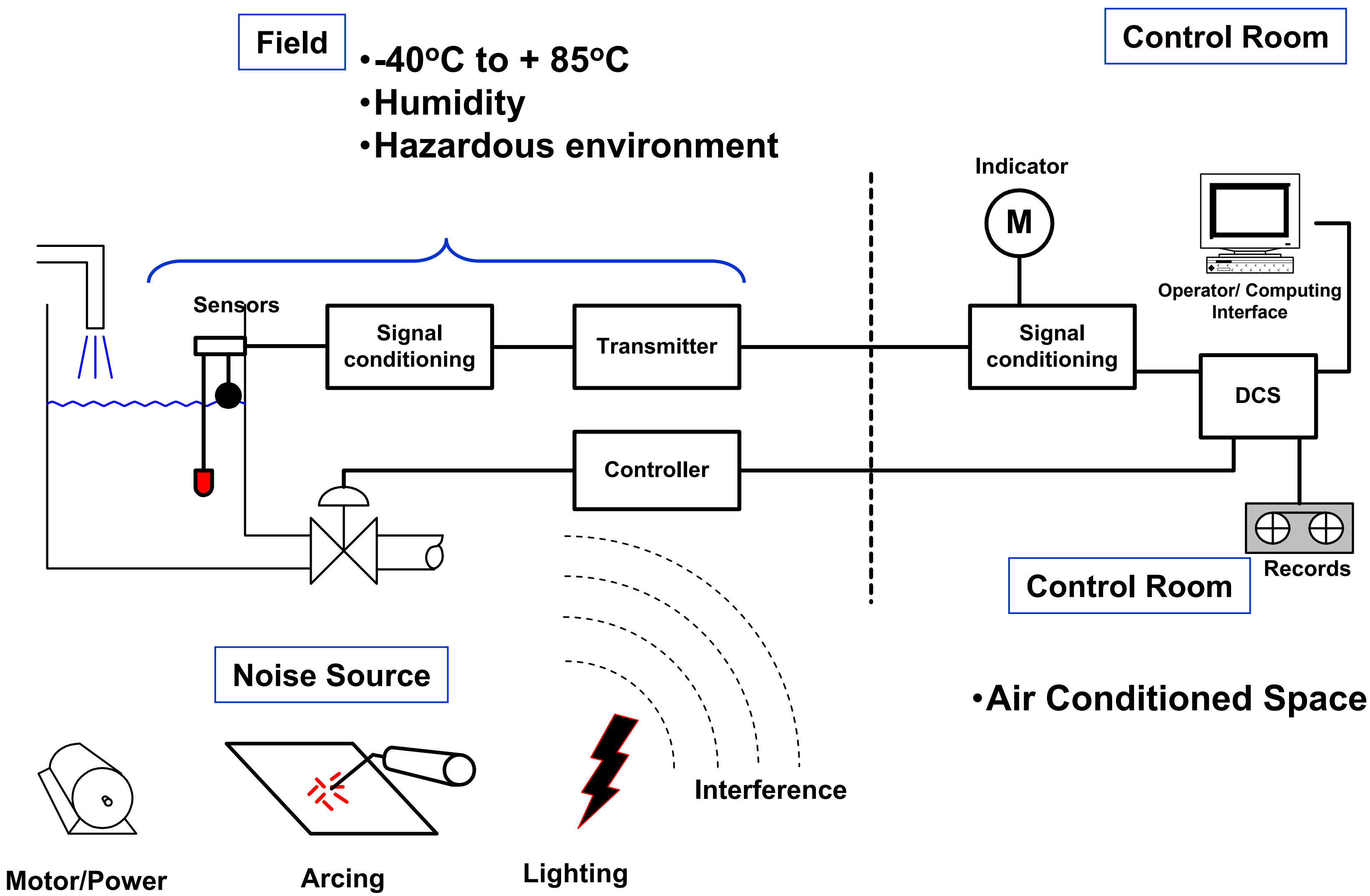
2102-487
Industrial Electronics

Transducers

Industrial Measurement Environment



Objectives

- Able to read and interpret the manufacturer’s specifications
- Understand the physical principles of various sensors
- Able to design a simple measurement system from specifications:
  - Selection of Sensors
  - Design signal conditioners and transmitters

Definition

Transducer

- a device which, when actuated by energy in one system, supplies energy in the same form or in another form to a second system.

Sensor (input transducer)

- a device converts the physical or non-physical signal which is to be measured into an electrical signal which can be processed or transmitted electronically.

Actuator (output transducer)

- a device converts the modified electrical signal into a non-electrical signal.

Lists of Energy Forms

Chemical	**Atomic energy**	Related to the force between nuclei and electrons
Chemical	**Mass energy**	Is described by Einstein as part of his relativity theory,
Chemical	**Molecular energy**	Is the binding energy in molecules
Chemical	**Nuclear energy**	Is the binding energy between nuclei $E = mc^2$
	Electrical energy	Related to electric field, current, voltage etc.
Mechanical	**Gravitational energy**	Related to the gravitational attraction between a mass and earth
Mechanical	**Mechanical energy**	Related to the motion, displacement, force, etc.
	Magnetic energy	Deals with magnetic field etc.
	Radiant energy	Is related to electromagnetic radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays
	Thermal energy	Related to the kinetic energy of atoms and molecules

Signal domains with examples

Mechanical	Length, area, volume, all time derivatives such as linear/angular velocity/acceleration, mass flow, force , torque, pressure, acoustic wavelength and intensity
Thermal	Temperature, (specific) heat, entropy, heat flow, state of matter
Electrical	Voltage, current,charge, resistance, inductance, capacitance, dielectric constant, polarization, electric field, frequency, dipole moment
Magnetic	Field intensity, flux density, magnetic moment, permeability
Radiant	Intensify, phase, wavelength, polarization, reflectance, transmittance, refractive index
Chemical	Composition, concentration, reaction rate, pH, oxidation/reduction potential

Input \ Output	Mechanical	Thermal	Electrical	Magnetic	Radiant	Chemical
Mechanical	(Fluid) Mechanical and Acoustic Effects: e.g.: Diaphragm Gravity balance, Echo sounder	Friction Effects (e.g.. Friction Calorimeter) Cooling Effects (e.g. Thermal Flow meter)	Piezoelectricity Piezoresistivity Resistive, Capacitive, and Inductive effects	Magnetomechanical Effects: e.g. Piezomagnetic Effect	Photoelastic Systems (Stress-induced Birefringence) Interferometers Sagnac Effect Doppler Effect	
Thermal	Thermal Expansion (Bimetallic Strip, Liquid-in–Glass and Gas Thermometers, Resonant Frequency) Radiometer Effect (Light Mill)		Seebeck Effects Thermoresistance Pyroelecricity Thermal (Johnson) Noise		Thermooptical Effects (e.g. in Liquid Crystals) Radiant Emission	Reaction Activation eg. Thermal Dissociation
Electrical	Electron kinetic and Electromechanical Effects: eg. Piezoelectricity Electrometer Ampere's Law	Joule (Resistive) Heating Peltier Effect	Charge Collectors Langmuir Probe	Biot-Savart's Law	Electrooptical Effects: eg. Kerr Effect Pockels Effect Electroluminescence	Electrolysis Electromigration
Magnetic	Magnetomechanical Effects: eg. Magnetostriction Magnetometer	Thermomagnetic Effects: eg. Righi-Leduc Effect Galvanomagnetic Effects: eg. Ettingshausen Effect	Thermomagnetic Effects: e.g. Ettinghausen-Nerst Effect Galvanomagnetic Effects: e.g. Hall Effect, Magnetoresistance		Magnetooptical Effects: eg. Faraday Effect Cotton-Mouton Effect	
Radiant	Radiation Pressure	Bolometer Thermopile	Photoelectirc Effects: e.g. Photovoltaic Effect Photoconductive Effect		Photorefractive Effects Optical Bistability	Photosynthesis Photodissociation
Chemical	Hygrometer Electrodeposition cell Photoacoustic Effect	Calorimeter Thermal Conductivity Cell	Potentiometry, Conductimetry, Amperometry Flame Ionization Volta Effect Gas Sensitive Field Effect	Nuclear Magnetic Resonance	(Emission and Absorption) Spectroscopy Chemoluminescence	

Transduction Principles: Physic + Chemistry

Output

Primary input

	Mechanical	Thermal	Electrical	Magnetic	Radiant	Chemical
Mechanical						
Thermal						
Electrical						
Magnetic						
Radiant						
Chemical						

sensor

transducer

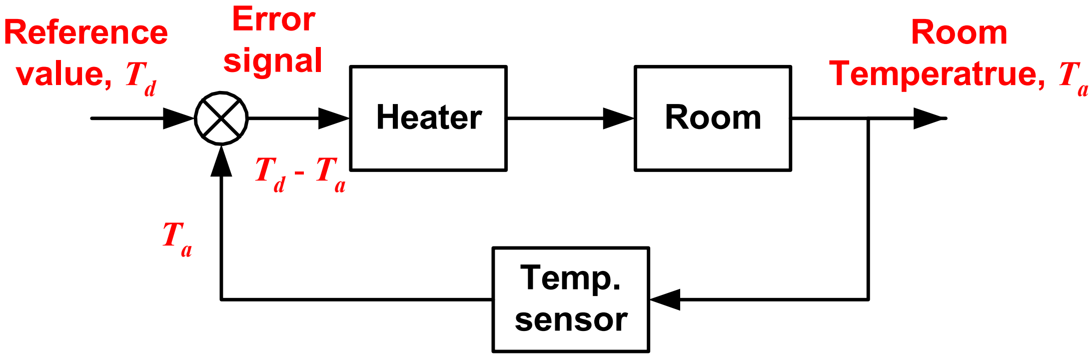
actuator

modifier

Classification of Sensors

Sensor Applications

- Monitoring of processes and operations
- Control of processes and operations
- Experimental engineering analysis
- Environment and safety measurement



A simple closed-loop control system

Dummy driver

Transducer Specifications

- Transducer specifications or characteristics give the information of how well and how quick … the transducer converts what is measuring into electrical signal.
  - Static Specifications
    - Accuracy
    - Resolution
    - Linearity
    - Repeatability
    - Linearity
    - etc.
  - Dynamic Specifications
    - Rise time
    - Time constant
    - Cut off frequency
    - Dead time or Time delay
    - Settling time
    - etc.

Static Characteristics: Static Calibration

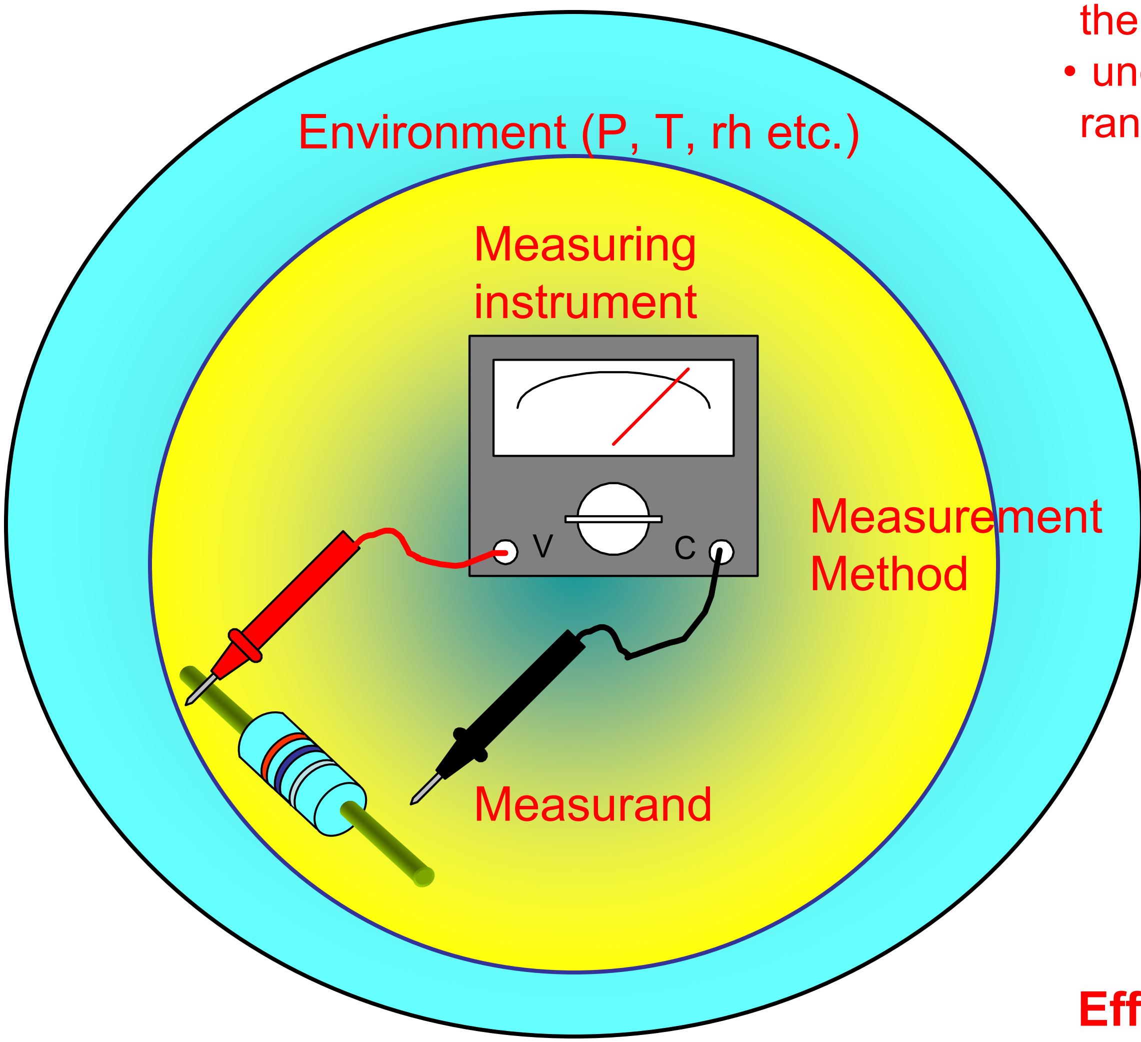
•Static calibration:

A test in which known values of the measurand (input) are applied to a sensor (measurement system) for the purpose of observing the sensor (system) output. The input-output relation is so-called "*Calibration curve*".

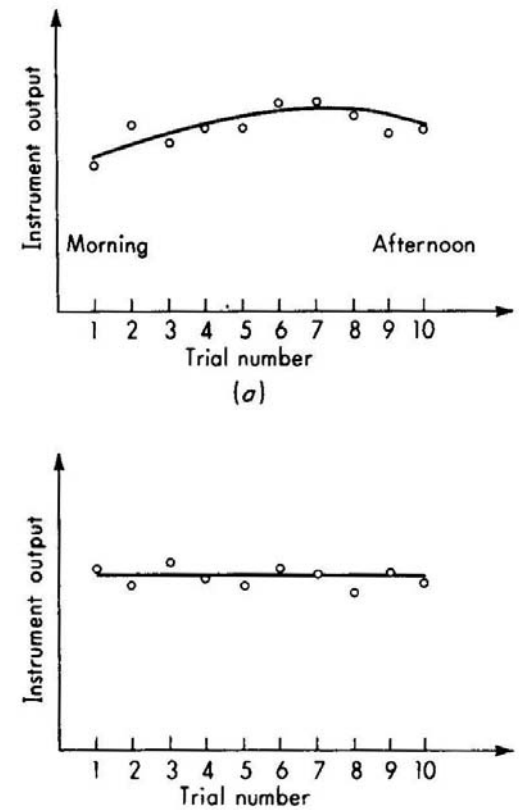
- **Unless specifically indicated, calibration is static. An input is applied and the output monitored until it has stopped changing.**
- **In any measurement, the error can not be known exactly since the true value (input) is not known. However, from the results of a calibration, the operator might feel confident that error is within certain bounds, a plus or minus range of the indicated reading.**

Static Calibration: Statistical Control

Measurement process



- Certain inputs which are largely contributed to the overall error must be kept constant.
- uncontrolled inputs affect the instrument in random nature



Effect of uncontrolled input on calibration

Static Characteristics

Measurand range, operating range, full-scale range, span: the range of input variable $(x_{max} - x_{min})$ that produces a meaningful output.

Dynamic range is defined as the ratio of the largest to the smallest input that instrument will faithfully measure. It is normally given in decibels (dB).

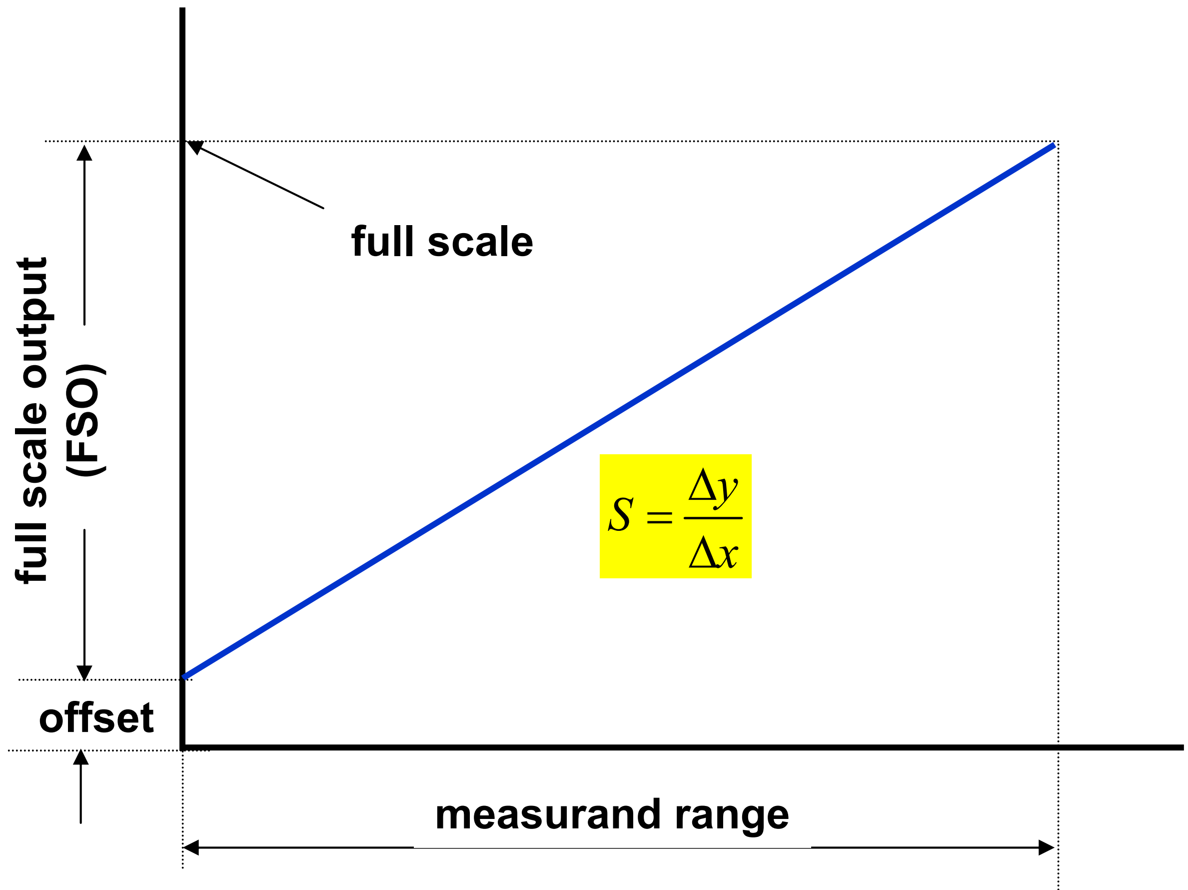
Full scale output (FSO): Difference between the end points of the output. The upper limit of output over the measurand range is called the full scale (FS)

Offset: The output of a transducer, under room temperature condition unless otherwise specified, with zero measurand applied.

Sensitivity: Incremental ratio of the output electrical signal (y) to the desired input signal (x).

$$S = \frac{\Delta y}{\Delta x}$$

Static Characteristics



Linear case: $y = Sx + \text{offset}$

Nonlinear case: $y = S(x)x + \text{offset}$

Static Characteristics

Accuracy: the difference between the true (expected) and measured values from the measurement system or sensor. Normally, it is quoted in as a fractional of the full scale output.

Percentage of reading

$$\varepsilon_a(\%) = \frac{(y_m - y_t)}{y_t} \times 100$$

Percentage of full scale

$$\varepsilon_f(\%) = \frac{(y_m - y_t)}{y_{\mathrm{FSO}}} \times 100$$

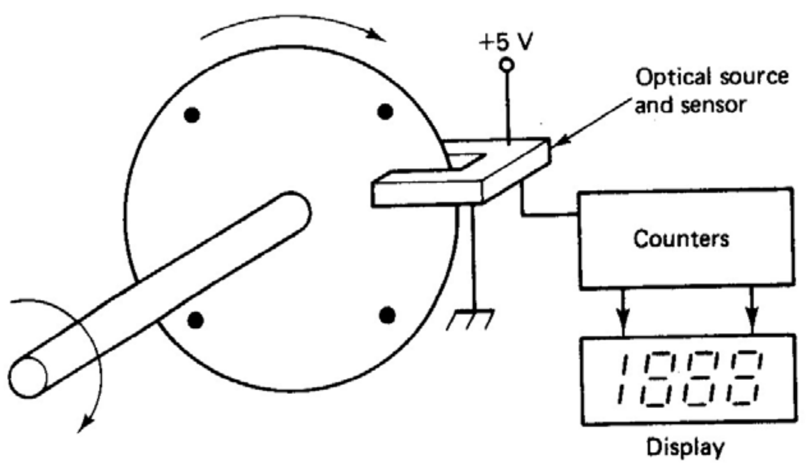
Absolute error: expressed in the units of the input parameter

Static Characteristics

Resolution: the smallest increment in the value of the measurand that results in a detectable increment in the output. It is expressed in the percentage of the measurand range

$$\text{Resolution }(\%) = \frac{\Delta x}{x_{max} - x_{min}} \times 100$$

If the input is increased from zero, there will be some minimum value below which no output change can be detected, This minimum value defines the **Threshold** of the instrument.



Simple optical encoder

Each time the shaft rotates ¼ of a revolution, a pulse will be generated. So, this encoder has a 90°C resolution.

Static Characteristics

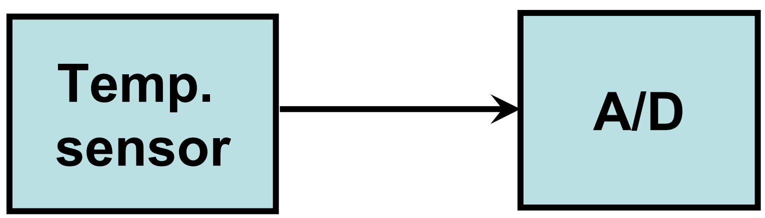
Example: A temperature transducer that outputs 10 mV/^{o}C is used to measure the temperature in a chamber that goes from 0 to 100^{o}C. Can 8 bit A/D converter with a 5-V full-scale input be used to produce a 1^{o}C resolution?

Solution: An 8-bit A/D converter has a resolution of 1 part in 2^8. So for 5-V full-scale input, each bit is worth

$$\frac{5\ \text{V}}{256} = 19.5\ \text{mV}$$

A 1^{o}C causes only a 10-mV input change. It appears that the converter does not enough resolution.

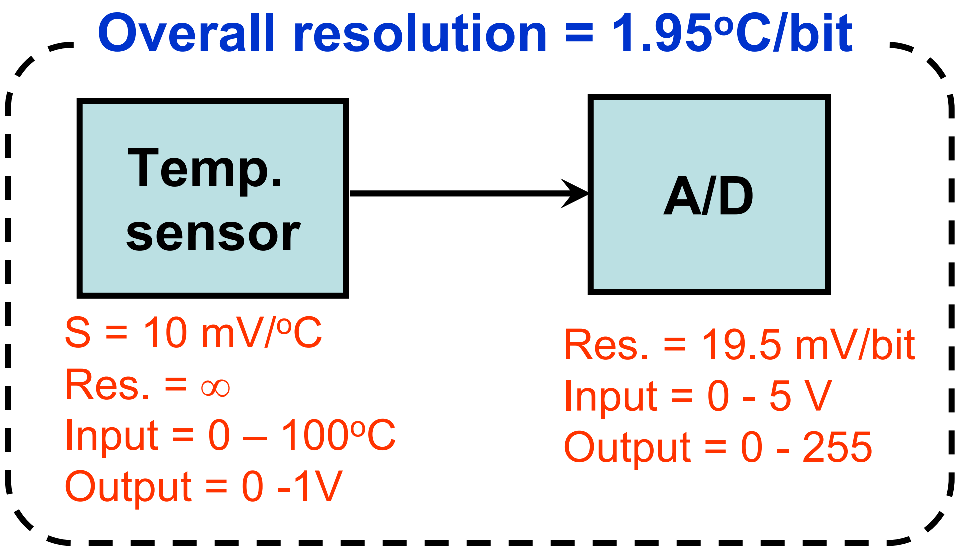
Overall resolution = 1.95^{o}C/bit

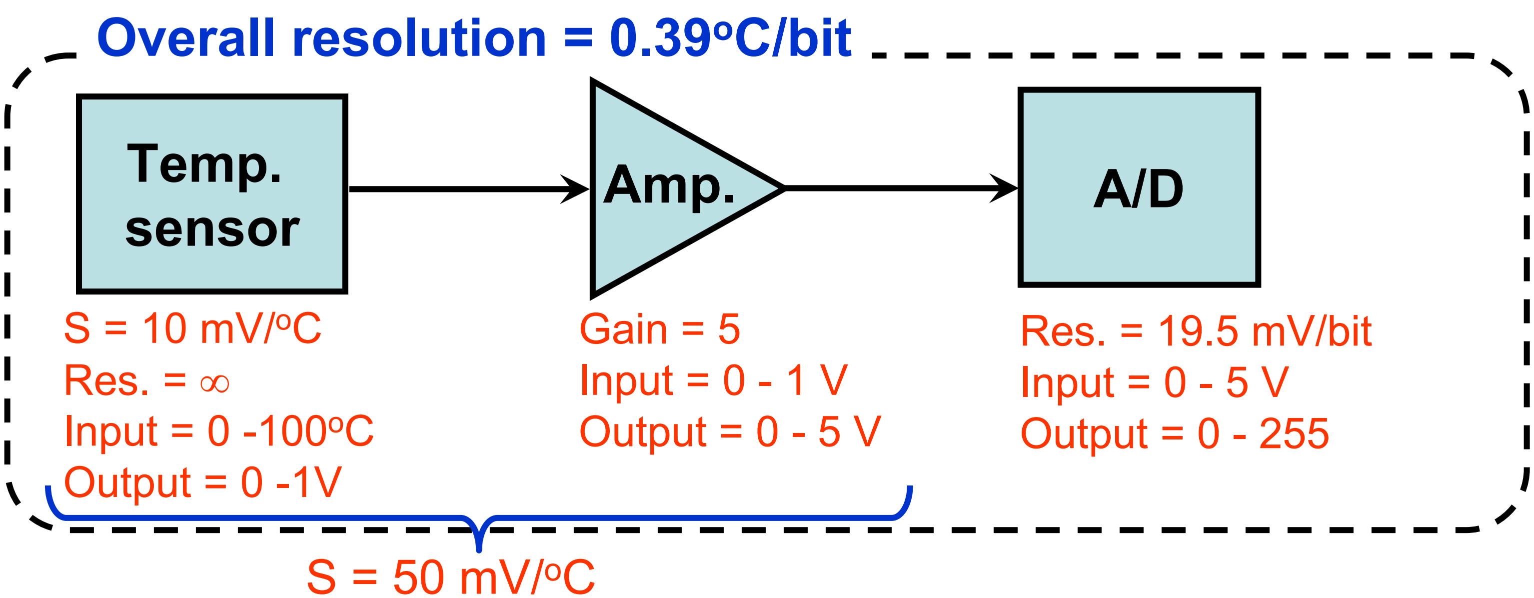


S = 10 mV/^{o}C
Res. = ∞
Input = 0 – 100^{o}C
Output = 0 -1V

Res. = 19.5 mV/bit
Input = 0 - 5 V
Output = 0 - 255

Static Characteristics





Static Characteristics

Repeatability: a measure of how well the output returns to a given value when the same precise input is applied several times. Or the ability of an instrument to reproduce a certain set of reading within a given accuracy.

Precision: how exactly and reproducibly an unknown value is measured.

$$\text{repeatability} = \frac{\text{maximum} - \text{minimum}}{\text{full scale}} \times 100\%$$

$$\text{repeatability} = \frac{\text{largest deviation} - \text{average}}{\text{full scale}} \times 100\%$$

How about: a transducer that is repeatable but not overly accurate

Static Characteristics

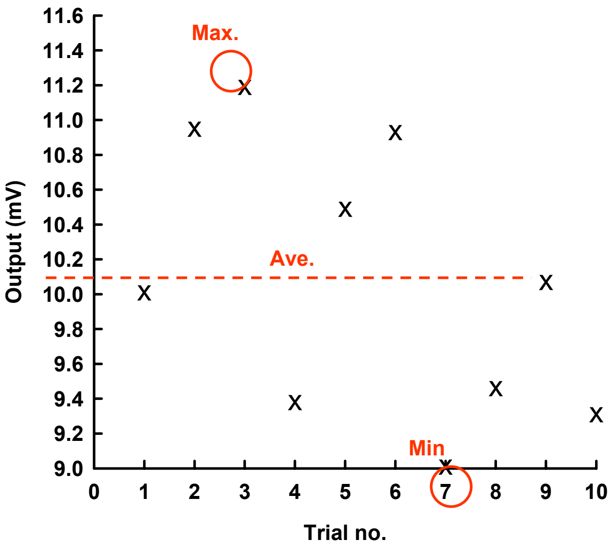
Example: Three load cells are tested for repeatability. The same 50-kg weight is placed on each load cell 10 times. The resulting data are given in the following table. Discuss the repeatability and accuracy of each transducer. If the full scale output of these load cells is 20 mV.

Trail no.	Load cell output (mV) A	B	C
1	10.02	11.50	10.00
2	10.96	11.53	10.03
3	11.20	11.52	10.02
4	9.39	11.47	9.93
5	10.50	11.42	9.92
6	10.94	11.51	10.01
7	9.02	11.58	10.08
8	9.47	11.50	10.00
9	10.08	11.43	9.97
10	9.32	11.48	9.98
Maximum	11.20	11.58	10.08
Average	10.09	11.49	9.99
Minimum	9.02	11.42	9.92

Static Characteristics

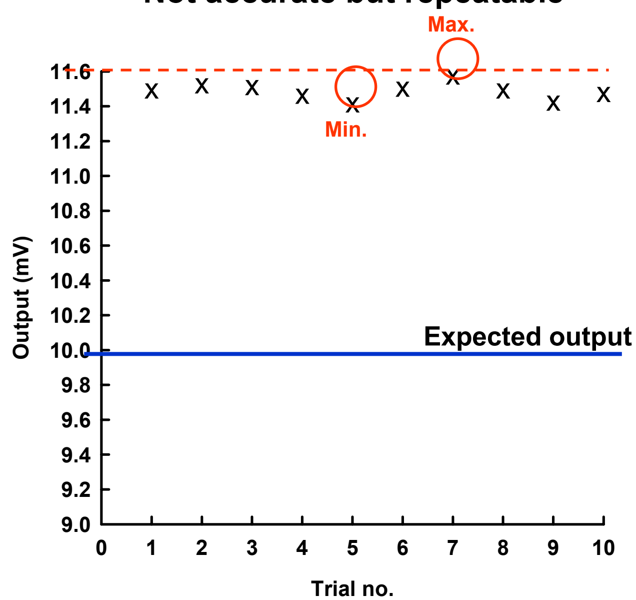
Load cell A

• Global accurate but not repeatable



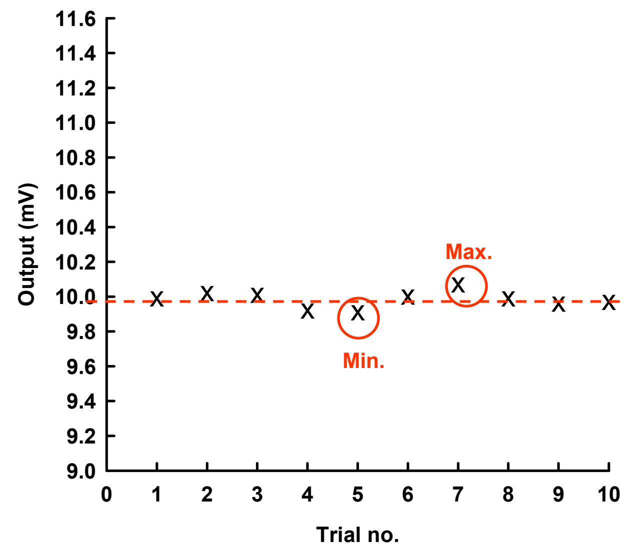
Load cell B

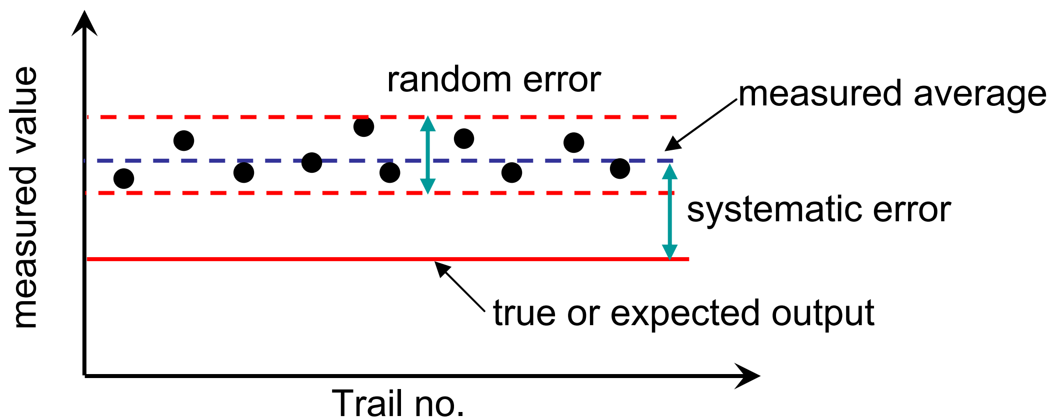
• Not accurate but repeatable



Load cell C

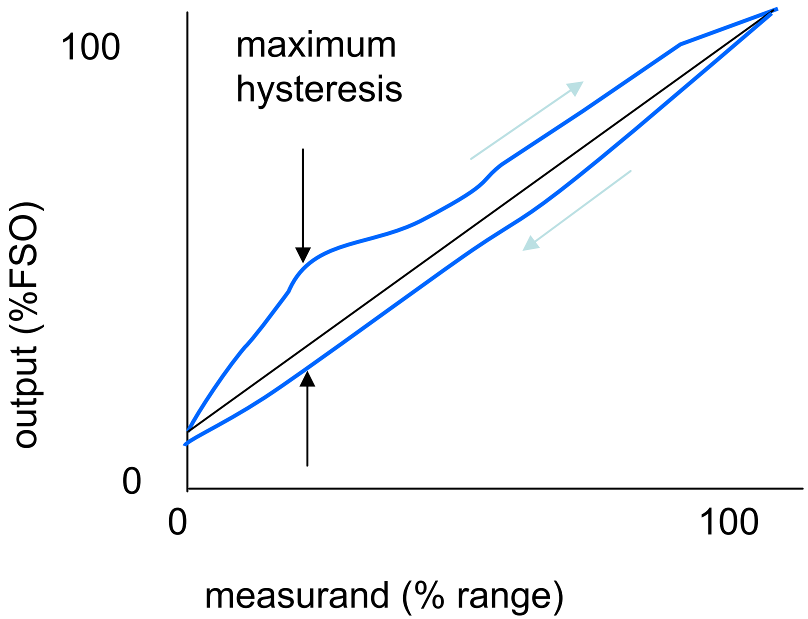
•Accurate and repeatable





Static Characteristics

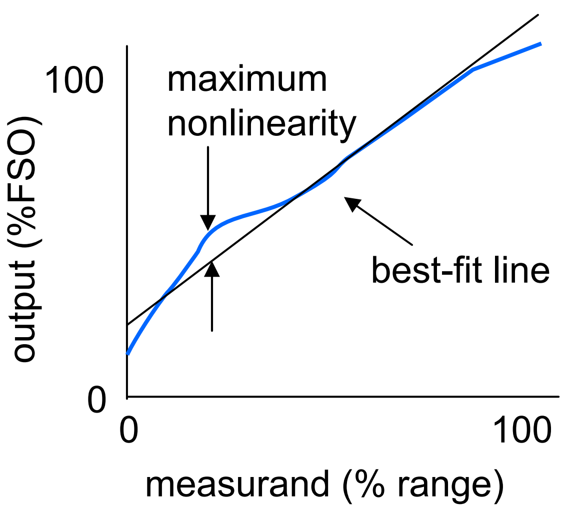
Hysteresis: Difference in the output of the sensors for a given input value x, when x is increased and decreased or vice versa. (expressed in % of FSO) (indication of reproducibility)

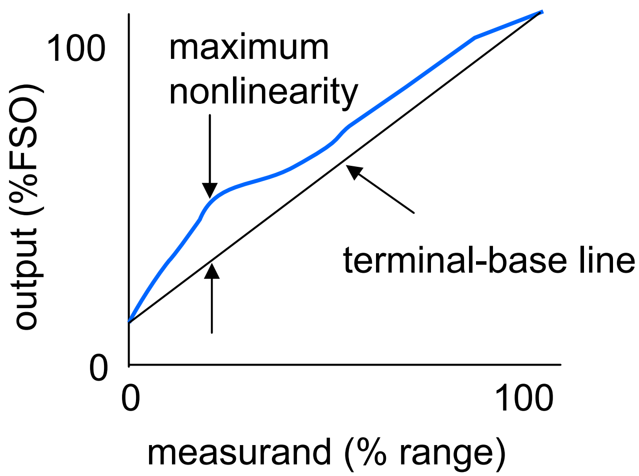


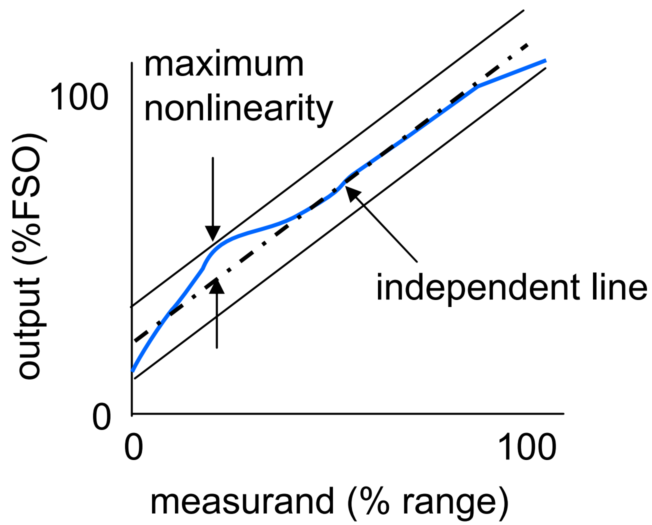
Static Characteristics

Linearity: (also called Nonlinearity) A measure of deviation from linear of the sensor, which is usually descried in terms of the percentage of FSO.

(1) best-fit straight line
(2) terminal-based straight line
(3) independent straight line



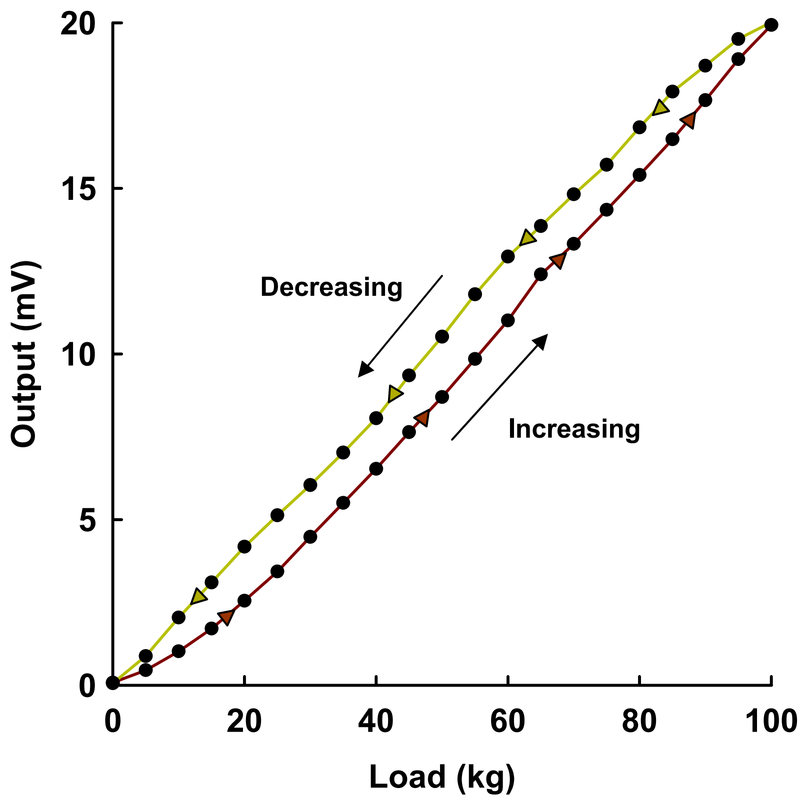




Static Characteristics

Example: A load cell is a transducer used to measure weight. A calibration record table is given below. Determine (a) accuracy, (b) hysteresis and (c) linearity of the transducer. If we assume that the true output has a linear relationship with the input.

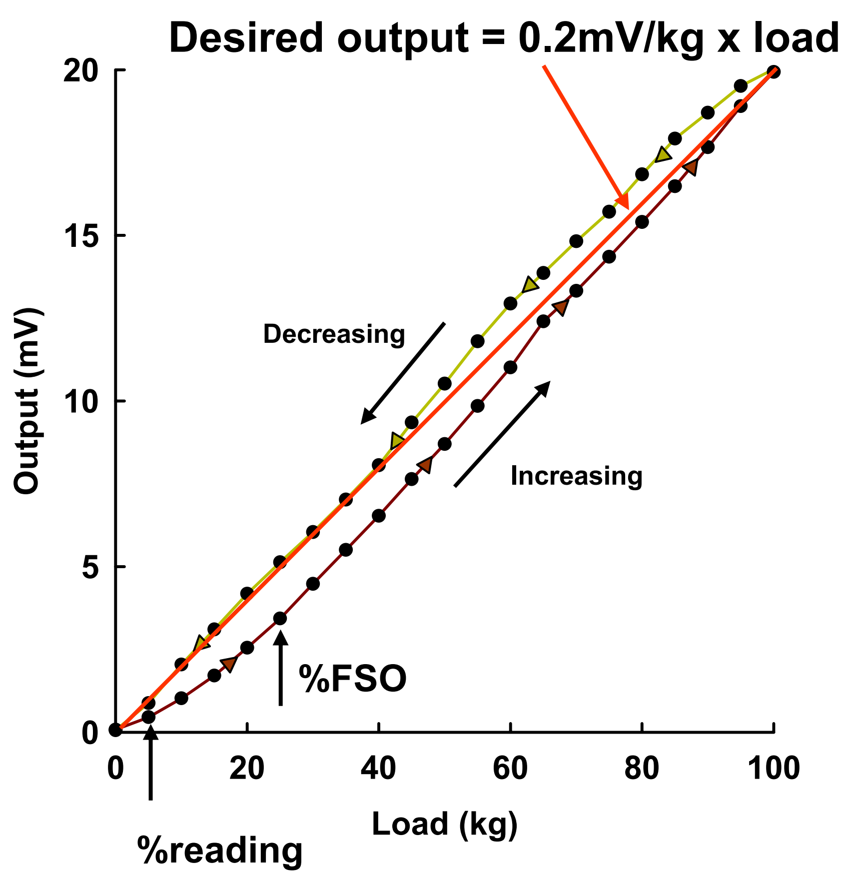
Load (kg)	Output (mV) Increasing	Output (mV) Decreasing
0	0.08	0.06
5	0.45	0.88
10	1.02	2.04
15	1.71	3.10
20	2.55	4.18
25	3.43	5.13
30	4.48	6.04
35	5.50	7.02
40	6.53	8.06
45	7.64	9.35
50	8.70	10.52
55	9.85	11.80
60	11.01	12.94
65	12.40	13.86
70	13.32	14.82
75	14.35	15.71
80	15.40	16.84
85	16.48	17.92
90	17.66	18.70
95	18.90	19.51
100	19.93	20.02



Static Characteristics

(a) Accuracy

Load (kg)	True Output (mV)	Actual Output (mV)	Error (mV)	%FSO	%reading
0	0	0.08	-0.08	-0.40	a
5	1	0.45	0.55	2.75	55.00
10	2	1.02	0.98	4.90	49.00
15	3	1.71	1.29	6.45	43.00
20	4	2.55	1.45	7.25	36.25
25	5	3.43	1.57	7.85	31.40
30	6	4.48	1.52	7.60	25.33
35	7	5.50	1.50	7.50	21.43
⋮	⋮	⋮	⋮	⋮	⋮
25	5	5.13	-0.13	-0.65	-2.60
20	4	4.18	-0.18	-0.90	-4.50
15	3	3.10	-0.10	-0.50	-3.33
10	2	2.04	-0.04	-0.20	-2.00
5	1	0.88	0.12	0.60	12.00
0	0	0.06	-0.06	-0.30	a



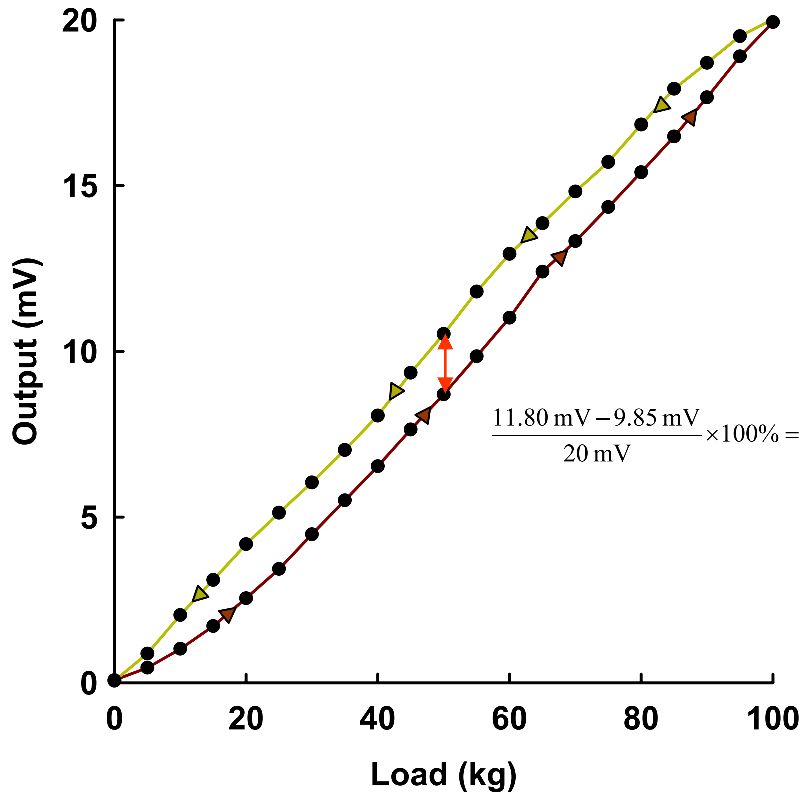
Accuracy: %FSO = 7.85% at 25 kg increasing

%reading = 55% at 5 kg increasing

Static Characteristics

(b) Hysteresis

Load (kg)	Output (mV) Increasing	Output (mV) Decreasing	Hysteresis (%FSO)
0	0.08	0.06	0.10
5	0.45	0.88	2.15
10	1.02	2.04	5.10
15	1.71	3.10	6.95
20	2.55	4.18	8.15
25	3.43	5.13	8.50
30	4.48	6.04	7.80
35	5.50	7.02	7.60
40	6.53	8.06	7.65
45	7.64	9.35	8.55
50	8.70	10.52	9.10
55	9.85	11.80	9.75
60	11.01	12.94	9.65
65	12.40	13.86	7.30
70	13.32	14.82	7.50
75	14.35	15.71	6.80
80	15.40	16.84	7.20
85	16.48	17.92	7.20
90	17.66	18.70	5.20
95	18.90	19.51	3.05
100	19.93	20.02	0.45



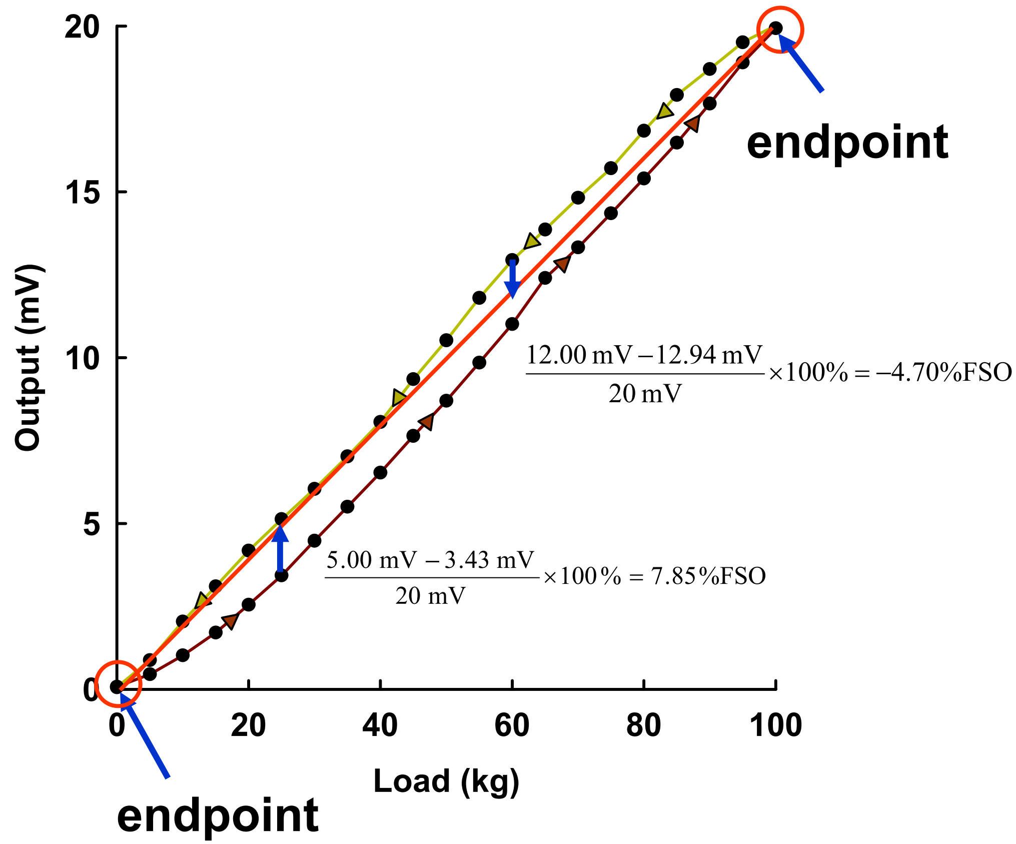
$$\frac{11.80\,\text{mV} - 9.85\,\text{mV}}{20\,\text{mV}} \times 100\% = 9.75\%\text{FSO}$$

Hysteresis = 9.75 %FSO at 55 kg

Static Characteristics

(c) Linearity: Terminal-based straight line (endpoint straight line)

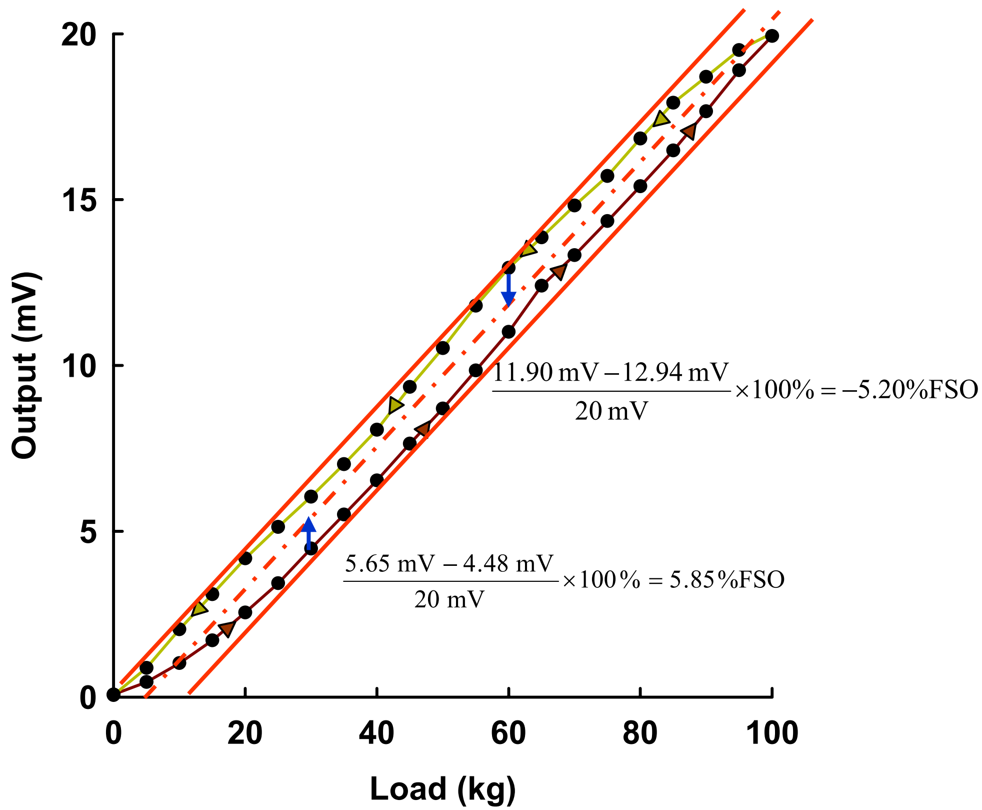
Load (kg)	Endpoint line (mV)	Actual Output (mV)	Linearity (%FSO)
0	0	0.08	-0.40
5	1	0.45	2.75
10	2	1.02	4.90
15	3	1.71	6.45
20	4	2.55	7.25
25	5	3.43	7.85
30	6	4.48	7.60
35	7	5.50	7.50
⋮	⋮	⋮	⋮
65	13	13.86	-4.30
60	12	12.94	-4.70
55	11	11.80	-4.00
50	10	10.52	-2.60
45	9	9.35	-1.75
40	8	8.06	-0.30
35	7	7.02	-0.10
30	6	6.04	-0.20
25	5	5.13	-0.65
20	4	4.18	-0.90
15	3	3.10	-0.50
10	2	2.04	-0.20
5	1	0.88	0.60
0	0	0.06	-0.30



Linearity = 7.85 %FSO at 25 kg
=-4.70 %FSO at 60 kg

Static Characteristics

(c) Linearity: Independent straight line



Linearity = 5.85 %FSO at 30 kg
=-5.20 %FSO at 60 kg

Static Characteristics

(c) Linearity: Best-fit straight line

Least square method: minimizes the sum of the square of the vertical deviations of the data points from the fitted line.

Here, we will estimate y by $y = mx + b$

$$m = \frac{N\sum xy - \sum x \sum y}{N\sum x^2 - \left(\sum x\right)^2}$$

$$b = \frac{\sum y}{N} - m\frac{\sum x}{N}$$

N = Total number of data points

Static Characteristics

x = Load (kg)
y = Load cell output (mV)

x	y	x^2	xy
0	0.08	0.00	0
5	0.45	25.00	2.25
10	1.02	100.00	10.2
15	1.71	225.00	25.65
20	2.55	400.00	51
25	3.43	625.00	85.75
30	4.48	900.00	134.4
35	5.50	1225.00	192.5
40	6.53	1600.00	261.2
45	7.64	2025.00	343.8
⋮	⋮	⋮	⋮
45	9.35	2025.00	420.75
40	8.06	1600.00	322.4
35	7.02	1225.00	245.7
30	6.04	900.00	181.2
25	5.13	625.00	128.25
20	4.18	400.00	83.6
15	3.10	225.00	46.5
10	2.04	100.00	20.4
5	0.88	25.00	4.4
0	0.06	0.00	0
Σ 2100	409.89	143500	28499.45

Here No. of Data $N = 42$

$m = 0.2079$ mV/kg
$b = -0.6368$ mV

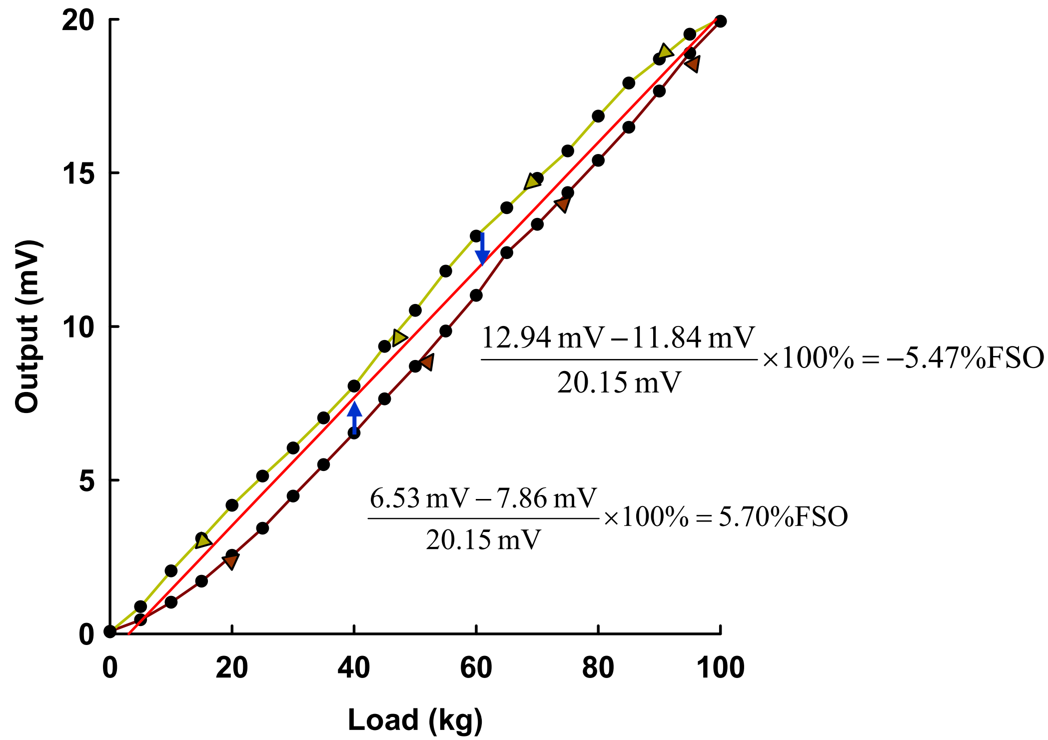
Obtained eq.

$y = 0.2079 \text{ mV/kg } x - 0.6368 \text{ mV}$

Static Characteristics

(c) Linearity: Best-fit straight line

Load (kg)	best-fit line (mV)	Actual Output (mV)	Linearity (%FSO)
0	-0.64	0.08	-3.56
5	0.40	0.45	-0.23
10	1.44	1.02	2.10
15	2.48	1.71	3.83
20	3.52	2.55	4.82
25	4.56	3.43	5.61
30	5.60	4.48	5.56
35	6.64	5.50	5.66
40	7.68	6.53	5.70
45	8.72	7.64	5.35
50	9.76	8.70	5.25
⋮	⋮	⋮	⋮
65	12.88	13.86	-4.88
60	11.84	12.94	-5.47
55	10.80	11.80	-4.97
50	9.76	10.52	-3.78
45	8.72	9.35	-3.13
40	7.68	8.06	-1.89
35	6.64	7.02	-1.89
30	5.60	6.04	-2.18
25	4.56	5.13	-2.83
20	3.52	4.18	-3.27
15	2.48	3.10	-3.07
10	1.44	2.04	-2.97
5	0.40	0.88	-2.37
0	-0.64	0.06	-3.46



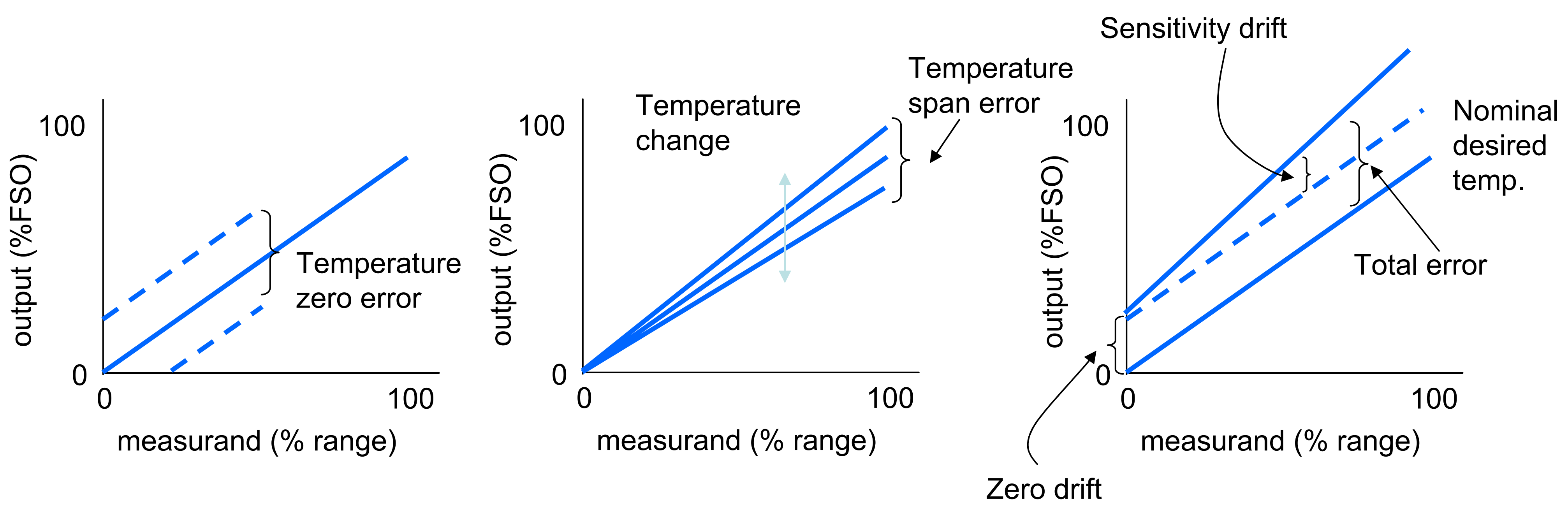
Linearity = 5.70 %FSO at 40 kg
=-5.47 %FSO at 60 kg

Static Characteristics

Operating conditions: Ambient conditions may have profound effects on sensor operation. These include temperature, acceleration, vibration, shock, pressure, moisture, corrosive materials, and electromagnetic field.

Temperature zero drift: the change in the output level of a transducer due to temperature variation when the input is set to zero.

Temperature sensitivity drift: the change in the output level of a transducer due to temperature when the input is set to the specific range.



Static Characteristics

Overall Performance: An estimate of the overall sensor error is made based on all known errors. An estimate is computed from

The worst case approach:

$$e_c = |e_1| + |e_2| + |e_3| + \cdots + |e_n|$$

The root of sum square approach:

$$e_{rss} = \sqrt{e_1^2 + e_2^2 + e_3^2 + \cdots e_n^2}$$

Specifications: Typical Pressure Transducer

Operation	
Input range	0-1000 cm H_2O
Excitation	±15 V dc
Output range	0-5 V
Temperature range	0-50°C nominal at 25°C
Performance	
Linearity error e_L	±0.5%FSO
Hysterisis error e_h	Less than ±0.15%FSO
Sensitivity error e_S	±0.25%of reading
Thermal sensitivity error e_{ST}	0.02%/°C of reading from 25°C
Thermal zero drift e_{ZT}	0.02%/°C FSO from 25°C

Worst case error

$$e_c = |e_L| + |e_h| + |e_S| + |e_{ST}| + |e_{ZT}|$$

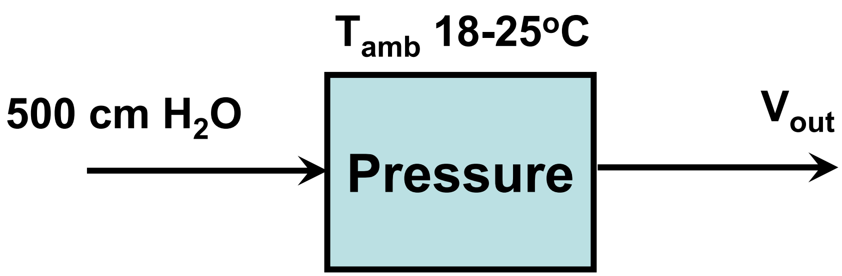
Root of sum square error

$$e_{rss} = \sqrt{e_L^2 + e_h^2 + e_S^2 + e_{ST}^2 + e_{ZT}^2}$$

Specifications: Typical Pressure Transducer

Operation	
Input range	0-1000 cm H_2O
Excitation	±15 V dc
Output range	0-5 V
Temperature range	0-50°C nominal at 25°C
Performance	
Linearity error e_L	±0.5%FSO
Hysteresis error e_h	Less than ±0.15%FSO
Sensitivity error e_S	±0.25%of reading
Thermal sensitivity error e_{ST}	0.02%/°C of reading from 25°C
Thermal zero drift e_{ZT}	0.02%/°C FSO from 25°C

The transducer is used to measure a pressure of 500 cm H_2O the ambient temperature is expected to vary between 18°C and 25°C . Estimate the magnitude of each elemental error affecting the measured pressure



Error budget calculation of a pressure transducer

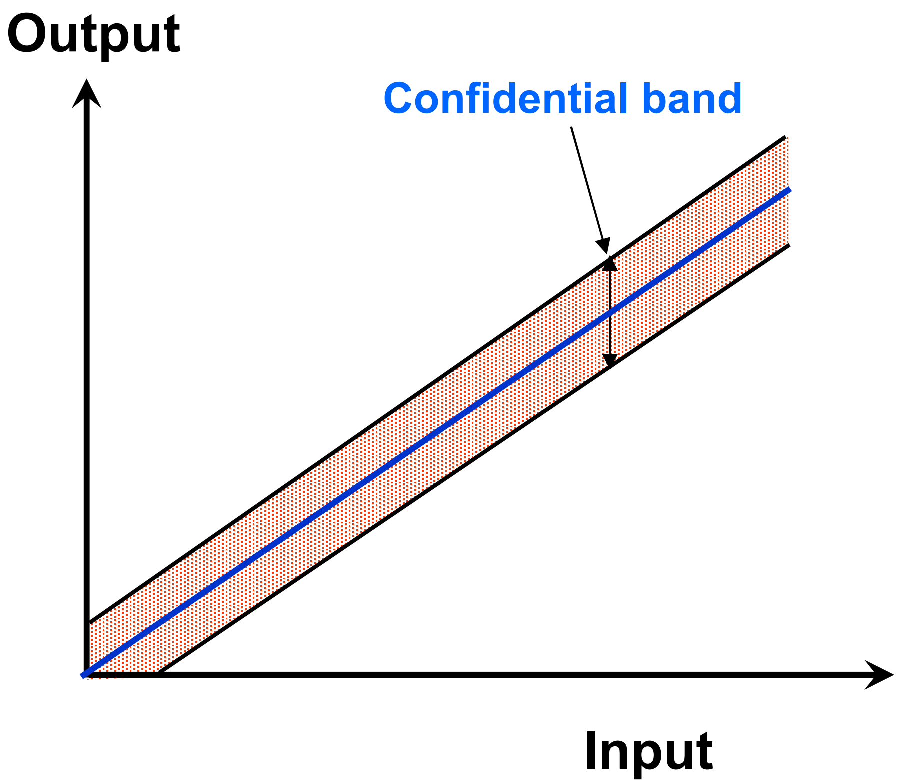
Performance	*Absolute error output*	*Absolute error transfer to input*
Linearity error e_L	± 25 mV	± 5 cm H_2O
Hystersis error e_h	± 7.5 mV	± 1.5 cm H_2O
Sensitivity error e_S	± 6.25 mV	± 1.25 cm H_2O
Thermal sensitivity error e_{ST}	+ 3.5 mV	+0.7 cm H_2O
Thermal zero drift e_{ZT}	+ 7.0 mV	+1.4 cm H_2O
Worst case error	± 49.25 mV = 0.99 %FSO	± 9.9 cm H_2O
Root square error	± 27.95 mV = 0.56 %FSO	± 5.6 cm H_2O

Worst case error

$$
\begin{aligned}
e_c &= |e_L| + |e_h| + |e_S| + |e_{ST}| + |e_{ZT}| \\
&= \pm 25 \pm 7.5 \pm 6.25 \pm 3.5 \pm 7 \;= \pm 49.25\ \mathrm{mV} \\
&= 0.99\ \%\mathrm{FSO} = 1.98\ \%\mathrm{reading}
\end{aligned}
$$

Root of sum square error

$$
\begin{aligned}
e_{rss} &= \sqrt{e_L^2 + e_h^2 + e_S^2 + e_{ST}^2 + e_{ZT}^2} \\
&= \sqrt{25^2 + 7.5^2 + 6.25^2 + 3.5^2 + 7^2} = \pm 27.95\ \mathrm{mV} \\
&= \pm 0.56\ \%\mathrm{FSO} = \pm 1.12\ \%\mathrm{reading}
\end{aligned}
$$



Basic specifications

- Input range
- Output range
- Offset
- Sensitivity

Performance specifications

- Accuracy
- Resolution
- Repeatability
- Hysteresis
- Linearity
- environmental parameter