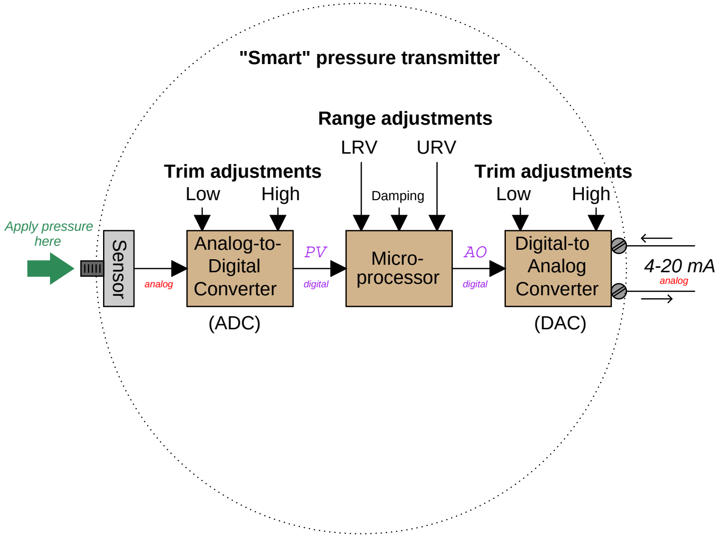
Technical Means of Automation

Sensor Characteristics

Institute of Information Engineering, Automation and Mathematics

September 27, 2016

Sensor - Transmitter



Sensor Characteristics

Static characteristics:

- Range
- Sensitivity
- Offset and drift
- Precision
- Accuracy
- Resolution (discrimination)
- Linearity
- Hysteresis
- Stability
- Errors

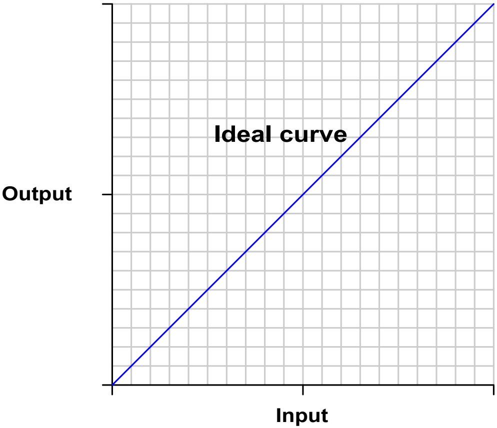
Dynamic characteristics:

- Zero order system
- First order system
- Second order system
- Sampling rate

Static Characteristics

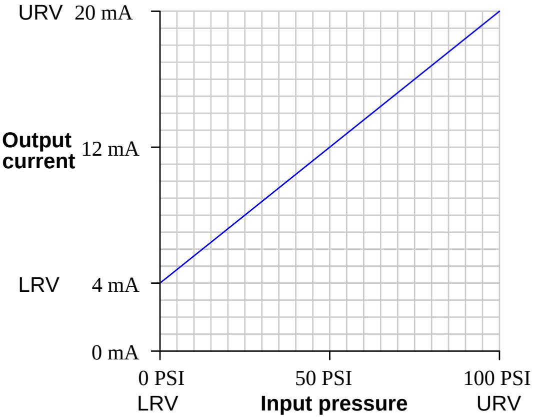
Sensor Characteristics

Ideal (perfect) sensor



Sensor Characteristics

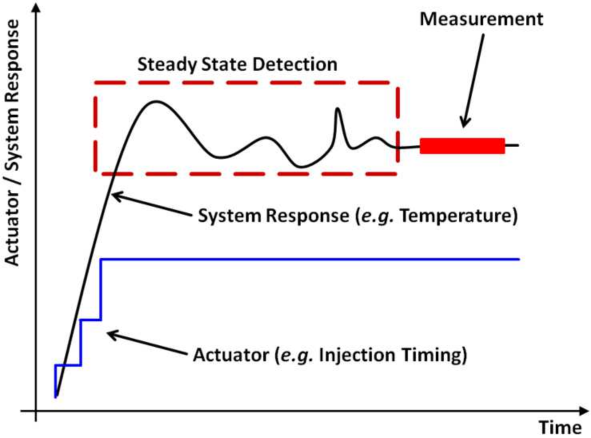
Ideal pressure sensor



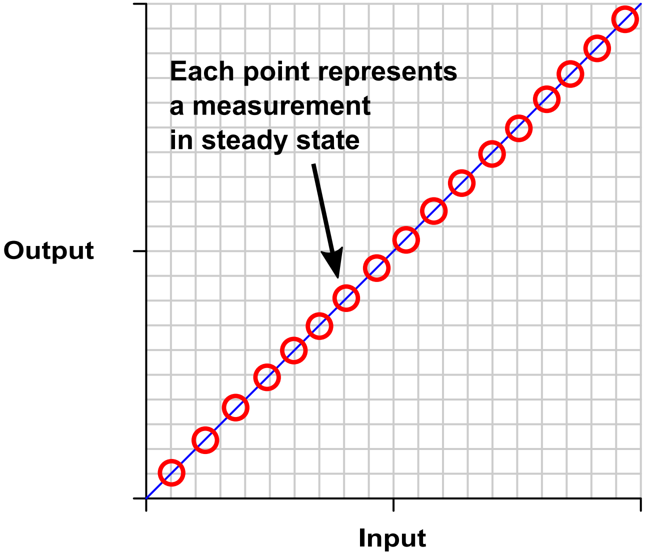
Static Characteristics

The properties of the system after all transient effects have settled to their final or steady state.

Steady state



Static Characteristics



How to Obtain Static Characteristics?

Calibration of sensor:

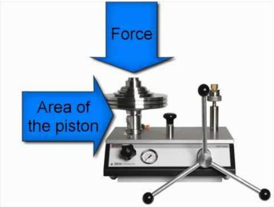
1. force system's quantity to LRV steady state (reference)
2. perform sensor's output and reference measurement (evaluate 5)
3. force system's quantity a step ahead of last reference measurement
4. let system to reach steady state (go to 2)
5. if measurement reaches URV: continue to 6; else: go back to 3
6. record data and perform 1-5 for opposite direction URV to LRV
7. now you have all the data to plot static characteristic of sensor

What is the Reference Measurement?

Reference measurement is a reliable method to determine an actual value of physical quantity.

Some examples of reference measurements:

- range/distance - rulers, meter sticks
- temperature - boiling water ($100\,^{\circ}\mathrm{C}$) and ice bath ($0.01\,^{\circ}\mathrm{C}$) at sea level
- pressure - Dead Weight Tester
- acceleration - gravity is a constant (1G) on the surface of the earth

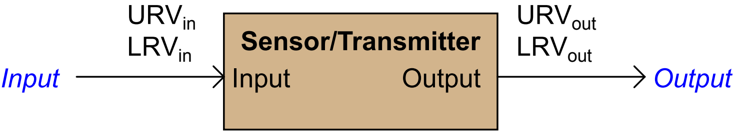


Static Characteristics - Range

Range

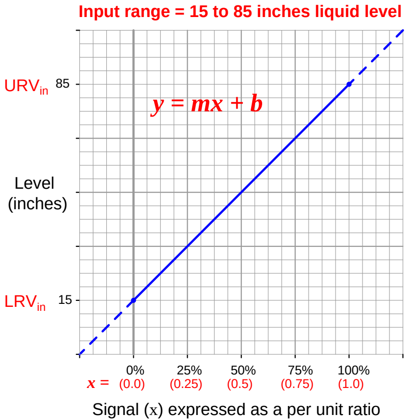
- Input range (e.g. 20 – 150 $^\circ\mathrm{C}$, 250 – 800 PSI, ...)
  - represents a maximum and minimum value of the physical variable that can be measured
  - determines the applicability of sensor for **physical conditions**
- Output range (e.g. 4 – 20 mA, 0 – 10 V)
  - represents a maximum and minimum value of signal produced by sensor/transmitter
  - corresponds to measured quantity
  - determines the applicability of sensor for **data acquisition equipment**

Static Characteristics - Range



$$\frac{\textit{Input} - LRV_{in}}{URV_{in} - LRV_{in}} = \begin{array}{c}\text{Per unit of span}\\ \text{(from 0 to 1 inclusive)}\end{array} = \frac{\textit{Output} - LRV_{out}}{URV_{out} - LRV_{out}}$$

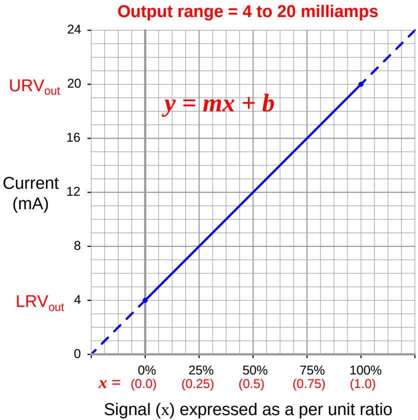
Static Characteristics - Range



$y = (85 - 15)\,x + 15$

$y = 70x + 15$

Input = (URV_{in}-LRV_{in})(per unit) + LRV_{in}



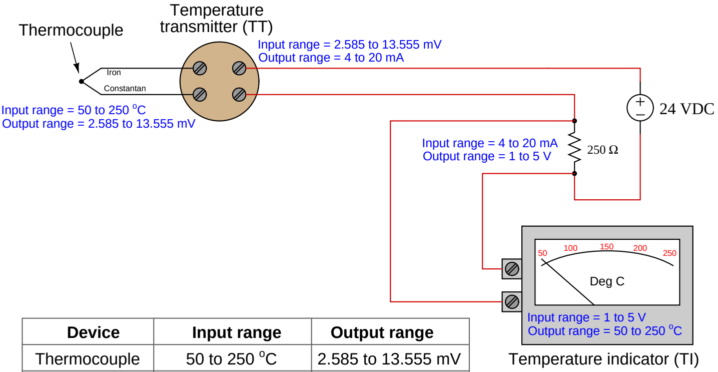
$y = (20 - 4)\,x + 4$

$y = 16x + 4$

Output = (URV_{out}-LRV_{out})(per unit) + LRV_{out}

Static Characteristics - Range

Actually, there are more ranges in sensing system.



Device	Input range	Output range
Thermocouple	50 to 250 °C	2.585 to 13.555 mV
Transmitter	2.585 to 13.555 mV	4 to 20 mA
Resistor	4 to 20 mA	1 to 5 V
Indicator	1 to 5 V	50 to 250 °C

Sensitivity

Determines how large response of sensor is produced by a normalized change of input (usually one-step increment).

- **gain** of sensor's transfer function
- represented by a **slope** of calibration curve $y(x) = f(x) = \mathbf{a}x + b$

Possible scenarios (positive gain):

gain ≈ 1 - medium sensitivity, 1-to-1 proportional, smallest information loss

gain > 0 - good sensitivity, possible information loss

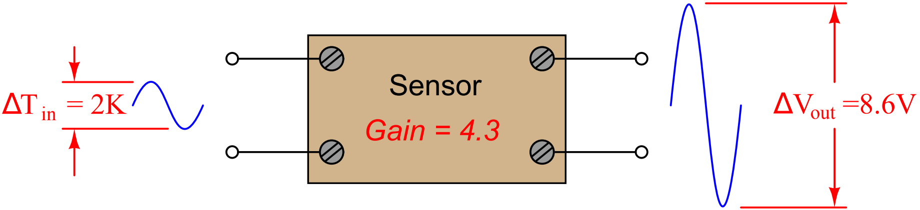
$1 >$ gain > 0 - poor sensitivity, possible information loss

gain > 1 - high sensitivity, possible information loss

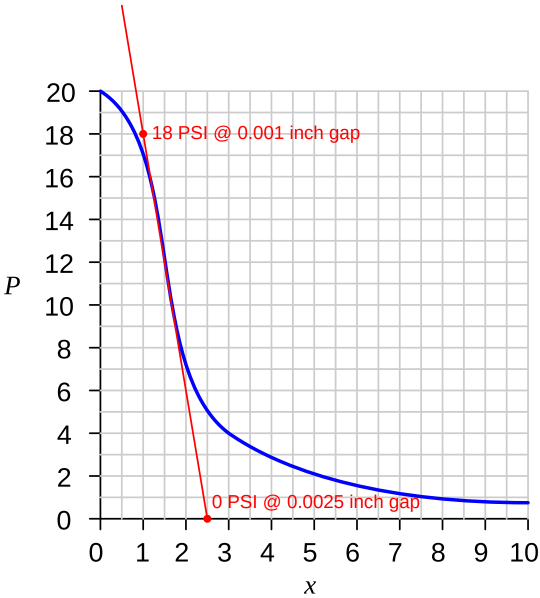
gain $\rightarrow$ inf - extreme sensitivity, high information loss

gain $\rightarrow 0$ - no sensitivity, high information loss

Static Characteristics - Sensitivity



Static Characteristics - Sensitivity



Static Characteristics - Offset (zero shift) and drift

Offset

Determines the value of shift of static characteristics in y-axis from the zero reference.

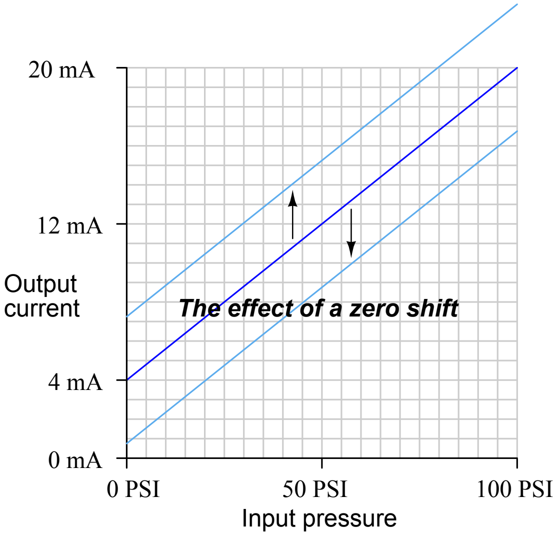
- represented by a **intercept** of calibration curve $y(x) = f(x) = ax + \mathbf{b}$
- simple correction - shift the curve back to origin

Drift

Determines how the offset is changing in time.

- long-time effect – wear of sensor
- short-time effect – variable physical interference

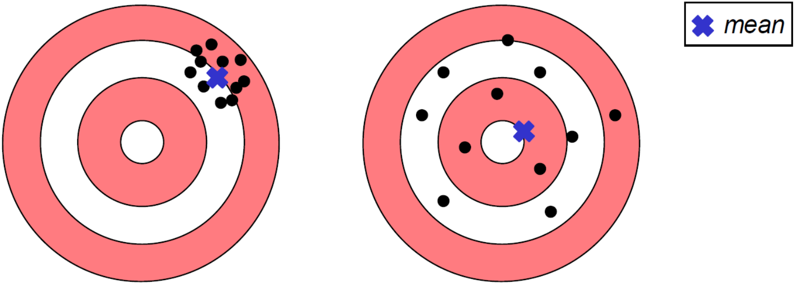
Static Characteristics - Offset (zero shift) and drift



Precision vs Accuracy

Static Characteristics - Precision vs Accuracy

Which one is more accurate?



Precision vs. Accuracy

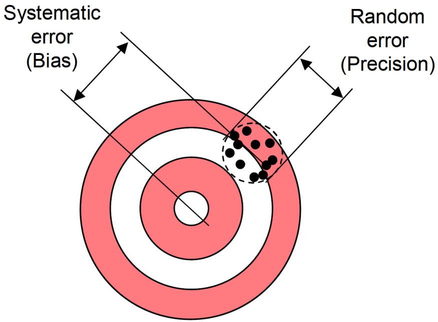
Precision:

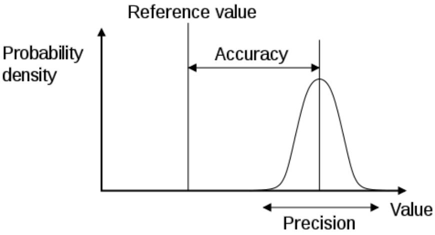
- degree of **reproducibility** of measurement
- ideal sensor provides exactly same values over numerous measurements
- measured value is not necessarily the true value of quantity

Accuracy:

- a maximum **difference between true and measured value** of quantity
- is related to the **bias** of a set of measurements
- inaccuracy – error
- various representations:
  - Absolute error $=$ Result $-$ True value
  - Relative error $= \frac{\text{Absolute error}}{\text{True value}}$

Precision vs. Accuracy





Static Characteristics - Resolution

Resolution (Discrimination)

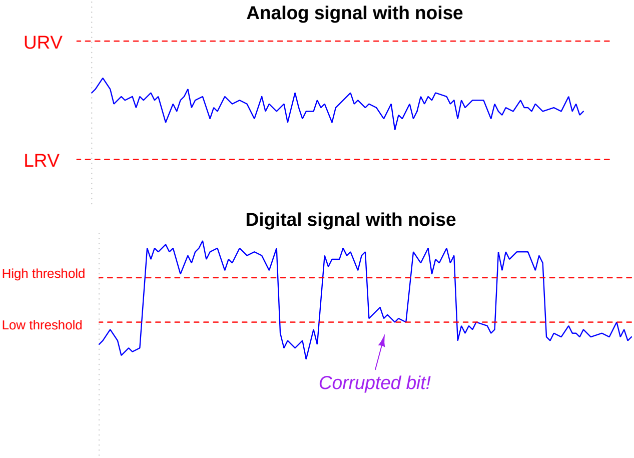
Resolution is the minimal change of the input necessary to produce a detectable change at the output.

- increment from zero – **threshold**
- domain of analog world
- perfect analog sensor – infinite resolution

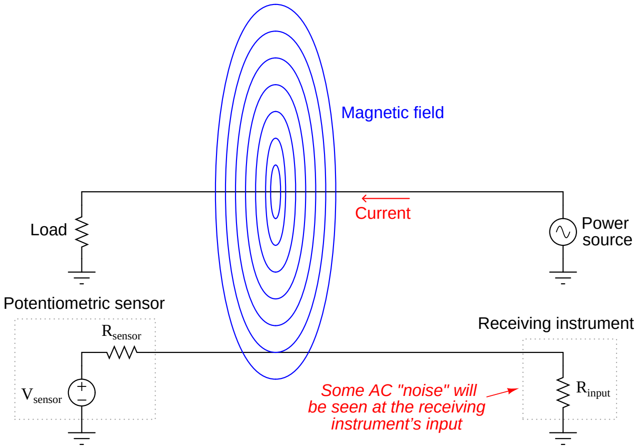
What can contribute to loss of resolution?

- electrical noise (SNR $\gg 1$)
- analog-to-digital quantization

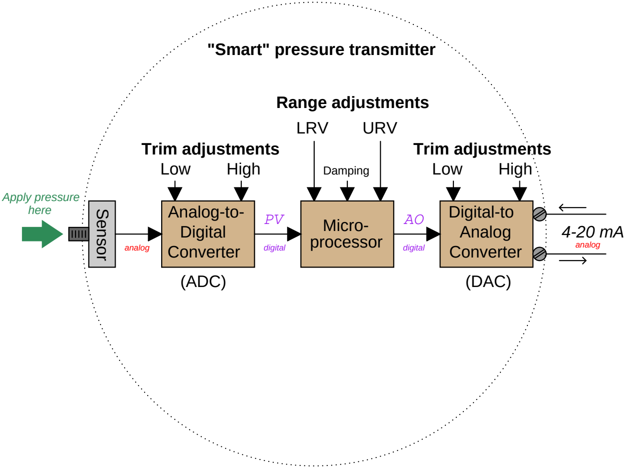
Noise (Analog vs Digital)



Noise (Source)

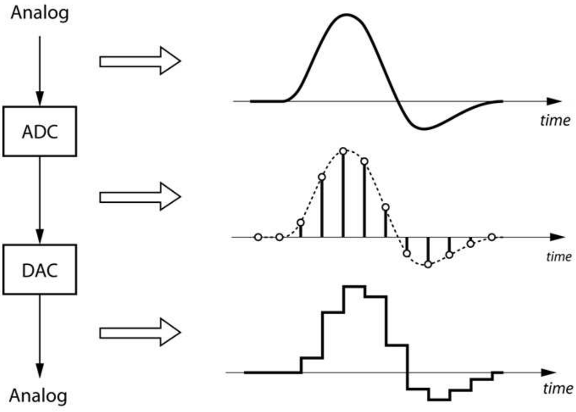


Analog to Digital Conversion (Quantization)



Static Characteristics - ADC Impact on Resolution

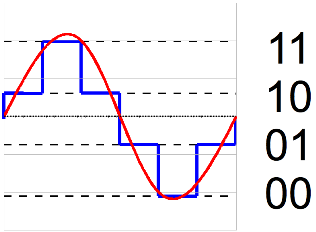
Analog to Digital Conversion (Quantization)

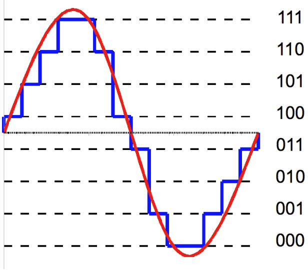


Analog to Digital Quantization

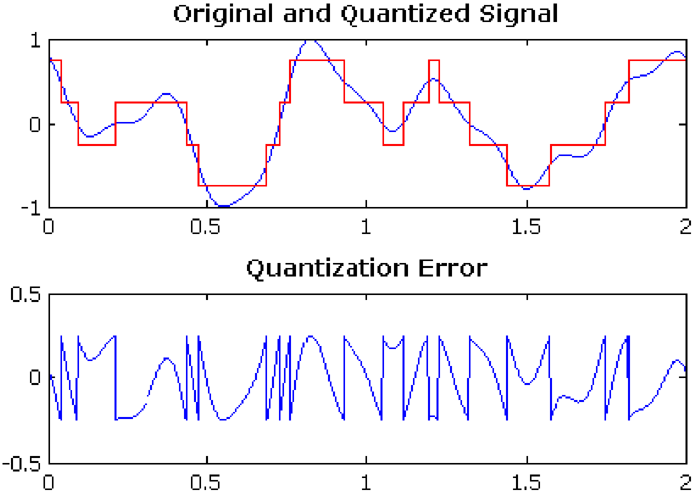
Quantization is mapping of large data sets into a smaller set.

- analog to digital converters (ADC)
- actual measurement is transferred into binary representation
- loss of information – **quantization error**



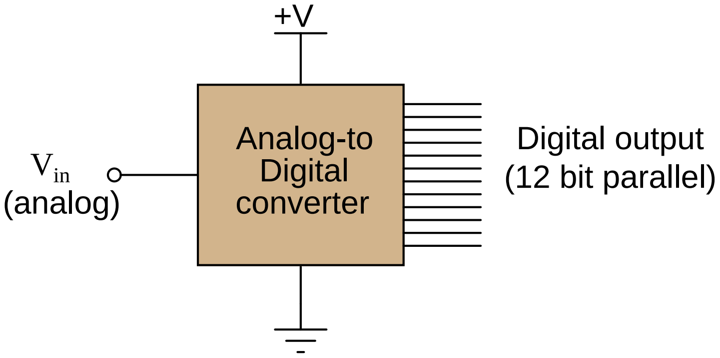


Quantization Error

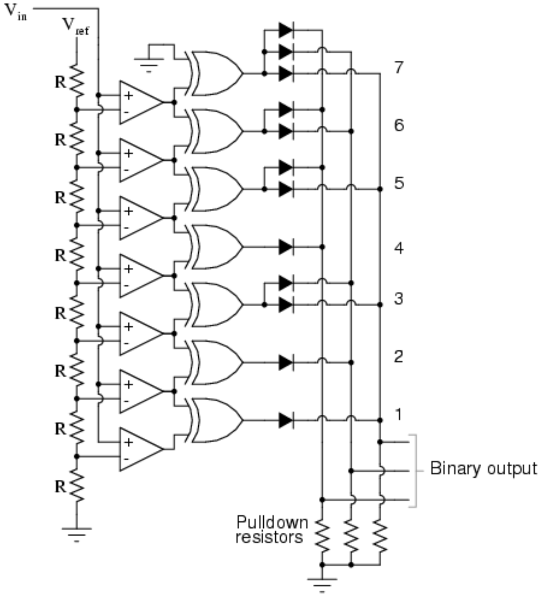


Static Characteristics - ADC Impact on Resolution

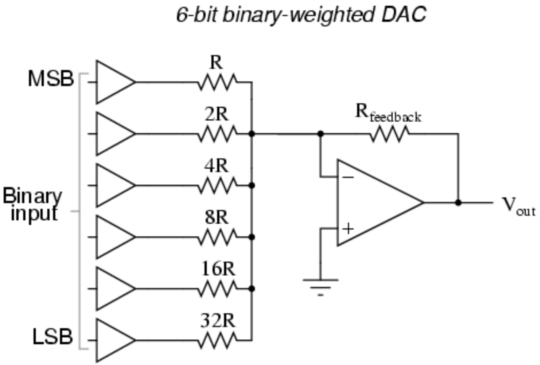
Analog to Digital Converters



Simple ADC Schematics



Simple DAC Schematics



Analog to Digital Converters

Resolution of ADC/DAC:

$$\text{Analog resolution} = \frac{\text{Analog range}}{2^n - 1}$$

Numerical representation of input:

$$\frac{V_{in}}{V_{range}} = \frac{\text{Counts}}{2^n - 1}$$

V_{in}	Counts (dec,12-bit)
0 V	0
2.46 mV	1
3.85 V	1576
4.59 V	1879
6.11 V	2502
9.998 V	4094
10 V	4095

Static Characteristics - ADC Impact on Resolution

Decimal range vs. number of bits

bits	range unsigned	Range signed
8	0 – 255	-127 – 127
10	0 – 1023	-511 – 511
12	0 – 4095	-2 047 – 2 047
14	0 – 16 383	-8 191 – 8 191
16	0 – 65 535	-32 768 – 32 768
20	0 – 10 048 575	-524 287 – 524 287
24	0 – 16 777 216	-8 388 607 – 8 388 607

Static Characteristics - ADC Impact on Resolution

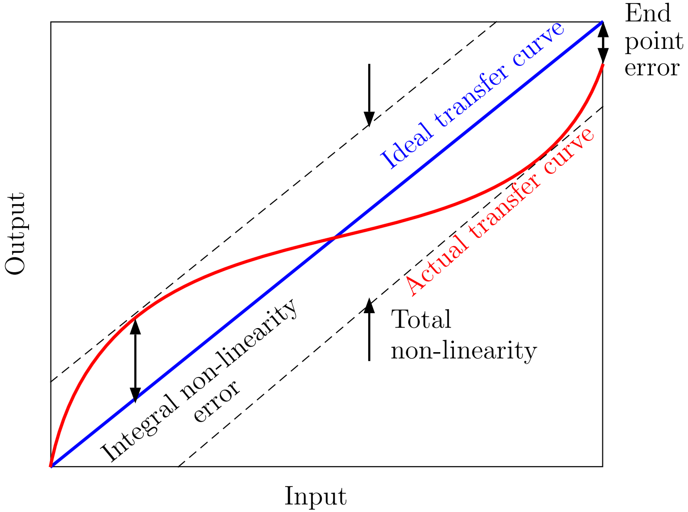
Task 1 – calculate the analog resolution of ADC (in voltage and Kelvin) for following case:

- range of quantity: 0–150K (temperature)
- range of input: 0–10V
- 8-bit ADC

Task 2 – calculate the measured pressure if:

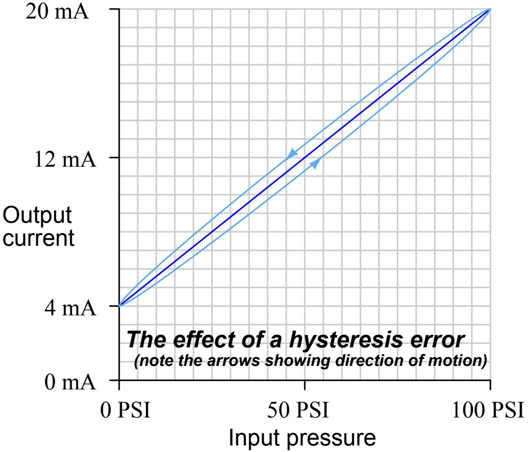
- range of quantity: 10–400 kPa
- range of input: -10–10V
- 10-bit ADC
- ADC returns a decimal number of 524

Linearity


End
point
error
Ideal transfer curve
Actual transfer curve
Total
non-linearity
Integral non-linearity
error
Output
Input

Hysteresis

The difference between two output values that correspond to the same input depending on the trajectory followed by the sensor.



Stability

The ability of a sensor to retain its performance characteristics for a relatively long period of time. Unless otherwise stated, stability is the ability of a sensor to reproduce output readings obtained during its original calibration, at room conditions, for a specified period of time. It is then typically expressed as being *within X percent* of full scale output or *measured units* for a period of *Y months*.

- freedom from undesirable deviation
- a measure of controllability of process
- related to sensitivity, offset, drift, accuracy, precision, resolution and linearity
- main cause – aging of sensor

Errors

Systematic errors – result from a variety of (often **human**) factors

- interfering or modifying variables
- measurement process changes the value of process quantity
- improper range selection (non-monotonic characteristics)
- human observers (parallax error)

Random errors – **this is not our fault!**

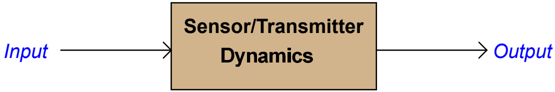
- a signal that carries no information (noise)
  - caused by inability to reproduce the measurement
  - environmental noise
  - transmission noise
- true random errors
  - Gaussian distribution
  - white noise

Dynamic Characteristics

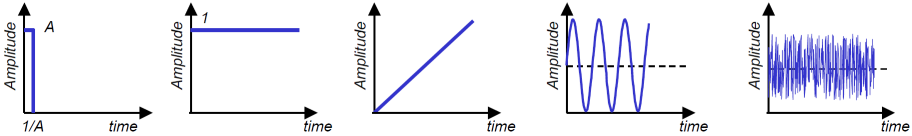
Dynamic Characteristics

The sensor response to a variable input is different from that exhibited when the input signals are constant (static characteristics).

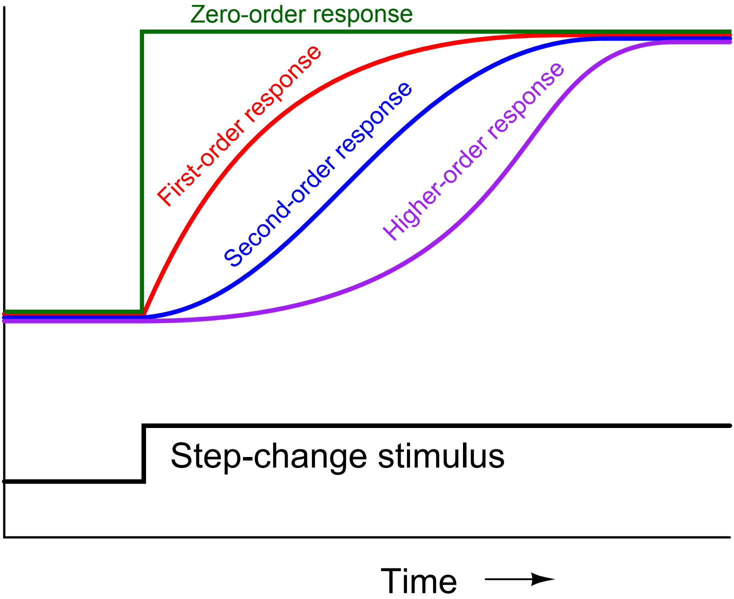
How the sensor acts as the dynamical input-output system?



Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:



Dynamic Characteristics - Step Response



Dynamic Characteristics – Zero-Order Sensor

Input and output of sensor are related by a algebraic equation:

$$y(t) = k \cdot x(t) \Rightarrow \frac{Y(s)}{X(s)} = k$$

Zero-order sensor – perfect sensor:

- no dynamics
- acts only as amplifier
- no accumulation of energy or mass

Examples:

- electric circuit switches
- potentiometers

Dynamic Characteristics – First-Order Sensor

Input and output of sensor are related by an equation:

$$a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t) \Rightarrow \frac{Y(s)}{X(s)} = \frac{1}{a_1 s + a_0} = \frac{k}{Ts + 1}$$

First-order sensor:

- step response: $y(t) = \Delta x(t) \cdot k \left(1 - e^{\frac{-t}{T}}\right)$
- characterized by time constant and gain
- accumulation of energy or mass

Examples:

- thermistor
- thermocouple

Dynamic Characteristics – Second-Order Sensor

Input and output of sensor are related by an equation:

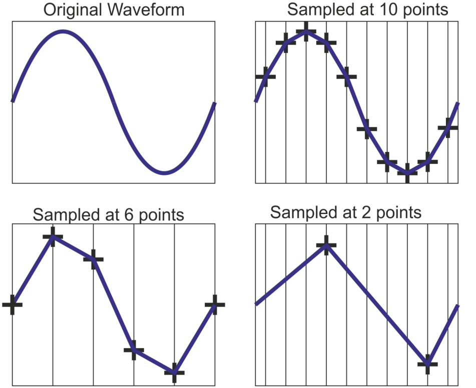
$$a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t) \Rightarrow \frac{Y(s)}{X(s)} = \frac{1}{a_2 s + a_1 s + a_0}$$

Second-order sensor:

- characterized by:
  - time to peak
  - peak overshoot
  - settling time and value
- response types:
  - underdamped ($\xi < 1$)
  - critically damped ($\xi = 1$)
  - overdamped ($\xi > 1$)
- accumulation of energy or mass in two elemental subsystems in series

Dynamic Characteristics – Sampling

How often we perform the measurements of the physical quantity.



Nyquist Sampling Theorem:

"The absolute minimum sample rate necessary to capture an analog waveform is twice the waveform's fundamental frequency."