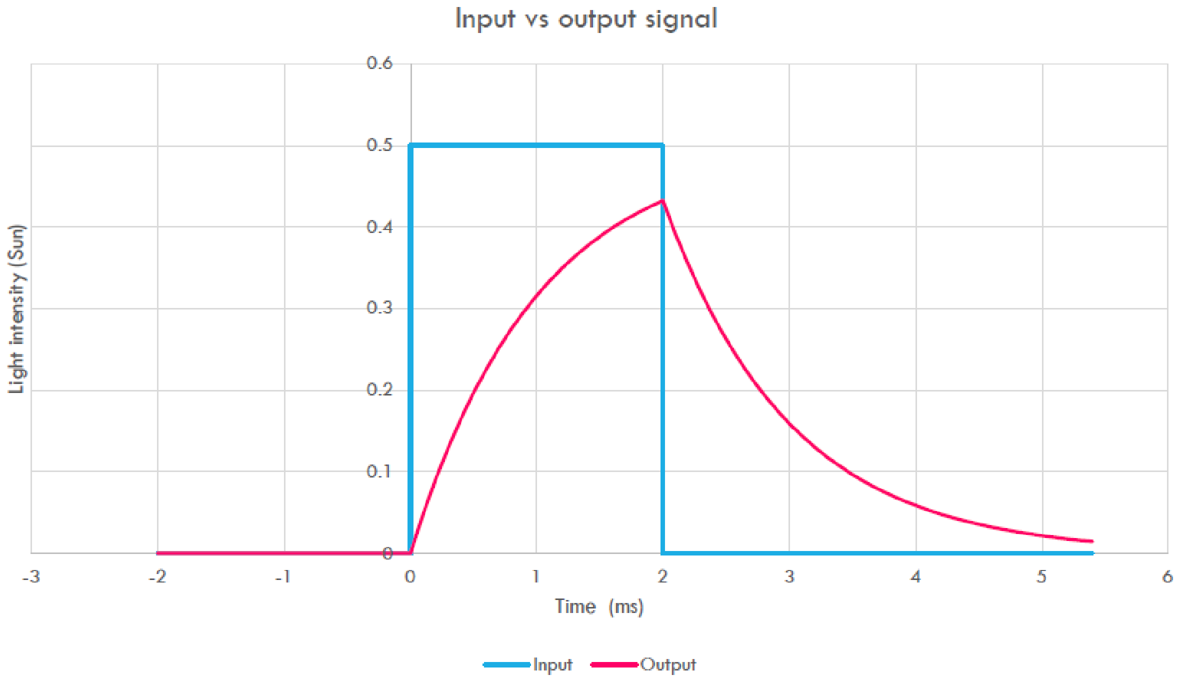
Sensor Characteristics

Dynamic Characteristics:

First order system: (contains one energy storing element)

- Solving for $t = 2 \quad \rightarrow \quad y(2) = 0.5(1 - e^{-2}) = 0.432$

$$y(t) = \begin{cases} 0 & t < 0 \\ 0.5\left(1 - e^{\frac{-t\text{ ms}}{1\,ms}}\right) & 0 \le t \le 2\,ms \\ 0.432\left(e^{\frac{-(t-2\,ms)}{1\,ms}}\right) & t > 2\,ms \end{cases}$$



Sensor Characteristics

Dynamic Characteristics:

Second order system:

- A second order system may have a more complicated response.
- The output may oscillate until reaching its final value in response to a step or pulse function.
- The response to a second order system can be described as:

Recall the main equation:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \cdots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^{m-1} x(t)}{dt^{m-1}} + b_{m-1} \frac{d^{m-2} x(t)}{dt^{m-2}} + \cdots + b_2 \frac{dx(t)}{dt} + b_1 x(t) + b_0,$$

$$\Longrightarrow \quad a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_1$$

Sensor Characteristics

Dynamic Characteristics:

Second order system:

- The second-order equation can then be written as:

$$a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_1. \Longrightarrow \frac{1}{\omega^2}\frac{d^2 y(t)}{dt^2} + \frac{2\xi}{\omega}\frac{dy(t)}{dt} + y(t) = K$$

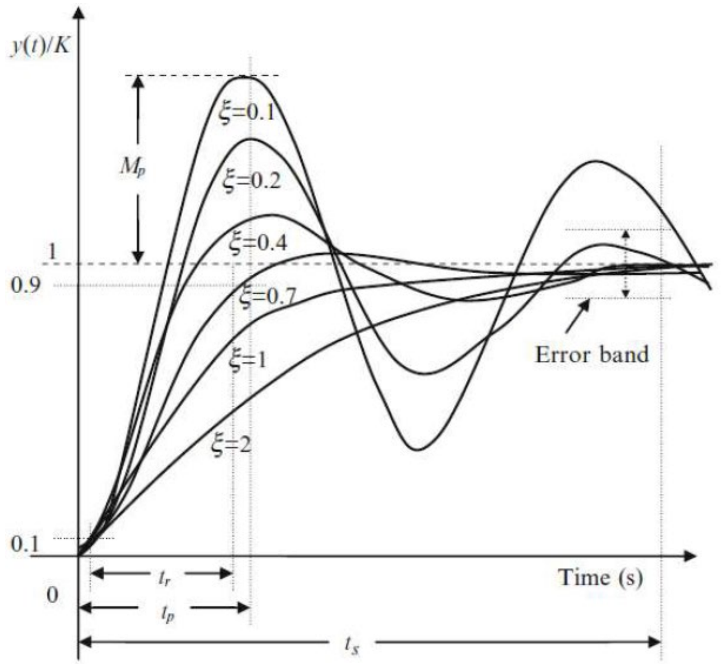
Where: $\omega^2 = \frac{a_\circ}{a_2}$ And $\xi = \frac{a_1}{2(a_\circ a_2)^{1/2}}$

- That means, the response of the system is governed by its natural frequency (ω), and damping ratio (ξ).

Sensor Characteristics

Dynamic Characteristics:

Second order system:



- If there is no dampening (i.e. ξ = 0) then the output of the sensor will oscillate constantly with a sinusoidal pattern with frequency equal to (ω).
- If the dampening is less than $\left(\frac{1}{\sqrt{2}}\right)$ then the system is under damped and will eventually get to the output but with lots of oscillation.
- At $\xi = \frac{1}{\sqrt{2}}$ the system is critically damped, and the output will reach steady state without oscillation.
- If $\xi > \frac{1}{\sqrt{2}}$ the system is overdamped and will take a long time to reach steady state.
- Ideally a sensor should have $0.6 < \xi < 0.8$

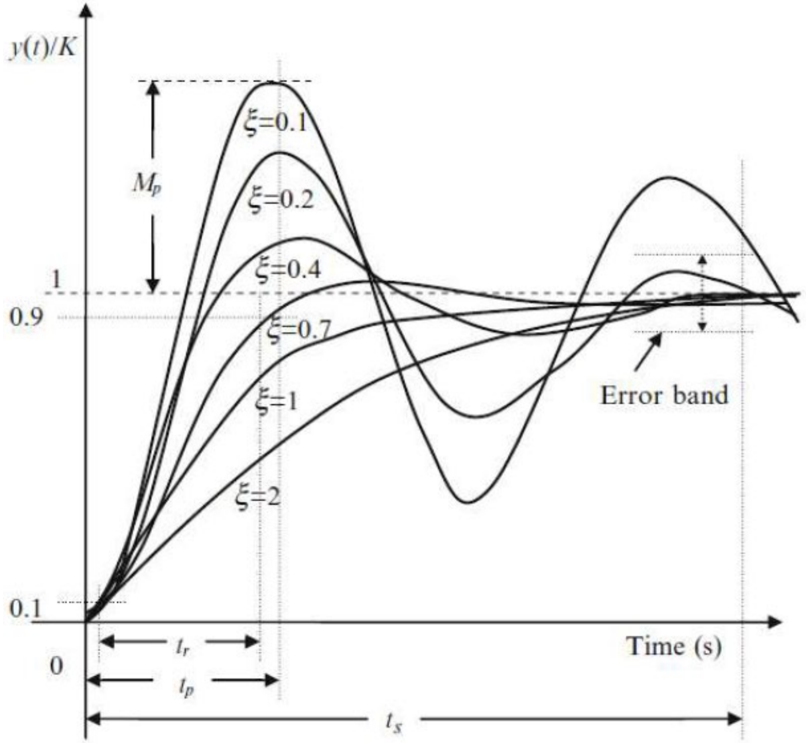
Sensor Characteristics

Dynamic Characteristics:

Second order system:

- The Spec sheet of most sensors will not provide natural frequency and damping ratio, but rather they provide:

  - Rise time (t_r).
  - Peak overshoot (M_p).
  - Time to first peak (t_p).
  - Settling time (t_s).

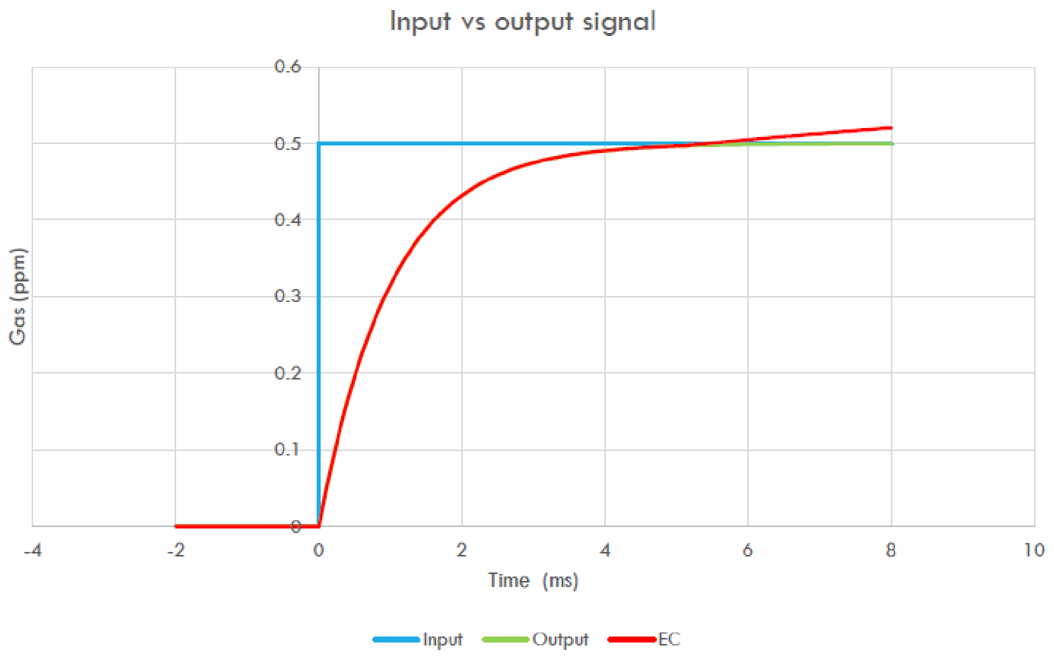


Sensor Characteristics

Dynamic Characteristics:

Higher order system:

- Most sensing systems can be nicely described either with the first or second-order equations.
- However, more complexity systems can exist.
- For instance, in semiconducting gas sensors, after the initial interactions of the gas with the surface, which is generally a first-order response, many other interactions might occur to change the order of the system.

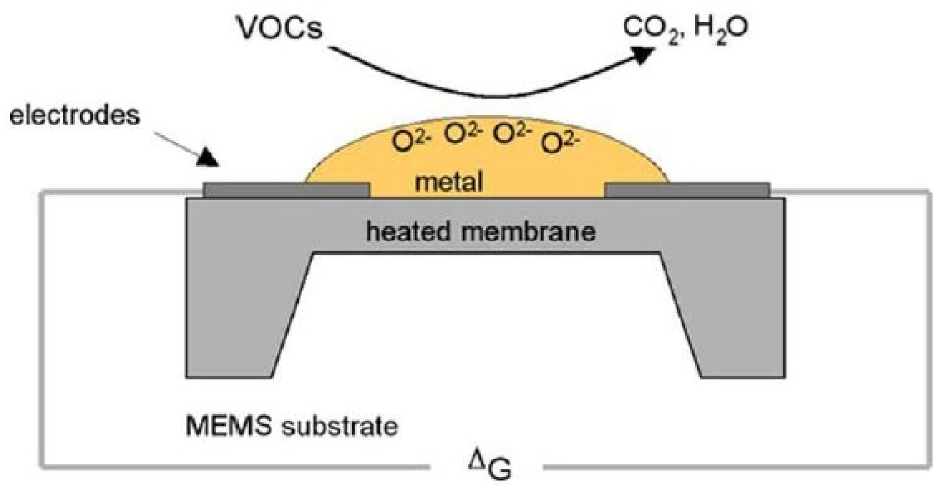


Sensor Characteristics

Dynamic Characteristics:

Higher order system:

- Gas molecules might further diffuse into the bulk of the materials, the morphology of the
- sensitive material might change, and several stages of interaction might occur.
- In such systems, obtaining the mathematical description of the dynamic responses can be quite a challenging task.



The End of Lecture #7

BIRZEIT UNIVERSITY
Department of Mechanical and
Mechatronics Engineering

ENMC3361
Sensors and Instrumentation

Lecture #8

Ihab Abu Ajamieh, PhD.

Sensor Characteristics

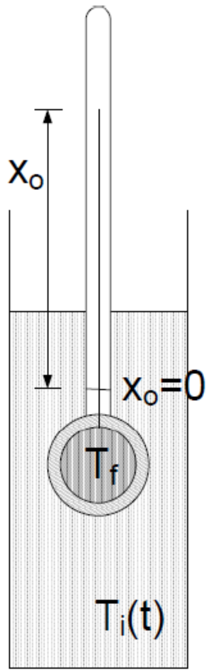
Dynamic Characteristics:

Example:

Find the sensitivity (k) and the time constant (τ) of the liquid in glass thermometer shown in the figure.

- The conservation of energy provides relation between thermometer temperature (T_f) and liquid temperature (T_i) - First order response
- The differential equation that describes the system is:

$$V_b \rho C \frac{dT_f}{dt} + U A_b T_f = U A_b T_i \quad \ldots\ldots\ldots \quad (1)$$



Where:

V_b: the bulb volume in $[m^3]$.

ρ : mass density of thermometer fluid $[kg/m^3]$.

C : specific heat of thermometer fluid [J/(kg°C)].

U : overall heat-transfer coefficient across bulb wall [W/(m2°C)]

A_b : heat transfer area of bulb wall $[m^3]$.

Sensor Characteristics

Dynamic Characteristics:

Example Contd.:

Relation between thermometer liquid level (x_o) and liquid temperature (T_i) given as:

$$x_o = \frac{K_{ex}V_b}{A_c}T_f \quad \dots\dots\dots \quad (2)$$

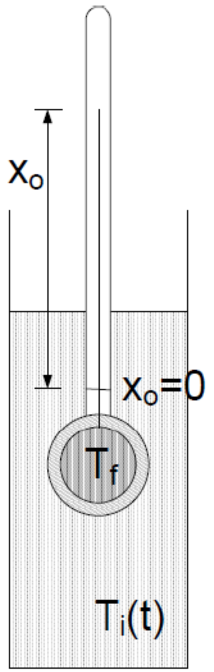
Where:

x_o : Displacement from reference mark [m] - The system output.

K_{ex} : Differential expansion coefficient of fluid and bulb [m^3/(m^3°C)]

V_b: the bulb volume in [m^3].

A_c : cross sectional area of capillary tube [m^2].



Sensor Characteristics

Dynamic Characteristics:

Example Contd.:

- Rearrange Eq. (2) to get : $T_f = \frac{A_c\, x_o}{K_{ex}\, V_b}$ …….. (3)
- Then substitute Eq. (3) in Eq. (1) to get: $\frac{\rho C A_c}{K_{ex}} \frac{dx_o}{dt} + \frac{U A_b A_c}{K_{ex} V_b} x_o = U A_b T_i$ …….. (4)
- Recall the first order system Eq.: $\tau \frac{dy(t)}{dt} + y(t) = K$ …….. (5)
- Rearrange Eq. (4) by multiplying it by the output $y(t)$ term $\left[\frac{K_{ex} V_b}{U A_b A_c}\right]$ to get Eq. (6):

$$\left[\frac{K_{ex} V_b}{U A_b A_c}\right] \frac{\rho C A_c}{K_{ex}} \frac{dx_o}{dt} + \left[\frac{K_{ex} V_b}{U A_b A_c}\right] \frac{U A_b A_c}{K_{ex} V_b} x_o = \left[\frac{K_{ex} V_b}{U A_b A_c}\right] U A_b T_i$$

$$\rightarrow \quad \frac{\rho C V_b}{U A_b} \frac{dx_o}{dt} + x_o = \left[\frac{K_{ex} V_b}{A_c}\right] T_i \qquad …….. \quad (6)$$

- Compare Eq. (6) with Eq. (5) to get: $\tau = \frac{\rho C V_b}{U A_b}$ and $K = \frac{K_{ex} V_b}{A_c}$

Calibration

Calibration Introduction:

What is calibration?

- Calibration is the development of a mathematical model that would describe the behavior of a sensor to the measurand and external environment
- Calibration is the derivation of the static and dynamic characteristics of a sensor.
- Understanding the static and dynamic characteristics of a sensor can be an impossible task.
- Often it is assumed that some characteristics of a sensor are common among all sensors manufactured or at least all sensors in the batch.

Calibration

Calibration Introduction :

The challenge:

To be able to fully characterize all sensor characteristics, the calibration procedure must.

- Provide the exact measurand.
- Hold or change the measurand over time as required by the calibration procedure.
- Control all other factors that may affect sensor response such as external environment and supply voltage.

Time for Projects discussion

The End of Lecture #8

ENMC3361

Sensors and Instrumentation

Lecture #9

Project discussion

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