Instrumentation & Measurement

Winter 2024

Sensor Characteristics

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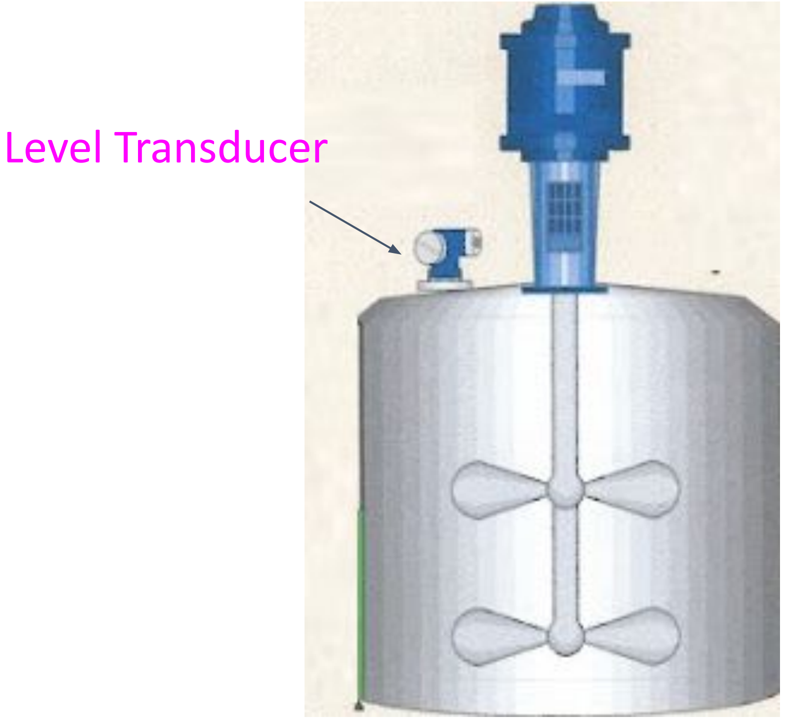
Homework 1

There is a level transducer measuring level of a tank. The measurement range is 0.3 to 1.8 meter and the output range is 2-10 volt. The transducer is linear sensor like previous example.

Question 1 - If the sensor output voltage is 5 volt what is the level of the tank in meter?

Question 2 - If the level of the tank is 1 meter what would be the the sensor output voltage value?



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$$O = a \times I + b$$

$$a = \frac{\Delta O}{\Delta I} = \frac{10\,V - 2\,V}{1.8\,m - 0.3\,m} = 5.33\,\frac{V}{m}$$

$$2\,V = 5.33 \times 0.3 + b \;\Rightarrow\; b = 0.4\,V$$

$$O = 5.33 \times I + 0.4\,V$$

Question 1:

$$5 = 5.33 \times I + 0.4\,V \;\Rightarrow\; I = 0.863\,m$$

Question 2:

$$O = 5.33 \times 1 + 0.4\,V \Rightarrow O = 5.73$$

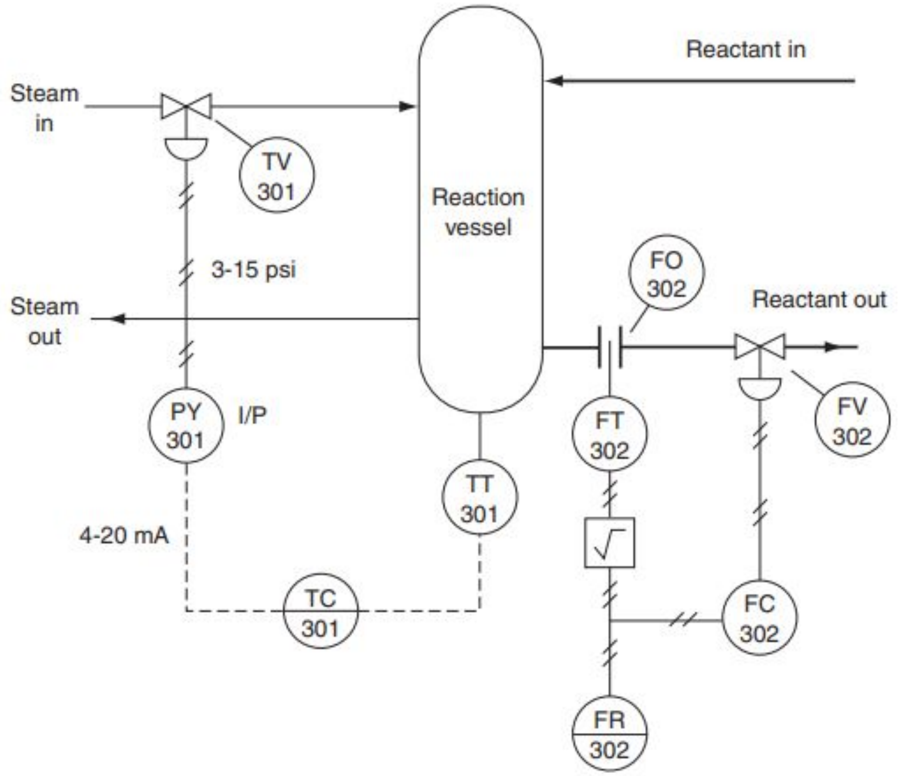
Homework 2

In front P&ID TT-301 is a temperature transducer. Lets assume the measurement range of the transducer is -50 to 150 °C and its output range is 0 - 20 mA

Question 1 - If the sensor output current is 8 mA. what would be the tank temperature in °C ?

Question 2 - If the temperature is 120 °C what would be the the sensor output current?

Based on data sheet the transducer is linear sensor



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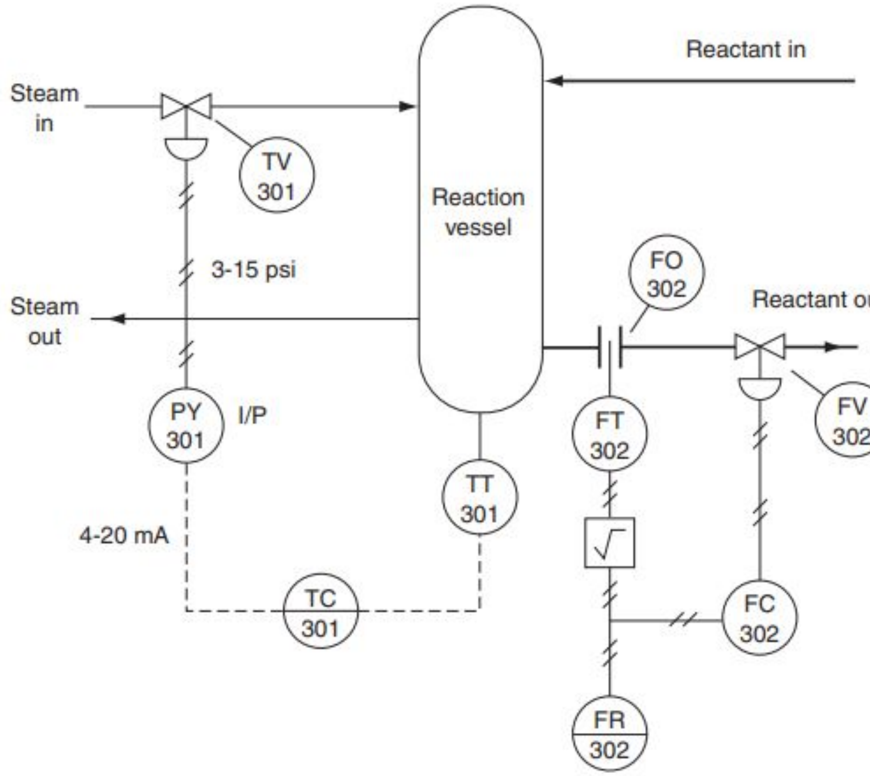

$$O = a \times I + b$$

$$a = \frac{\Delta O}{\Delta I} = \frac{20\ mA - 0\ mA}{150\ ℃ - (-50℃)} = 0.1\ \frac{mA}{℃}$$

$$0\ mA = 0.1 \times (-\ 50℃) + b \quad \Rightarrow \quad b = 5\ mA$$

$$O = 0.1 \times I + 5\ mA$$

Question 1:

$$8 = 0.1 \times I + 5\ mA \quad \Rightarrow \quad I = 30\ ℃$$

Question 2:

$$O = 0.1 \times 120\ ℃ + 5\ mA \Rightarrow O = 17\ mA$$

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Introduction to Process Control

- **Source Book 1:**

  Measurement and Instrumentation: Theory and Application

  Alan S. Morris, Reza Langari

  Third Edition , Academic Press 2020

  Chapter 2

- **Source Book 2:**

  Principles of Measurement Systems

  John P. Bentley, Pearson Canada 4th Edition (Nov 2004)

  Chapter 1

- **Source Book 3:**

  Process Control Instrumentation Technology

  Curtis D. Johnson

  Eighth Edition

  Pearson Education Limited 2014

  Principles of Measurement Systems

  John P. Bentley

  Pearson Canada 4th Edition (Nov 2004)

Measurement Units

SI Units

Table 1.1: Fundamental SI units.

Quantity	Standard unit	Symbol
(a) Fundamental units		
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	kelvin	K
Luminous intensity	candela	cd
Matter	mole	mol
(b) Supplementary fundamental units		
Plane angle	radian	rad
Solid angle	steradian	sr

Derived units

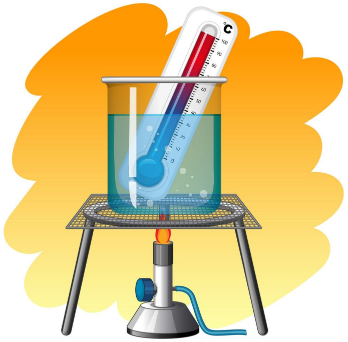
Quantity Symbol	Quantity Definition	Unit Name	Unit Symbol	Unit Definition
f	Frequency	Hertz	Hz	s^{-1}
W	Energy	Joule	J	$kg \cdot m^2/s^2$
F	Force	Newton	N	$kg \cdot m/s^2$
R	Resistance	Ohm	Ω	$kg \cdot m^2/(s^3 \cdot A^2)$
V	Voltage	Volt	V	$A \cdot \Omega$
p	Pressure	Pascal	Pa	N/m^2
ω	Angular frequency	Radians per second	rad/s	rad/s
E	Illuminance	Lux	lx	lm/m^2
Q	Charge	Coulomb	C	$A \cdot s$
L	Inductance	Henry	H	$kg \cdot m^2/(s^2 \cdot A^2)$
C	Capacity	Farad	F	$s^4 \cdot A^2/kg\text{-}m^2$
G	Conductance	Siemen	S	Ω^{-1}
Φ	Luminous flux	Lumen	lm	cd/sr
	Luminous efficacy	Lumen per watt	lm/W	lm/W
P	Power	Watt	W	J/s

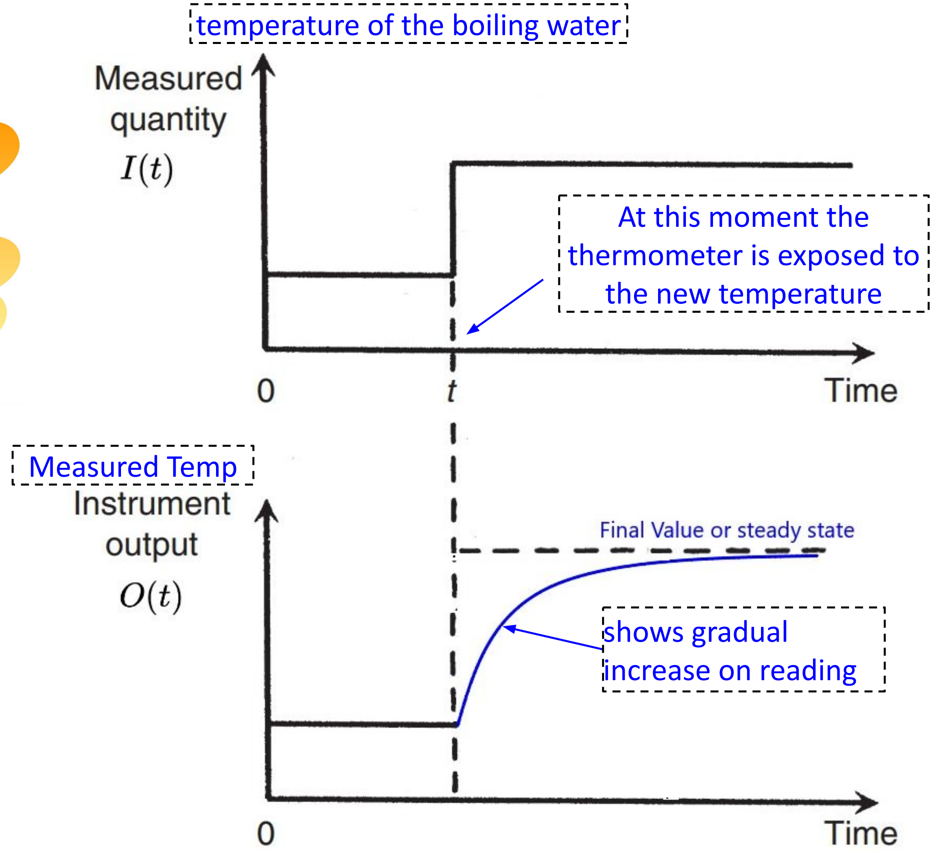
English System Units

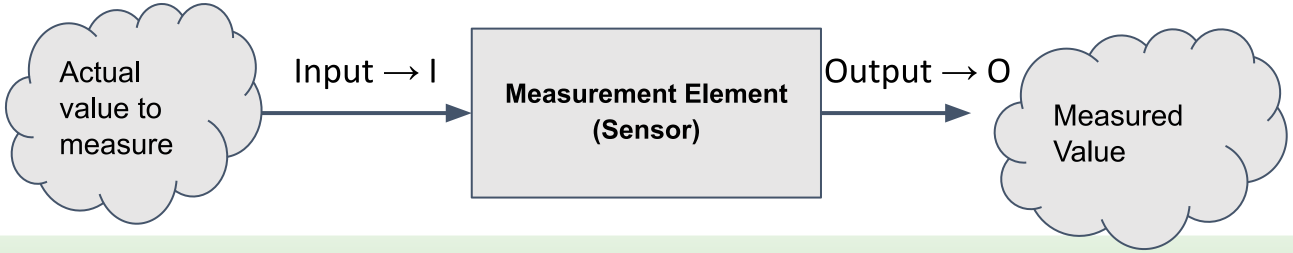
Quantity	English Unit	Variations	Conversion to SI
Length	Foot (ft)	inch (in.): 12 in. = 1 ft yard (yd): 1 yd = 3 ft mile (mi): 1 mi = 5280 ft	1 in. = 0.02540 m (exact)
Area	Foot^2(ft^2)	inch^2 (in.^{2}): 144 in.^{2} = 1 ft^2 acre: 1 acre = 21,789 ft^2	10.76 ft^2 = 1 m^2
Volume	Foot^3(ft^3)	inch^3 (in.^{3}): 1728 in.^{3} = 1 ft^3 gallon (gal): 1 gal = 0.134 ft^3 quart (qt): 4 qt = 1 gal pint (pt): 2 pt = 1 qt	35.31 ft^3 = 1 m^3 1 gal = 3.785 liters 1 gal = 0.003875 m^3
Force	Pound (lb)	ounce (oz): 16 oz = 1 lb	1 lb = 4.448 N
Mass	Slug (not used) Pound (lb) (see "Mass Note")		1 slug = 14.59 kg 1 lb (mass) = 0.454 kg
Energy	Foot-pound (ft-lb)		1 ft-lb = 1.356 J
Pressure	Pound/inch^2 (psi)	atmosphere (atm): 1 atm = 14.7 psi	1 psi = 6895 Pa
Power	Horsepower (hp)		1 hp = 746 W

Static and Dynamic Characteristic

- The static characteristics of measuring instruments are about the final measured value by the sensor. For example how accurate is the measurement.
- The dynamic characteristics of a measuring instrument describe its behavior between the time the instrument is exposed to a new measuring quantity and the final measured value. For example how fast the final value is reached.







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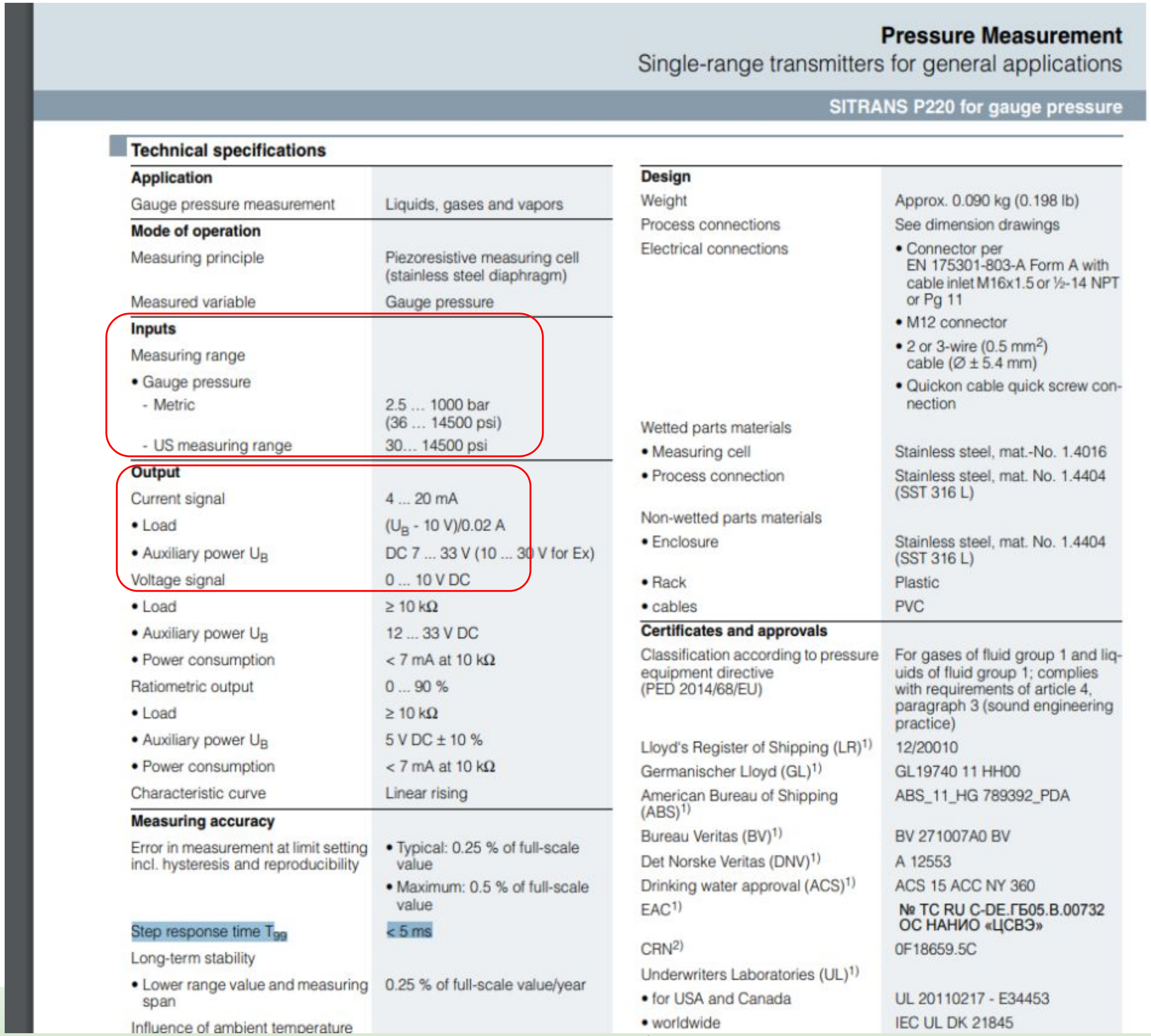
Sensor Characteristic

- Static Characteristic
  - Range or Span
  - Sensitivity
  - Linearity , Sensitivity and Bias
  - Dead Zone
  - Nonlinearity
  - Hysteresis
  - Repeatability & Reproducibility
  - Accuracy
  - Precision
  - Resolution
- Dynamic Characteristic
  - Zero order response
  - First order response
  - Time constant
  - Response time
  - Second order response

Range or Span

The *input* range or span of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure.

The *output* range or span of an instrument defines the minimum and maximum of the output value the sensor provides for measured quantity.



Pressure Measurement
Single-range transmitters for general applications

SITRANS P220 for gauge pressure

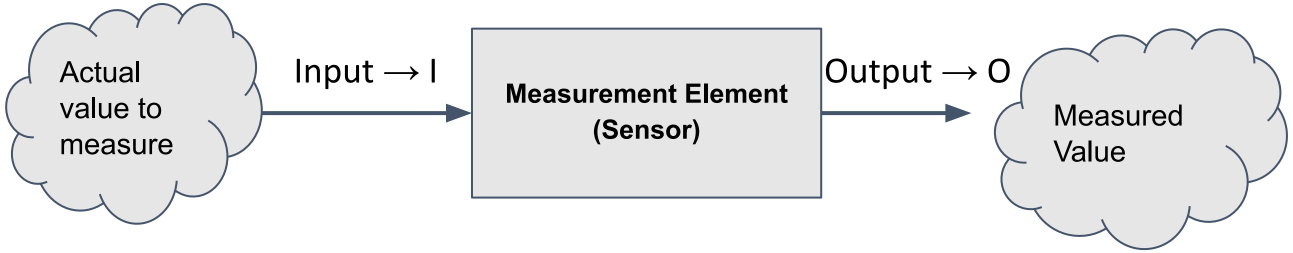
Technical specifications

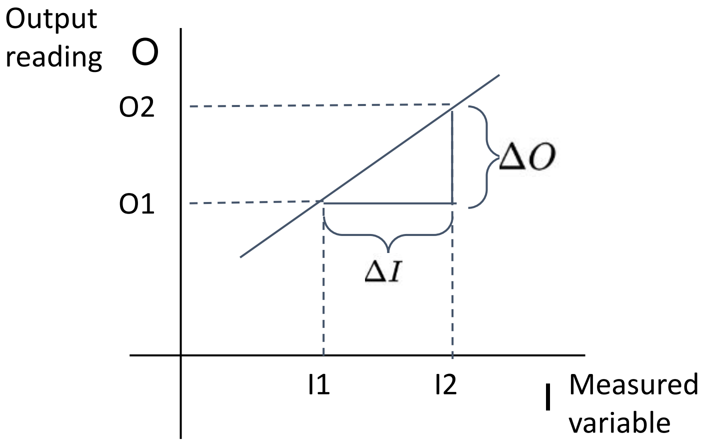
Application	
Gauge pressure measurement	Liquids, gases and vapors
Mode of operation	
Measuring principle	Piezoresistive measuring cell (stainless steel diaphragm)
Measured variable	Gauge pressure
Inputs	
Measuring range	
• Gauge pressure	
- Metric	2.5 ... 1000 bar (36 ... 14500 psi)
- US measuring range	30... 14500 psi
Output	
Current signal	4 ... 20 mA
• Load	$(U_B$ - 10 V)/0.02 A
• Auxiliary power U_B	DC 7 ... 33 V (10 ... 30 V for Ex)
Voltage signal	0 ... 10 V DC
• Load	≥ 10 kΩ
• Auxiliary power U_B	12 ... 33 V DC
• Power consumption	< 7 mA at 10 kΩ
Ratiometric output	0 ... 90 %
• Load	≥ 10 kΩ
• Auxiliary power U_B	5 V DC ± 10 %
• Power consumption	< 7 mA at 10 kΩ
Characteristic curve	Linear rising
Measuring accuracy	
Error in measurement at limit setting incl. hysteresis and reproducibility	• Typical: 0.25 % of full-scale value • Maximum: 0.5 % of full-scale value
Step response time T_{99}	< 5 ms
Long-term stability	
• Lower range value and measuring span	0.25 % of full-scale value/year
Influence of ambient temperature	

Design	
Weight	Approx. 0.090 kg (0.198 lb)
Process connections	See dimension drawings
Electrical connections	• Connector per EN 175301-803-A Form A with cable inlet M16x1.5 or ½-14 NPT or Pg 11 • M12 connector • 2 or 3-wire (0.5 mm²) cable (Ø ± 5.4 mm) • Quickon cable quick screw connection
Wetted parts materials	
• Measuring cell	Stainless steel, mat.-No. 1.4016
• Process connection	Stainless steel, mat. No. 1.4404 (SST 316 L)
Non-wetted parts materials	
• Enclosure	Stainless steel, mat. No. 1.4404 (SST 316 L)
• Rack	Plastic
• cables	PVC
Certificates and approvals	
Classification according to pressure equipment directive (PED 2014/68/EU)	For gases of fluid group 1 and liquids of fluid group 1; complies with requirements of article 4, paragraph 3 (sound engineering practice)
Lloyd's Register of Shipping (LR)[1]	12/20010
Germanischer Lloyd (GL)[1]	GL19740 11 HH00
American Bureau of Shipping (ABS)[1]	ABS_11_HG 789392_PDA
Bureau Veritas (BV)[1]	BV 271007A0 BV
Det Norske Veritas (DNV)[1]	A 12553
Drinking water approval (ACS)[1]	ACS 15 ACC NY 360
EAC[1]	№ TC RU C-DE.ГБ05.B.00732 ОС НАНИО «ЦСВЭ»
CRN[2]	0F18659.5C
Underwriters Laboratories (UL)[1]	
• for USA and Canada	UL 20110217 - E34453
• worldwide	IEC UL DK 21845

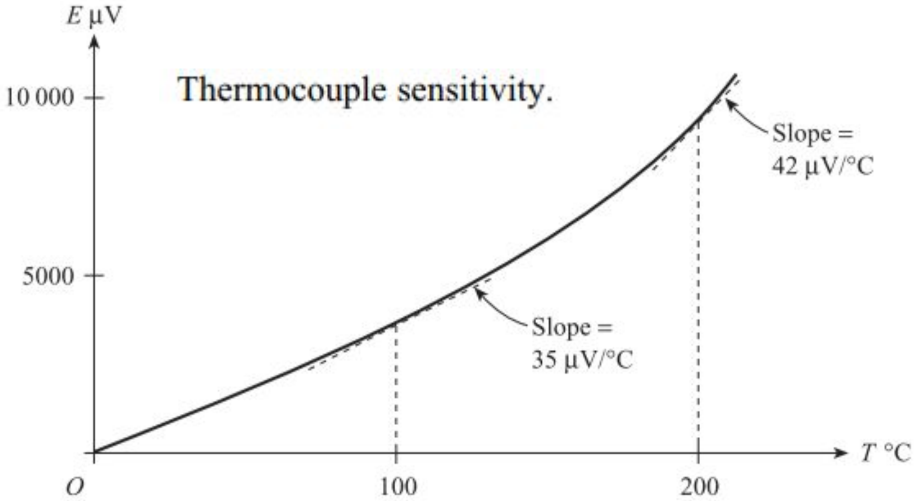
Sensitivity

- Sensitivity is defined as change of output per unit change of input or in another word the ratio of output change over the corresponding input change.
- For a linear instrument this would be the slope of Input/output graph.
- For nonlinear instrument the slope would be the gradient of graph at each point of measurement.





$$Sensitivity = \frac{O_2 - O_1}{I_2 - I_1} = \frac{\Delta O}{\Delta I}$$



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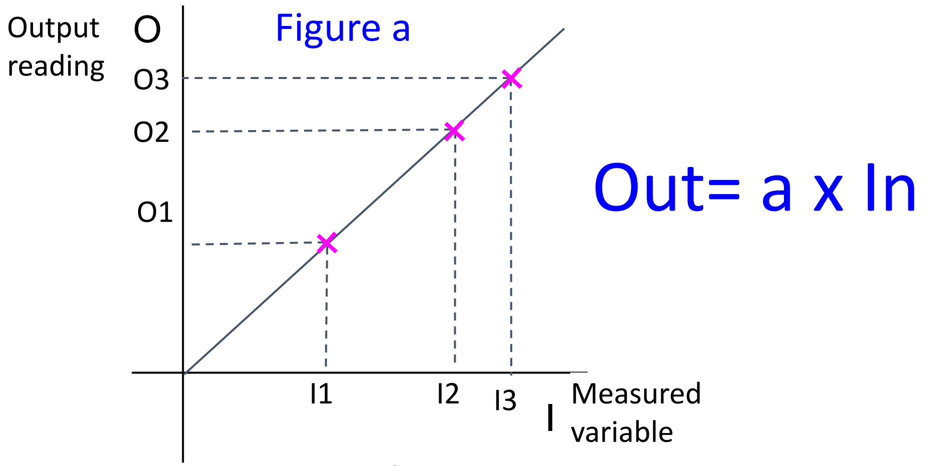
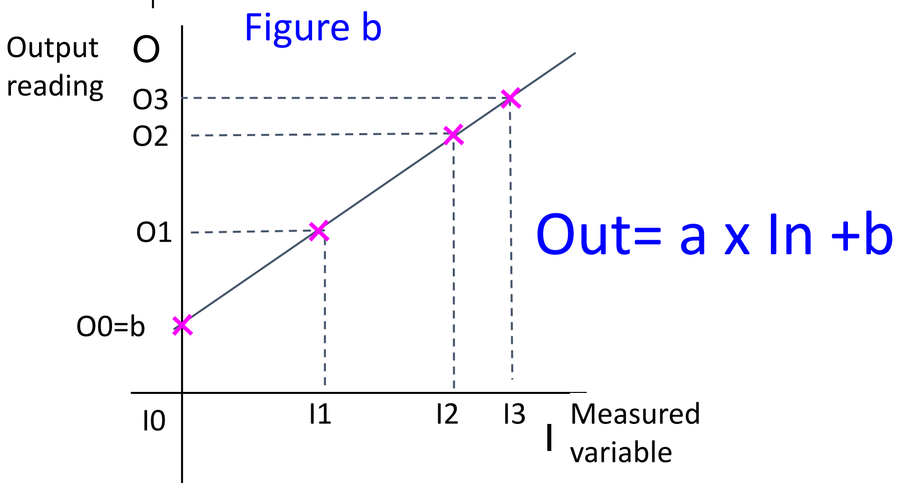
Linearity , Sensitivity and Bias

- An instrument is called to be linear when the output is directly proportional to input values.
- On graph presentation, the output graph vs input is a straight line. The straight line might pass through intersection of two axis like figure and sometimes might not like figure b.
- In both figures a= ΔO/ΔI represents the slope of the line which is also known as sensitivity of the sensor.
- In figure b when I=0 (means no input is applied to the sensor), the sensor output will be equal to b . The b in known as Bias.
- In another word, Bias is the sensor output when no input is applied to it.
- Figure a shows a zero output sensor and figure b a biased output sensor





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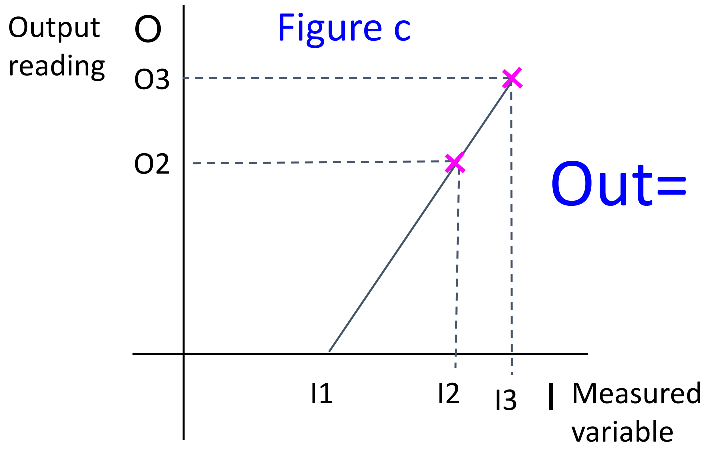
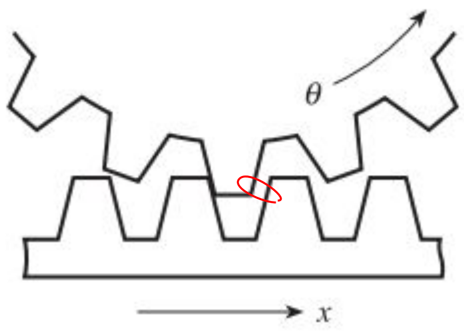
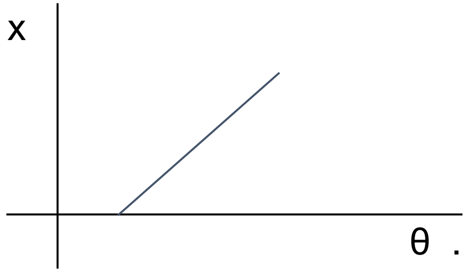
Sensor with Dead zone

- In figure c , the input less than I1 is applied to the sensor but output does change and stay constant. This property is known as dead zone of the sensor.
- In other words when it is being said that a sensor has dead zone, it means that the sensor will not be responsive for small amount of inputs.
- Example Backlash in gears is a typical example of dead zone.



$$Out = a \times (I - I_1)$$





Example

In front figure you see part of a sensor datasheet. The sensor is a linear sensor within its measurement range. Find the:

a) measuring range
b) output range
c) Draw the IO graph.
d) then find the sensitivity as mA/psi?
e) Does the sensor have bias or dead zone? how much?

Technical specifications

Application	
Gauge pressure measurement	Liquids, gases and vapors
Mode of operation	
Measuring principle	Piezoresistive measuring cell (stainless steel diaphragm)
Measured variable	Gauge pressure
Inputs	
Measuring range	
• Gauge pressure	
- Metric	2.5 ... 1000 bar (36 ... 14500 psi)
- US measuring range	30... 14500 psi
Output	
Current signal	4 ... 20 mA
• Load	$(U_B - 10\ V)/0.02\ A$
• Auxiliary power U_B	DC 7 ... 33 V (10 ... 30 V for Ex)
Voltage signal	0 ... 10 V DC
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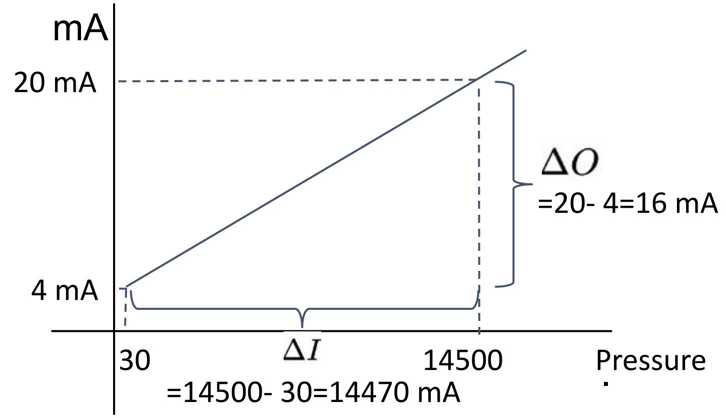
Characteristic curve	Linear rising

Example

In front figure you see part of a sensor datasheet. The sensor is a linear sensor within its measurement range. Find the:

a) measuring range 30 …14500 psi
b) output range 4-20 mA
c) Draw the IO graph.
d) then find the sensitivity as mA/psi?
e) Does the sensor have bias and dead zone? how much?
   bias , 4 mA - Dead zone 30 psi



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Characteristic curve	Linear rising

$$Sensitivity = \frac{20-4\ mA}{14500-30\ psi} = 0.00110574\ \frac{mA}{psi}$$

Non-Linearity

- It is very much desired to have a perfect linear sensor because it makes it easy to incorporate it into a control system and process its data in a controller.
- In reality, the sensor output might not fall on a straight line like the points denoted by x marks in front figure, In order to measure ow much a sensor is linear or not, a best-fit straight line can be placed over the measured X's points. This straight line represent the ideal linear response we are looking for. deviation from this line shows how much nonlinear the sensor is.
- The nonlinearity is expressed as ratio of maximum deviation from best fit straight line over the measurement range in percentage.
- For example at measurement point I=6, the sensor sensed value is 9 and the corresponding value on the straight line is 8.5. It means if the sensor was an ideal linear sensor then we should have measured 8.5 which we do not. The difference between actual measurement and ideal expected output is 0.5. If this sensor output range is from 0-15 then nonlinearity factor is 0.5/15*100=3.3 % .
- Nonlinearity is usually expressed as a percentage of full-scale reading.

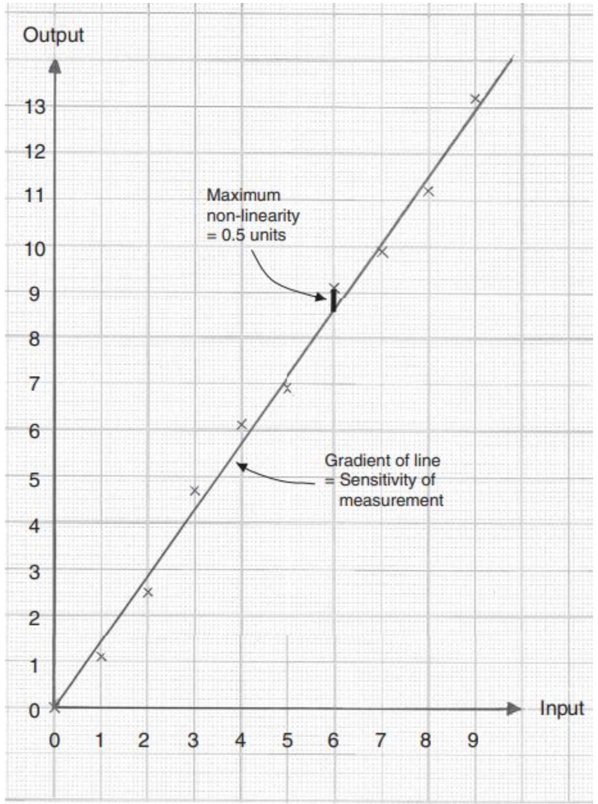

Figure 2.6
Instrument output characteristic.

$$O_{Linear}(I) = K \times I + c$$

$$N(I) = O_{actual}(I) - O_{Linear}(I)$$

$$Non - Linearity = \frac{N_{max}}{O_{max} - O_{min}} \times 100\%$$

$as\ \%\ of\ FS$

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Non-Linearity Example

There is a temperature sensor which measure 0-100 ℃. The sensor output is 0-10 volt. The sensor is assumed to be linear and Non-linearity factor is provided by data sheet as ±1% .

We put the temperature sensor in a glass of water and measure the sensor output by multimeter. The multimeter shows 5 volt. What could be the true temperature value?

Non-Linearity Example

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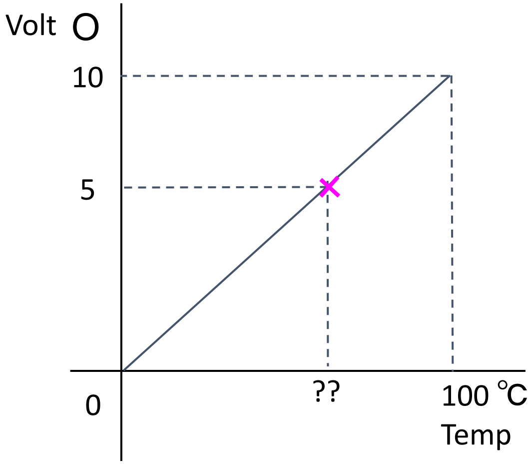

From the graph or calculation ut can be said the temperature should be 50, but for in real it is around 50

$$deviation\ from\ straight\ line \Rightarrow Non - Linearity\ error = \pm 1\,\% \times (100 - 0)\,°C = \pm 1\,°C$$

$$50 \pm 1\,°C \Rightarrow 49°C \leq true\ temperature \leq 51°C$$

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Hysteresis

Some instruments show different reading for the same measured quantity. The presented value depends on that the measured quantity (the input) is increasing or decreasing. This phenomena is known as hysteresis.

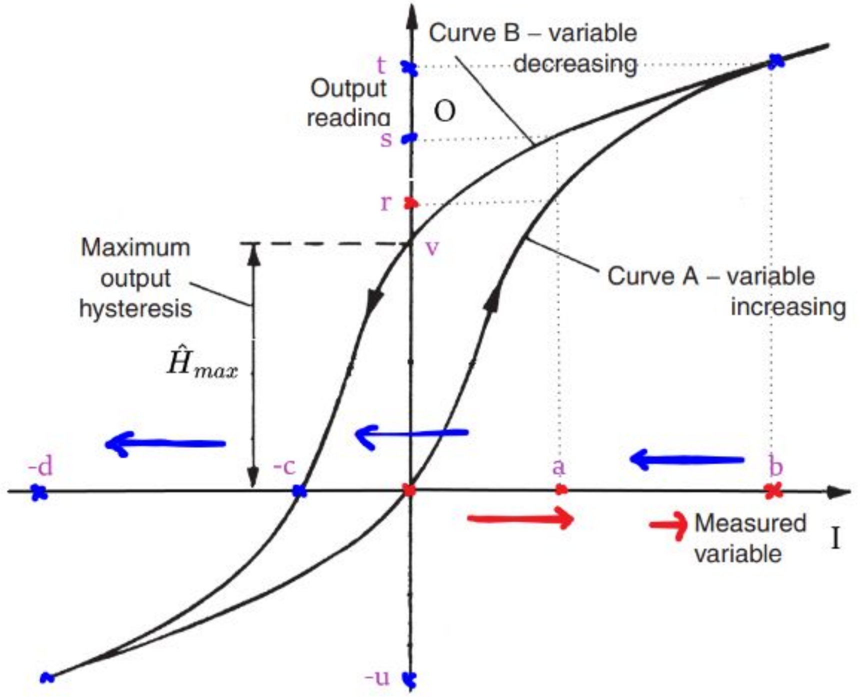
To understand this let's look at the front figure as example. This graph illustrates the relation between output and input of a sensor. Let's assume the input increases from I=0 to I=a on horizontal continuum, the sensor output will be r for I=a. The input continues to increase to I=b. At point b the sensor output will be equal to t.

Now the input starts decreasing and goes back to point a again but as graph shows, the reading value will be s. Then this instruments shows two values for the same input value a, r when the input increasing and s when the input decreasing. This is referred to as hysteresis. Let's keep decreasing the input, when I =0 the sensor output is v. When input was rising the output value was 0 and now it is v. There is difference between output reading for the same input.

Let's keep decreasing the input to the -c, at this point the output reading will be 0 again. When the input is decreased to -d, then the reading output will be -u.

As the graph shows at points b and -d the output reading will be the same no matter the input is decreasing or increasing. Between b and -d the sensor shows different values depending on I is increasing or decreasing.

The difference between the output readings when input increasing and decreasing is called hysteresis and normally specified as percentage of full scale of the output range as front formula.



$$Hysteresis \rightarrow H(I) = O(I)_{I\downarrow} - O(I)_{I\uparrow}$$

$$Hysteresis\,Max\,(\%\,FS) = \frac{H_{Max}}{O_{Max} - O_{Min}} \times 100$$

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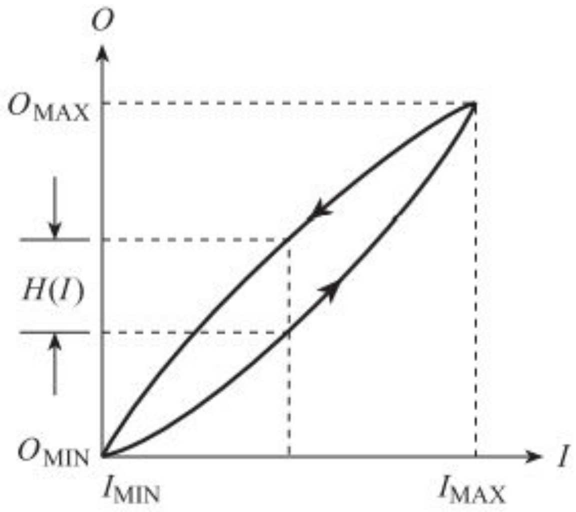
Hysteresis

- The front figure shows another example of a sensor with hysteresis behaviour.
- Example of hysteresis can be found in instruments that contain springs, such as the pressure gauges.
- Hysteresis can also occur in instruments that contain electrical windings formed round an iron core, because of magnetic hysteresis in the iron. (As example hysteresis appears in different opening and closing time in a relay)
- This occurs in devices such as the variable inductance displacement transducer, the linear variable differential transformer (LVDT) and the rotary differential transformer .
- Hysteresis is the property of the measuring instruments, for the same input two reading is produced. If we assume one of them is the actual value then the other will be deviation from the actual value. Then the hysteresis is one source of inaccuracy.



Repeatability & Reproducibility

Repeatability: is about the closeness of the sensor's output when the same input is repeatedly applied to it under identical conditions such as temperature, humidity, location, same observer or so on

Reproducibility: describes the closeness of the sensor's output when the same input is repeatedly applied to it under some changed conditions for example change of environment temperature, humidity, location, time of measurement or so on

The Non-repeatability or Non-reproducibility are usually expressed as percentage of full scale. For example 1% FS. If the measurement range is from 0-150 degree, then each reading could be deviated from true value by 1.5 degree.

The sensor repeatability or reproducibility is a factor to present the sensor's measurement reliability and precision.

Repeatability Example

In front you can see the data sheet of a pressure sensor (Setra Model 206). The sensor is used to measure compressed air pressure in a tank and its measuring range is 0-200 psi.

1- If the sensor shows 50 psi. What would be the pressure true value range and the maximum error due to Non-Repeatability?

2- The tank pressure rises from 0 to 100 and then returns to 0 again, would the sensor shows the same measurement for the tank pressure when the true pressure is 50 psi? If the sensor shows 50 psi when the pressure was rising what could be its measurement range at 50 psi when the pressure is dropping from 100 to 0 psi?

Model 206 | Industrial Pressure Transducer

setra

Specifications

Performance data

Accuracy RSS[1] (at constant temperature)	±0.13% FS
Non-linearity, (BFSL) 25 PSIG range[2]	±0.1% FS ±0.2% FS
Hysteresis	±0.08% FS
Non-repeatability	±0.02% FS
Response time	5 milliseconds
Long term stability	0.5% FS/YR

Thermal effects

Compensated range	-4 to +176°F (-20 to +80°C)
Zero shift	±1% FS/100°F (±0.9% FS/50°C)
Span shift	±1.5% FS/100°F (±1.4% FS/50°C)

Electrical data (voltage)

Excitation/ output	12 to 28 VDC reverse excitation protected
Power consumption	<0.15 watts (approx. 5mA @24VDC)
Output[8]	See ordering information[9]
Output impedance	100 ohms
Circuit	3-wire (exc, out, com)
Vibration	200g operating

Approvals

CE, RoHS

Physical description

Pressure fittings	See ordering information
Vent	Through electrical termination
Electrical connection	See ordering information
Case	Stainless steel
Zero/Span adjustments	Top external access
Weight (approx.)	6 oz.

Environmental data

Operating temperature[4]	-40 to 185°F (-40 to +85°C)
Storage temperature	-40 to +185°F (-40 to +85°C)
Acceleration	10g Maximum[5]
Shock[6]	200g operating
Vibration	20g 50-2000 Hz

Electrical data (current)

Circuit	2-wire
Output[10]	4 to 20 mA[11]
External load	See ordering information
Min. supply voltage (VDC)= 9 + 0.02 x (resistance of receiver plus line)	
Max. supply voltage (VDC)= 30 + 0.004 x (resistance of receiver plus line)	

Pressure media

Gases or liquids compatible with 17-4 PH stainless steel.[3]

Repeatability Example

In front you can see the data sheet of a pressure sensor (Setra Model 206). The sensor is used to measure compressed air pressure in a tank and its measuring range is 0-200 psi.

1- If the sensor shows 50 psi. What would be the pressure true value range and the maximum error due to Non-Repeatability?

None-repeatability error = ± 0.02 % x (200-0) = ±0.04 psi

50-0.04 ≤ true value ≤ 50+0.04 ⇒

49.96 ≤ true value ≤ 50.04

2- The tank pressure rises from 0 to 100 and then returns to 0 again, would the sensor shows the same measurement for the tank pressure when the true pressure is 50 psi? If the sensor shows 50 psi when the pressure was rising what *could be* its measurement range at 50 psi when the pressure is dropping from 100 to 0 psi?

Hysteresis = ± 0.08%x (200 - 0) = ±0.16 psi

50 ±0.16 psi ⇒ 48.4 …. 50.16

Model 206 | Industrial Pressure Transducer

setra

Specifications

Performance data

Accuracy RSS[1] (at constant temperature)	±0.13% FS
Non-linearity, (BFSL) 25 PSIG range[2]	±0.1% FS ±0.2% FS
Hysteresis	±0.08% FS
Non-repeatability	±0.02% FS
Response time	5 milliseconds
Long term stability	0.5% FS/YR

Thermal effects

Compensated range	-4 to +176°F (-20 to +80°C)
Zero shift	±1% FS/100°F (±0.9% FS/50°C)
Span shift	±1.5% FS/100°F (±1.4% FS/50°C)

Electrical data (voltage)

Excitation/ output	12 to 28 VDC reverse excitation protected
Power consumption	<0.15 watts (approx. 5mA @24VDC)
Output[8]	See ordering information[9]
Output impedance	100 ohms
Circuit	3-wire (exc, out, com)
Vibration	200g operating

Approvals

CE, RoHS

Physical description

Pressure fittings	See ordering information
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Max. supply voltage (VDC)= 30 + 0.004 x (resistance of receiver plus line)	

Pressure media

Gases or liquids compatible with 17-4 PH stainless steel.[3]

Accuracy

- The accuracy of a sensor is a measure of how close the sensor output is to the true value.

- In practice, it is more usual to quote the inaccuracy or measurement uncertainty value rather than the accuracy value for an instrument.

- Inaccuracy is the extent to which a reading might be wrong and is often quoted as a percentage of the Full Scale (FS) reading range.

$$\text{Measurement Inaccuracy} = \frac{\text{measured value by sensor} - \text{True value}}{\text{Measurement Range}} \times 100$$

Accuracy is commonly calculated in two ways:

- The worst case method

Worst Case Error = (non-linearity error) + (non-repeatability error) + (hysteresis error)

- RSS: The root of the sum squared

$$RSS\ Error = \sqrt{(\text{Non-Linearity})^2 + (\text{Non-Repeatability})^2 + (Hysteresis)^2}$$

Accuracy Example

The front figure shows part of a pressure sensor data sheet. The measurement range is 0-10 bar.

A) What is the maximum measurement error is expected from this sensor?

B) If the sensor is showing 1 bar of pressure on the display, what would be estimation for the true pressure value?

C) Now there is another sensor with same inaccuracy but measurement range is 0-1 bar. Repeat questions of A and B for the second sensor.

D) Compare C and B calculation, which sensor provides more accurate measurement?

E) If we know the required measurement range is 0-1 bar, which choice is better, a sensor with 0-10 bar full scale range or 0-1 bar?

Model 32CS

Heavy Duty Intrinsically Safe
CSA Rated Pressure Transducer

setra

GENERAL SPECIFICATIONS

Performance		Electrical Data	
Accuracy[1] RSS	±0.5% FS	Voltage[3]	
Long Term Drift	0.2% FS/YR (non-cumulative)	Output (3-Wire)	0V min to 10V max.
Thermal Error		Supply Voltage	1 Volt above full scale with min supply of 8V; max 30V at 4.5mA
32CS	±2% max	Source & Sinks	2 mA
Compensated Range	-40 to +176ºF (-40 to +80ºC)	Current[3]	
Operating Temp	-40 to +176ºF (-40 to +80ºC)	Output (2-Wire)	4-20 mA
Zero Tolerance Max.	0.5% of Span	Supply Voltage	8-24 Volts measured at the input to the transducer terminals
Span Tolerance Max.	0.5% of Span	Max Loop Resistance	(Supply Voltage - 8) x 50 ohms. See Graph Below
Fatigue Life	Designed for more than 100M cycles	Ratiometric Output	
Physcial Description		Output	0.5 to 4.5V (Source & Sink 2 mA)
Pressure Port	See Ordering Information	Supply Voltage	5 VDC ±10% at 4.5 mA

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Accuracy Example

The front figure shows part of a pressure sensor data sheet. The measurement range is 0-10 bar.

A) What is the maximum error is expected from this sensor?

B) If the sensor is showing 1 bar of pressure on the display, what would be estimation for actual pressure value?

C) Now there is another instrument with same inaccuracy but measurement range is 0-1 bar. Do the calculation of A and B for the second sensor.

D) Compare C and B calculation, which sensor provides more accurate measurement?

E) If we know the required measurement range is 0-1 bar, which choice is better, a sensor with 0-10 bar full scale range or 0-1 bar?

$$Inaccuracy\,of\,a\,measurement = \frac{\text{Measured - True}}{Measurement\ Range} \times 100$$

$A)$ Max Error$=$Max(Measured-True)

$$\pm 0.5 = \frac{Error}{10} \times 100$$

$$Error = \pm 0.05\,bar$$

$$B)\,Inaccuracy\,of\,a\,measurement = \frac{\text{Measured - True } value}{Measurement\ Range} \times 100$$

$$\Rightarrow \quad \pm 0.5 = \frac{1 - True\,value}{10} \times 100 \;\Rightarrow\; 0.95 \leqslant \text{True}\,value \leqslant\; 1.05$$

$C)$

$$\pm 0.5 = \frac{Error}{1} \times 100$$

$$Error = \pm 0.005$$

$$\pm 0.5 = \frac{1 - \text{true}\,value}{1} \times 100 \;\Rightarrow\; 0.995 \leqslant true\,value \leqslant\; 1.005$$

$D)$ The sensor with smaller range provide more accurate measurement

Precision

- If a measurement for same quantity is repeated a few times for one input, Precision is defined as closeness of the sensor outputs *to each other*.
- To express the precision with a number, the average of all outputs are are calculated then maximum difference of the measurements from their average represent the precision.
- From another perspective, Precision is a term that describes an sensor's degree of freedom from random errors.
- Precision is often, although incorrectly, confused with accuracy. Accuracy is about closeness of measurement to true value whereas precision is about closeness to each other.
- High precision does not imply anything about measurement accuracy. A high-precision instrument may have a low accuracy.

$$\textit{sensor measured values (outputs) for the same inputs are:}$$

$$O_1, O_2, O_3, O_4, \ldots, O_n$$

$$O_{average} = \frac{O_1 + O_2 + O_3 + O_4 + \ldots + O_n}{n}$$

$$\textit{Precision of output } i = O_1 - O_{average}$$

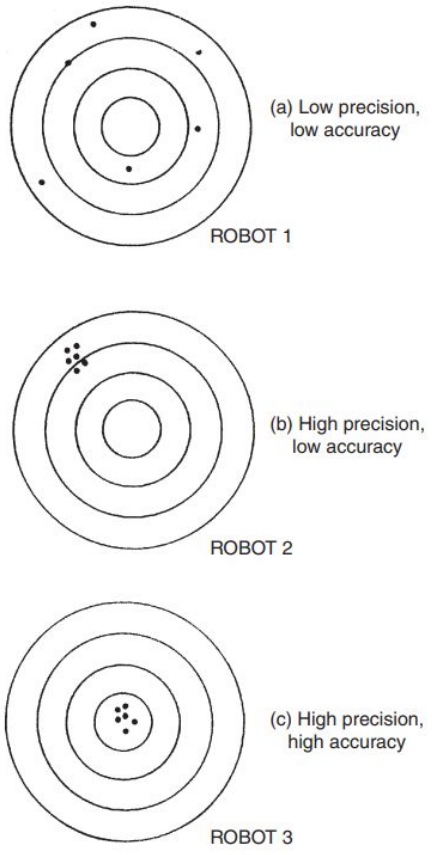

Figure 2.5
Comparison of accuracy and precision.

Precision Example:

The width of a room is measured 10 times by an ultrasonic rule and the following measurements are obtained (in meters):

5.381, 5.379, 5.378, 5.382, 5.380, 5.383, 5.379, 5.377, 5.380, and 5.381.

The width of the same room is then measured by a calibrated steel tape that gives a reading of 5.374 m, which can be taken as the correct value for the width of the room.

(a) What is the measurement precision of the ultrasonic rule?

(b) What is the maximum measurement inaccuracy of the ultrasonic rule?

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(a) What is the measurement precision of the ultrasonic rule?

(b) What is the maximum measurement inaccuracy of the ultrasonic rule?

$$\frac{5.381+5.379+5.378+5.382+5.380+5.383+5.379+5.377+5.380+5.381}{10} = 5.380$$

$$maximum(\,outputs - 5.380) = (5.383 - 5.380) = 3\,mm$$

$$\Rightarrow precision = +\,3\,mm$$

$$Maximum\ Inaccuracy = 5.383 - 5.374 = 9\,mm$$

Resolution

- The minimum measurable value of the input variable is called Resolution. In another words if the input changes less than the resolution value not changes in output reading will appear.
- Resolution is sometimes specified as an absolute value and sometimes as a percentage of the full-scale deflection.
- In front you see an example of level sensor with resolution of 1 mm. If the level changes for 0.5 mm the sensor will not be able to sense it.
- The sensor resolution is different than display resolution. If the display format is selected by technician to be xx.xx in meter, and the sensor shows the reading of 6.50, the measurement value could be between 6.545 and 6.555 but because the the there are two decimal point on the display then the presented value is rounded to 6.50.
- In this case less assume the measured value is is 6.547 and the level changes for 5 mm, the sensor will measure it and new measure value will be 6.547 +0.005 = 6.552 but the display still shows 6.50 .
- To use the sensor resolution the display should be set up to the format of x.xxx meter (a display with 3 decimal point) or any alternative format which can take 1 mm into account.

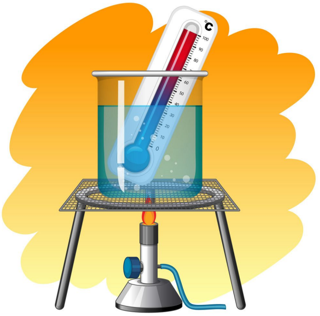
Radar - Level Control (turck.ca)

Sensor Characteristic

- Static Characteristic
  - Range or Span
  - Sensitivity
  - Linearity , Sensitivity and Bias
  - Dead Zone
  - Nonlinearity
  - Hysteresis
  - Repeatability & Reproducibility
  - Accuracy
  - Precision
  - Resolution

- Dynamic Characteristic
  - Zero order response
  - First order response
  - Time constant
  - Response time
  - Second order response

Sensor Response



As we learned static characteristic discuss about the measured value by sensor and dynamic response is about to reach to that measurement.

When a sensor is exposed to a new quantity for measurement, the input of the sensor changes suddenly. This sudden change known as step input (Figure-1). For example the thermometer shows the room temperature and then we put in boiling water. The temperature sensed by thermometer jumps up.

Different types of sensors respond in different way:

1. in very very short time so that we consider it instanously, these type of sensors are known as zero order sensors. (Figure-2)
2. The sensors which reach to the final measurement gradually and their output never goes beyond final output value. These type of sensors are known as first order sensors. (Figure-3)
3. Some sensors output might go beyond and below the final value and after a while settle down to the final value. These type of sensors are known as second order sensors. (Figure-4)

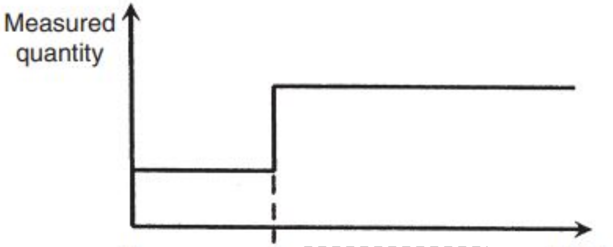


Figure-1

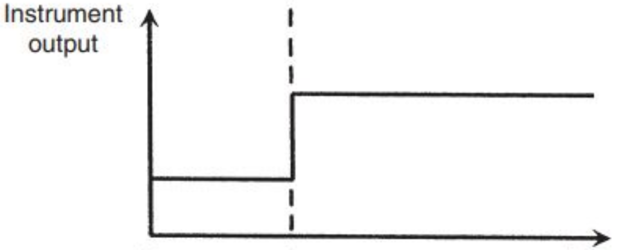


Figure-2

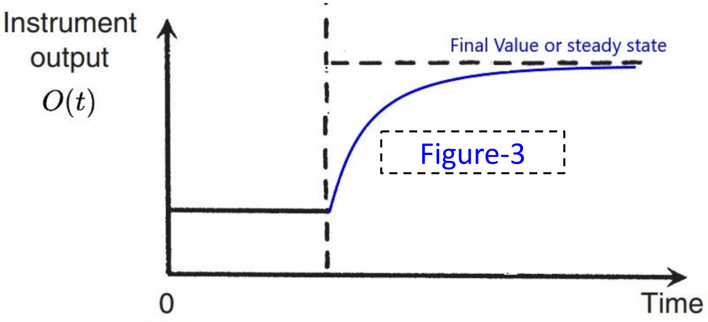


Figure-3

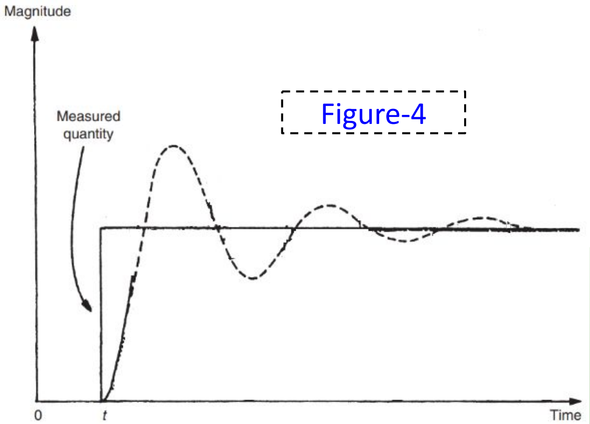
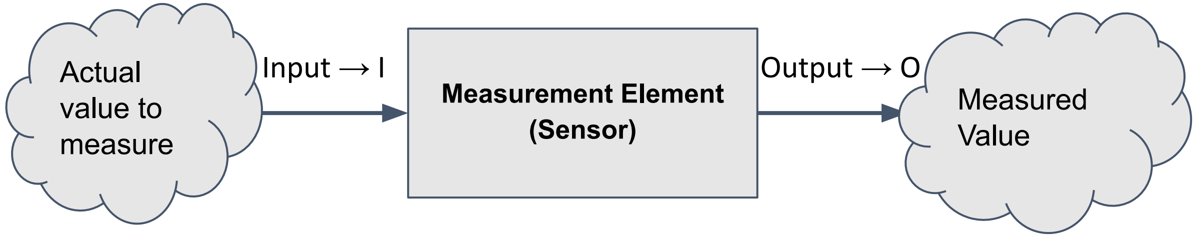
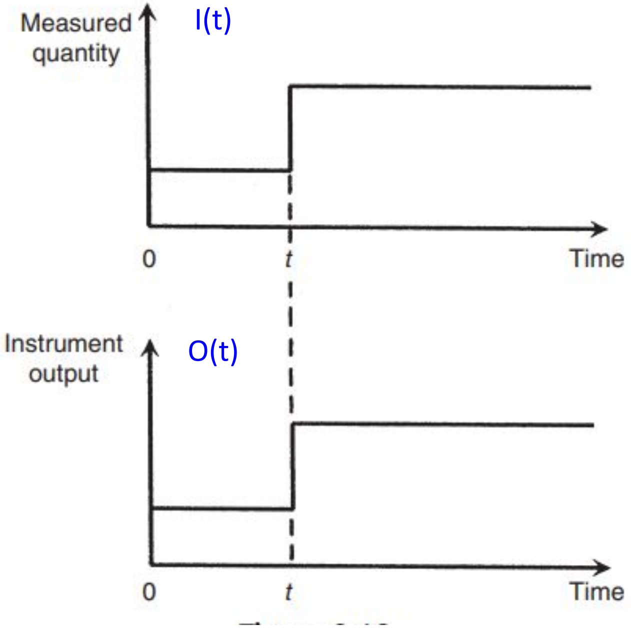


Figure-4

Sensors with Zero-order Response



After a step change in the measured quantity at time t, the instrument output moves immediately to a new value almost at the same time instant t, as shown on the front Figure.



A potentiometer, which measures motion, is a good example of such an instrument, in which the output voltage changes instantaneously as the slider is displaced along the potentiometer track.

In other words, the settling time delay for the measured value is so small that it can be ignored. In nature and reality there is nothing as instantaneous, every change takes time but the time might be so small that we ignore it by choice. Example is the travel time for the light to reach our eyes from surrounding objects. Sometimes this time might play role and it should not be ignored.

For zero order instruments relation between input and output is as below:

$$O(t) = K \times I(t)$$

K is consonant and also known as instrument sensitivity or gain

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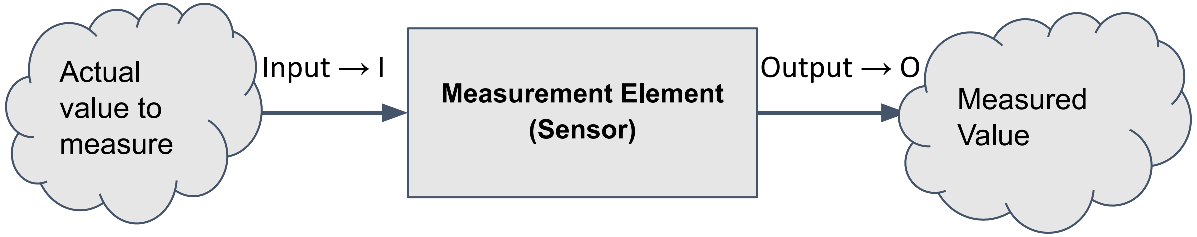
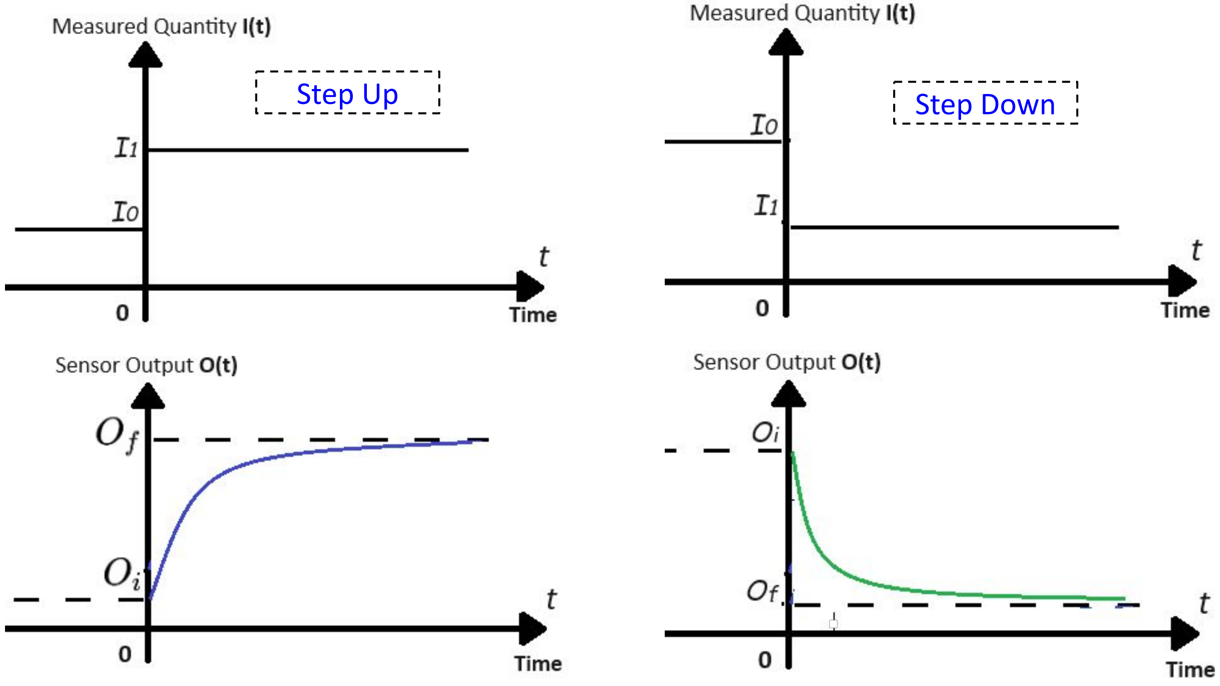
Sensors with First -order Response



- In this type of instrument, after the sensor is exposed to a step change in the measured quantity, the instrument output moves gradually to a new value, as shown on the front Figure.
- In other words, the settling time for the measured value is considerable and it's taken into account. Most of the sensor behaving in this manner.
- *This behavior does not contradict with the instrument being linear.*
- Linearity as defined in static character which is express the relation between the input and output final (steady state) value.
- This is called first order because the relation between output and input is determined by first order differential equation.
- The time response for the output is determined by below equation



$$O(t) = O_i + (O_f - O_i) \times \left[1 - e^{-\frac{t}{\tau}}\right]$$

$O_i \leftrightarrow$ sensor inital output

$O_f \leftrightarrow$ sensor final output

$\tau \leftrightarrow$ sensor time constant

$$sensitivity = \frac{O_f - O_i}{I_1 - I_0}$$

Time Constant

- The time constant, represented by τ in the output equation, plays a crucial role in the sensor's dynamic response. When the sensor encounters a new value to measure, the output ascends from its initial value (Oi) to the final value (Of). The overall change in the output, denoted as ΔO, is calculated as ΔO = Oi - Of. The time constant is defined as the duration it takes for 63.2% of this output change (ΔO) to occur.
- The front calculation is done for t=τ to investigate 63% of output change at time constant.
- Time constant is part of sensor specification and depends on the internal construct of sensor. It does not depend how much the input or output final values are. This parameter provides insight about how fast the sensor is in performing the measurement. Smaller time constant means faster sensor.
- Time constant can be found in sensor data sheets. It might be referred to as T_{63}

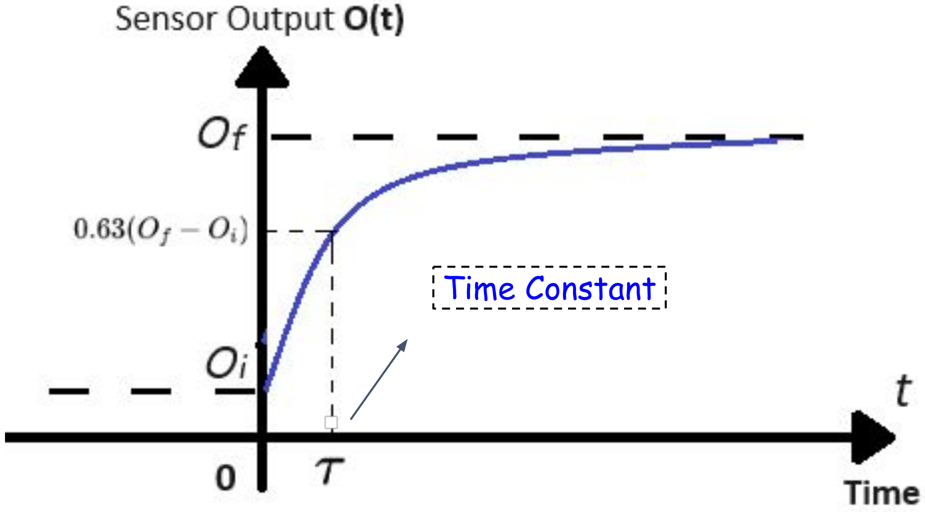
$$O(t) = O_i + (O_f - O_i) \times \left[1 - e^{-\frac{t}{\tau}}\right]$$

$$t = \tau$$

$$O(\tau) = O_i + (O_f - O_i) \times \left[1 - e^{-\frac{\tau}{\tau}}\right]$$

$$O(\tau) - O_i = (O_f - O_i) \times \left[1 - e^{-1}\right]$$

$$\Rightarrow O(\tau) - O_i = (O_f - O_i) \times 0.63$$



First -order instrument - Response Time

- In front three output calculations are presented for time instances equal to 4τ and 5τ.
- At t=4τ, the output reaches to 98% of its total change and has 2% to reach its final value. Therefore this time, 4τ, is known as **Response time**
- At t=5τ, it reaches to about 99% of rise and It is almost settled to the final value. This time, 5τ, is defined as sensor **Settling time.**
- Sometimes, these values are referred to as T_{98} (=4τ)or T_{99} (=5τ) in data sheet.
- In application where real time data are desired instead of waiting 4τ for 98% of rise, 90% can be taken as good enough measurement and then the response time will be 2.2τ which is shorter. This means that the accuracy is being traded off with speed.

$$O(t) = O_i + (O_f - O_i) \times \left[1 - e^{-\frac{t}{\tau}}\right]$$

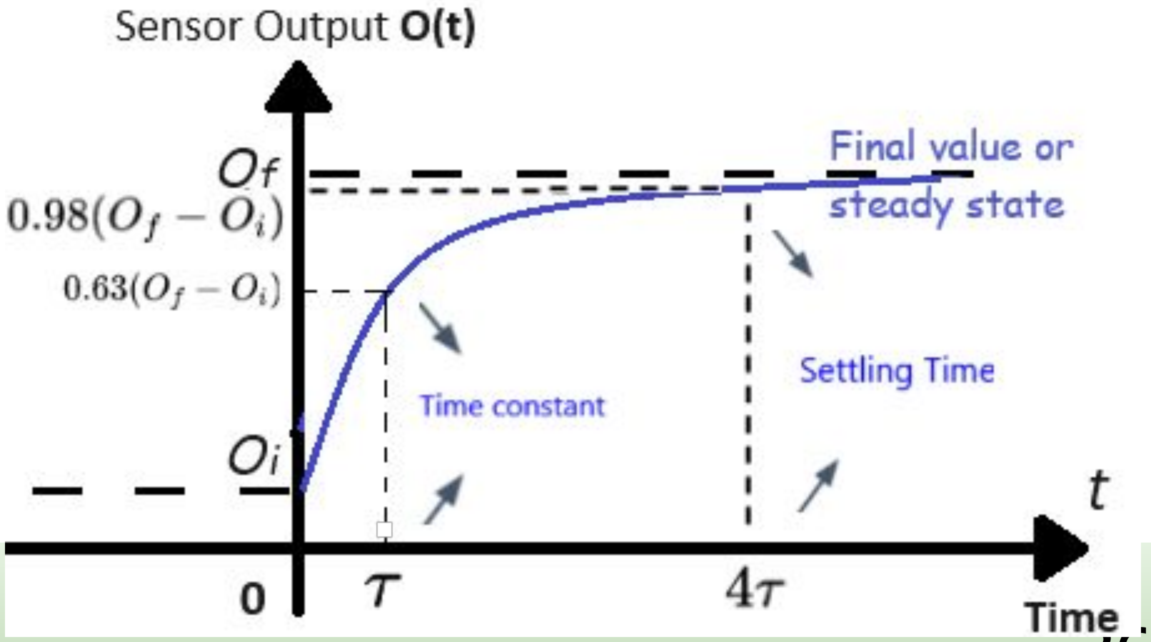
$$t = 4\tau$$

$$O(\tau) = O_i + (O_f - O_i) \times \left[1 - e^{-4}\right]$$

$$\Rightarrow O(\tau) = O_i + (O_f - O_i) \times 0.981$$

$$t = 5\tau$$

$$\Rightarrow O(\tau) = O_i + (O_f - O_i) \times 0.993$$



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HUMBER
Faculty of Applied Sciences & Technology

Exercise for output calculation

A temperature sensor sensitivity is specified as 33 mV/ °C . At 0 °C the sensor provides 0 volt. The time constant of the sensor is 2 seconds. If the temperature changes from 20 °C to 40 °C what would be:

A. The sensor output at 20 °C ?

B. The sensor output in voltage after 2 and 5 seconds?

C. The temperature reading after 2 and 5 seconds?

D. The temperature reading after 8 seconds?

E. Draw the sensor response in time domain?

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A temperature sensor sensitivity is specified as 33 mV/ ℃ . At 0 ℃ the sensor provides 0 volt. The time constant of the sensor is 2 seconds. If the temperature changes from 20 ℃ to 40 ℃ what would be:

A. The sensor output at 20 ℃ ?
B. The sensor output in voltage after 2 and 5 seconds?
C. The temperature reading after 2 and 5 seconds?
D. The temperature reading after 8 seconds?
E. Draw the sensor response in time domain and show time constant, settling and response time on it?

$A)\quad O_{20} = 33\,\frac{mV}{^\circ C} \times 20\,^\circ C = 660\ mV$

$B)\quad O(t) = O_{20} + (O_{45} - O_{20})\left[1 - e^{-\frac{t}{2}}\right]$

$$O_{45} = 33\,\frac{mV}{^\circ C} \times 45\,^\circ C = 1485\ mV$$

$$O(2) = 660 + (1485 - 660)\left[1 - e^{-\frac{2}{2}}\right] \Rightarrow O(2) = 1181.5\,mV$$

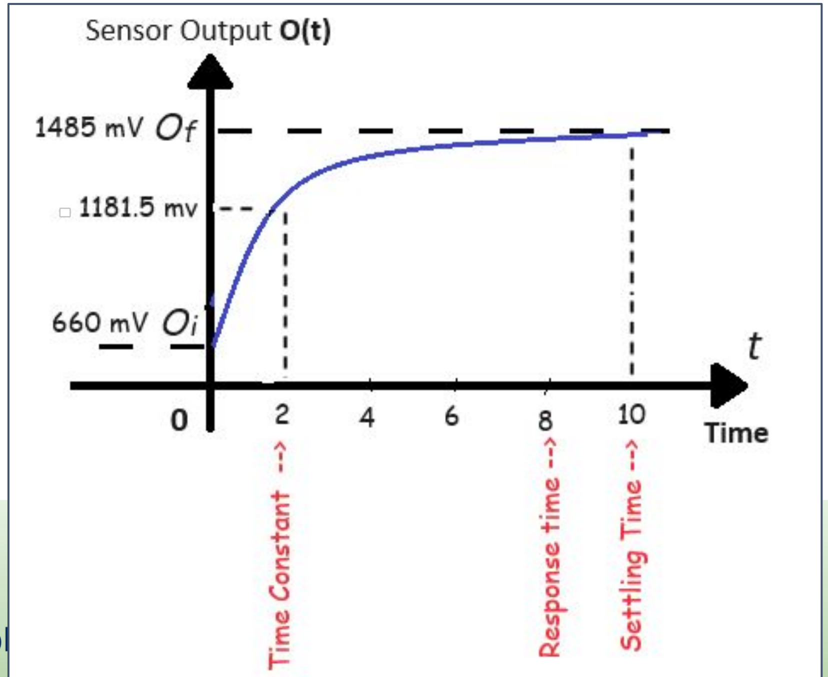
$$O(5) = 660 + (1485 - 660)\left[1 - e^{-\frac{5}{2}}\right] \Rightarrow O(5) = 1417.3\,mV$$

$C)\quad T(2) = \frac{O(2)}{33\,\frac{mV}{^\circ C}} = \frac{1181.5\,mV}{33\,\frac{mV}{^\circ C}} = 35.8\,^\circ C$

$$T(5) = \frac{O(5)}{33\,\frac{mV}{^\circ C}} = \frac{1417.3\,mV}{33\,\frac{mV}{^\circ C}} = 42.9\,^\circ C$$

$D)\quad O(8) = 660 + (1485 - 660)\left[1 - e^{-\frac{8}{2}}\right] \Rightarrow O(8) = 1469.9\,mV$

$$T(8) = \frac{O(8)}{33\,\frac{mV}{^\circ C}} = \frac{1469.9\,mV}{33\,\frac{mV}{^\circ C}} = 44.54\,^\circ C$$



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Exercise for response time

There is a pressure sensor which its measurement range is 0-40 bar. The sensor data sheets has provided the T99 equal to 420 ms. The pressure changes from 0 to 10.

A) At what time the pressure reading will be 6.3 bar?
B) At what time the pressure will be 9.81?
C) At what time the pressure will be 8?

This sensor is installed on a tank and there is alarm for high pressure. Every time pressure goes above 30 bars the alarm light and the siren must turn on immediately as safety precaution. We read the pressure value in computer and compare it with number 30 (P>=30) then we turn on the alarm.

D) The current pressure is 25 bar and suddenly increases to 30 bar. How long will it take to alarm turns on?
E) How can this lagging time be reduced? Discussion

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Exercise for response time

There is a pressure sensor which its measurement range is 0-40 bar. The sensor data sheets has provided the T99 equal to 420 ms. The pressure changes from 0 to 10.

A) At what time the pressure reading will be 6.3 bar?
B) At what time the pressure will be 9.81?
C) At what time the pressure will be 8?

This sensor is installed on a tank and there is alarm for high pressure. Every time pressure goes above 30 bars the alarm light and the siren must turn on immediately as safety precaution. We read the pressure value in computer and compare it with number 30 (P>=30) then we turn on the alarm.

D) The current pressure is 25 bar and suddenly increases to 30 bar. How long will it take to alarm turns on? 420 ms
E) How can this lagging time can be reduced? Discussion

Setting the alarm at 28 bar instead of 30 if it is possible

$$T_{99} = 5\tau \quad \tau = \frac{420\,ms}{5} = 84\,ms$$

$$A)\ \frac{6.3}{10-0} \times 100 = 63\% \Rightarrow t \approx \tau = 84\,ms$$

$$B)\ \frac{9.8}{10-0} \times 100 = 98\% \Rightarrow t \approx 4\tau = 336\,ms$$

$$C)\ P(t) = P_0 + (P_{10} - P_0)\left(1 - e^{-\frac{t}{\tau}}\right)$$

$$8 = 0 + (10-0)\left(1 - e^{-\frac{t}{0.084}}\right) \Rightarrow t = 135\,ms$$

Dead Time - Example Data Sheet

Sensor Model Number:

PMP71-DMC1W61RDAAU

Cerabar S

0-6000 PSI

Profibus PA

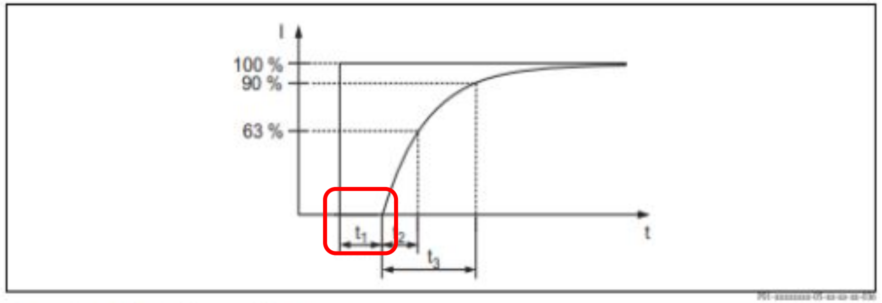
24 VDC

resistance of 250 Ω must exist within the loop.

Resolution

- Current output: 1 µA
- Display: can be set (factory setting: presentation of the maximum accuracy of the transmitter)

Dead time, time constant



Presentation of the dead time and the time constant

Dynamic behavior, current output

Type	Dead time t_1	Time constant (T63), t_2	Time constant (T90), t_3
PMC71	90 ms	120 ms	276 ms
PMP71	45 ms	▪ 400 mbar (6 psi) measuring cell: 70 ms ▪ Measuring cells ≥ 1 bar (15 psi): 35 ms	▪ 400 mbar (6 psi) measuring cell: 161 ms ▪ Measuring cells ≥ 1 bar (15 psi): 81 ms
PMP75	PMP71 + influence of the diaphragm seal		

Dynamic behavior, HART

Type	Dead time t_1	Time constant (T63), t_2	Time constant (T90), t_3
PMC71	340 ms	120 ms	276 ms
PMP71	295 ms	▪ 400 mbar (6 psi) measuring cell: 70 ms ▪ Measuring cells ≥ 1 bar (15 psi): 35 ms	▪ 400 mbar (6 psi) measuring cell: 161 ms ▪ Measuring cells ≥ 1 bar (15 psi): 81 ms
PMP75	PMP71 + influence of the diaphragm seal		

Reading cycle

- HART commands: 3 to 4 per second on average.
  The Cerabar S commands the BURST MODE function for cyclic value transmission via the HART communication protocol.

Response time

≤ 250 ms

Cycle time (update time)

On average 250 to 330 ms.

Second -order Sensors

Some sensor output oscillate around the final value. The output goes up and down until reaches to final value.

This is called second order response because the relation between input and output is determined by a second order differential equation.

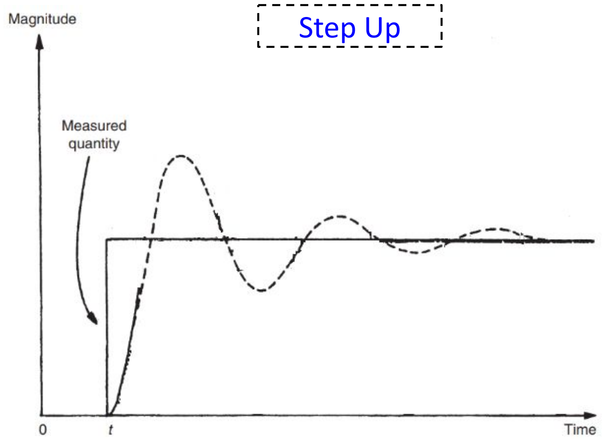
If an output shows behavior like A, this is full oscillation without damping.

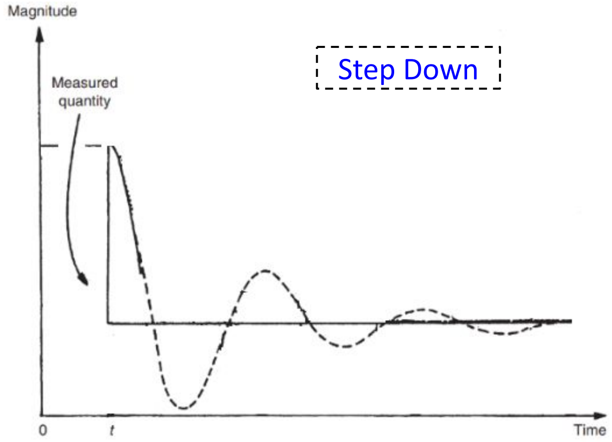
In graph B the output put goes above final value and difference between maximum value and final value is called overshoot.

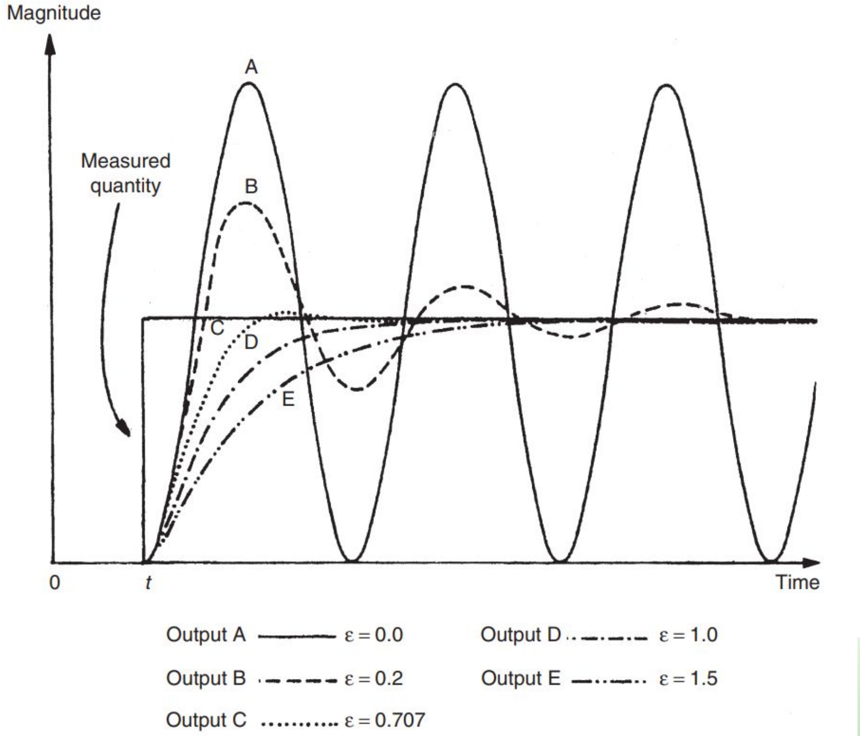
Graph C has a small overshoot, D and E have no overshoot.

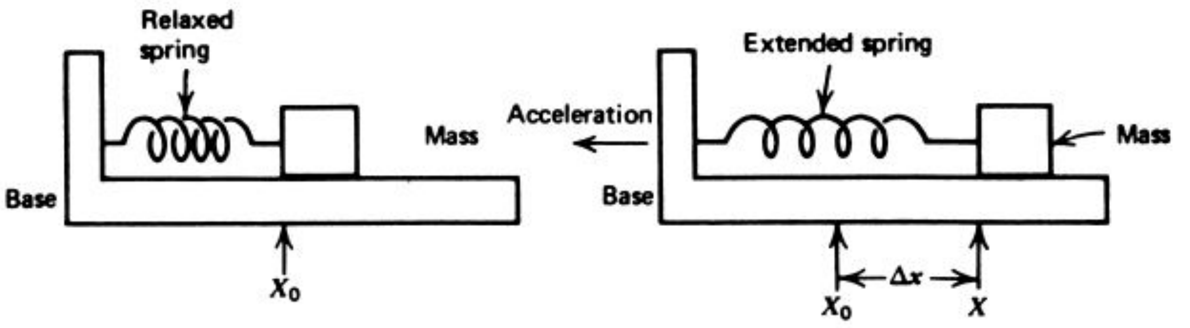
As graph shows B react faster at the beginning but takes longer to reach to the final value compare to C,D and E.

Higher overshoot higher rising time , faster initial reaction









a) Spring-mass system with no acceleration

b) Spring-mass system with acceleration

$$ma = k\Delta x$$

where
k = spring constant in N/m
Δx = spring extension in m
m = mass in kg
a = acceleration in m/s^2

If an spring shows oscillation when a acceleration is measured Like B in previous slide (Second order response), what can be done to
to make the response like graph D in previous slide?

End