



INTRODUCTION

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- Syllabus
- Test Pattern
- Evaluation
- objective

**UNIT-I****INTRODUCTION**

Basics of Measurement – Classification of errors – Error analysis – Static and dynamic characteristics of transducers – Performance measures of sensors – Classification of sensors – Sensor calibration techniques – Sensor Output Signal Types.

UNIT-II MOTION, PROXIMITY AND RANGING SENSORS**10**

Motion Sensors – Brush Encoders, Potentiometers, Resolver, Encoders – Optical, Magnetic, Inductive, Capacitive, LVDT – RVDT – Synchro – Microsyn, Accelerometer, – GPS, Range Sensors – RF beacons, Ultrasonic Ranging, Reflective beacons, Laser Range Sensor (LIDAR).

UNIT-III FORCE, MAGNETIC AND HEADING SENSORS**8**

Strain Gage, Load Cell, Magnetic Sensors – types, principle, requirement and advantages: Magneto resistive – Hall Effect – Current sensor Heading Sensors – Compass, Gyroscope, Inclometers.

UNIT-IV OPTICAL, PRESSURE AND TEMPERATURE SENSORS**8**

Photo conductive cell, photo voltaic, Photo resistive, LDR – Fiber optic sensors – Pressure – Diaphragm, Bellows, Piezoelectric, Temperature – IC, Thermistor, RTD, Thermocouple.

UNIT-V SIGNAL CONDITIONING**12**

Need for Signal Conditioning – DC and AC Signal conditioning – Filter and Isolation Circuits – Operational Amplifier Specifications, Characteristics and Circuits – Voltage, Current and Power Amplifiers – Transmitting Circuits – Fundamentals of Data Acquisition System.

TOTAL: 45 PERIODS



COURSE OBJECTIVES

- To learn the various types of Sensors, Transducers, Sensor output signal types, Calibration techniques and its characteristics.
- To understand basic working principle, construction and characteristics of sensors used for different application.
- To understand and analyze the working principle, construction and characteristics of sensors working in different principle but can be used for same application.
- To derive the equations relating input and output parameter of a sensor. Also train them to select suitable sensor for the application based on specification.
- To familiarize students with different signal conditioning circuits design and Data Acquisition System.



R2019-Syllabus

UNIT-I SENSOR CLASSIFICATION, CHARACTERISTICS AND SIGNAL TYPES

8

Basics of Measurement – Classification of Errors – Error Analysis – Static and Dynamic Characteristics of Transducers – Performance Measures of Sensors – Classification of Sensors – Sensor Calibration Techniques – Sensor Output - Signal Types - Analog and Digital Signals, PWM, PPM.

UNIT - II DISPLACEMENT, PROXIMITY AND RANGING SENSORS

9

Displacement Sensors – Brush Encoders - Potentiometers, Resolver, Encoders – Optical, Magnetic, Inductive, Capacitive, LVDT – RVDT – Synchro – Microsyn, Accelerometer – Range Sensors - Ultrasonic Ranging - Reflective Beacons - Laser Range Sensor (LIDAR) – GPS - RF Beacons.

UNIT - III FORCE, MAGNETIC AND HEADING SENSORS

9

Strain Gage – Types, Working, Advantage, Limitation, and Applications: Load Measurement – Force and Torque Measurement - Magnetic Sensors – Types, Principle, Advantage, Limitation, and Applications - Magneto Resistive – Hall Effect, Eddy Current Sensor - Heading Sensors – Compass, Gyroscope and Inclinometers.

UNIT - IV OPTICAL, PRESSURE, TEMPERATURE AND OTHER SENSORS

9

Photo Conductive Cell, Photo Voltaic, Photo Resistive, LDR – Fiber Optic Sensors – Pressure – Diaphragm – Bellows - Piezoelectric - Piezo-resistive - Acoustic, Temperature – IC, Thermistor, RTD, Thermocouple – Non Contact Sensor - Chemical Sensors - MEMS Sensors - Smart Sensors.

UNIT - V SIGNAL CONDITIONING

10

Need for Signal Conditioning – Resistive, Inductive and Capacitive Bridges for Measurement - DC and AC Signal Conditioning - Voltage, Current, Power and Instrumentation Amplifiers – Filter and Isolation Circuits – Fundamentals of Data Acquisition System.

TOTAL: 45 PERIODS



R2019-Syllabus

OUTCOME

Upon the completion of this course, the students will able to;

- Use concepts in common methods for converting physical parameters into an electrical quantity.
- Select suitable sensor based on application requirement.
- Understand the limitations and advantages in using sensors working in different principle and used for same application.
- Obtain transfer function and empirical relation of sensors. They can analyze the Sensor response.
- Select and design suitable signal conditioning circuit with proper compensation and linearizing element based on sensor output signal.

REFERENCES

1. Ernest O. Doebelin, "Measurement system, Application and Design", Tata McGraw Hill Publishing Company Ltd., Fiftieth Edition, 2004
2. Jacob Fraden, " Handbook of Modern sensors, Physics, Design and Applications", Springer, Fifth Edition, 2016
3. John P. Bentley., "Principle of Measurement systems", Pearson Prentice Hall, Fourth edition, 2005.
4. Patranabis D., "Sensor and Actuators", Prentice Hall of India (Pvt) Ltd., 2005.
5. Renganathan S., "Transducer Engineering", Allied Publishers (P) Ltd., 2003



SENSORS AND SIGNAL CONDITIONING LABORATORY

COURSE OBJECTIVES

- To learn and gather the practical experience on sensors and its measurements for mechatronics system development.
- To have hands on experience on various sensors to understand the working principle and its characteristics.
- To do experiments on designing of signal conditioning circuit based on sensor output signal.

LIST OF EXPERIMENTS

1. Experiments Using Strain Gauge Sensor: Load Measurement, Torque Measurement and Force Measurement.
2. Experiments with Pressure Sensor and Piezoelectric Force Sensor.
3. Experiment on Displacement Measurement using LVDT and Hall Effect Sensor.
4. Experiment on Eddy Current Sensor for Thickness Measurement.
5. Determine the Characteristics of Various Temperature Sensors.
6. Determine the Characteristics of Various Light Detectors (Optical Sensors).
7. Experiment on Ultrasonic Sensors for Distance Measurement.
8. Experimentation on Laser Sensor for Dimension Measurement.
9. Experiment with Gyroscope for angular velocity, Accelerometer for vibration measurement and Magnetometer for direction measurement.
10. Experimentation with Speed and Position Measurement Using Encoders.
11. Experiments on Design of Amplifiers and Study on frequency response of Active Filters.
12. Experiments on Bridges for unknown resistance, Inductance and Capacitance Measurement.

TOTAL: 60 PERIODS

COURSE OUTCOMES

Upon the completion of this course, the students will be able to;

- Demonstrate the ability to understand and compare the characteristics of sensors.
- Design and develop signal conditioning circuits for sensors.
- Select suitable sensor for the application



Useful information

- <http://www.todayifoundout.com>
- <http://forvo.com>
- <http://www.techhive.com>
- www.quora.com
- <http://greatist.com>
- <http://www.howstuffworks.com>



LIST OF EXPERIMENTS

- Study on various kinds of sensors and its characteristics.
 - Study on signal conditioning units.
 - Experimentation on voltage, current, power, and frequency measurement.
 - Strain gage, load cell and torque transducer characterization & applications – data acquisition & instrument control.
-
- Experimentation with tactile sensor for force and touch detection.
 - LVDT, acoustics ranging, Hall Effect sensor and ultrasonic distance measurement applications.
 - Temperature & Optical transducers Characterization – Data Acquisition & Instrument Control.
 - Study on eddy current sensor for thickness measurement.
-
- Study on ultrasonic sensors for material fault diagnosis.
 - Experimentation on laser sensor for non-contact dimension measurement.
 - Study on Experimentation with Gyroscope, Accelerometer and magnetometer.
 - Experimentation with speed and position measurement using encoders.

TOTAL: 30 PERIODS



Test Pattern

Assessment-I	100
Assessment-II	100
Practical's	100



Question pattern & Evaluation

- Theory
- Part-A
 - $5 \times 2 = 10$
- Part-B
 - 6th question with choice (13 marks)
 - 7th question with choice (13 marks)
- Part-C
 - 8th question without choice (14 marks)

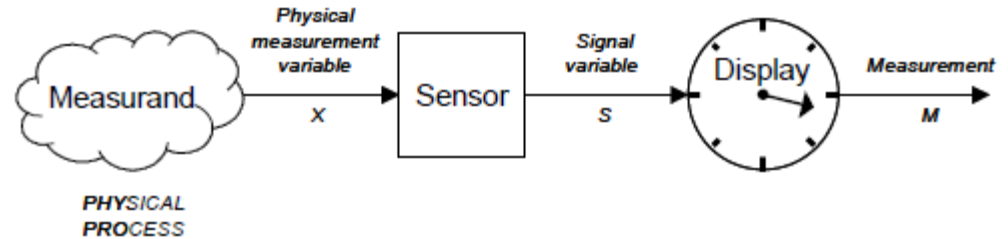


Some More Objectives.....

- The overall goal of this course is for students to attain a broad familiarity with many different sensors useful in a broad definition of "HCI" (Human-Computer Interaction)
- Develop judgment of what sensors and modalities are appropriate for different applications
- Know how to electronically condition the sensor, hook it up to a microcomputer, and process the signal (at least basically)
- Have some idea of how/where these sensors were used before
- Have a reasonable idea of how different sensors work
- Develop a sense for recognizing bad data and an intuition of how to resolve problems

Basics of measurement

- A simple instrument model



- A observable variable X is obtained from the measurand
- X is related to the measurand in some KNOWN way (i.e., measuring mass)
- The sensor generates a signal variable that can be manipulated:
 - Processed, transmitted or displayed
- In the example above the signal is passed to a display, where a measurement can be taken

Measurement

- The process of comparing an unknown quantity with a standard of the same quantity (measuring length) or standards of two or more related quantities (measuring velocity)

Solar Panel Tracking



Solar Inverter Current



Wind Speed Sensing



Electric Commutated
(EC) Motor



Motor Current
Sensing



Valve Position



Proximity
Detection



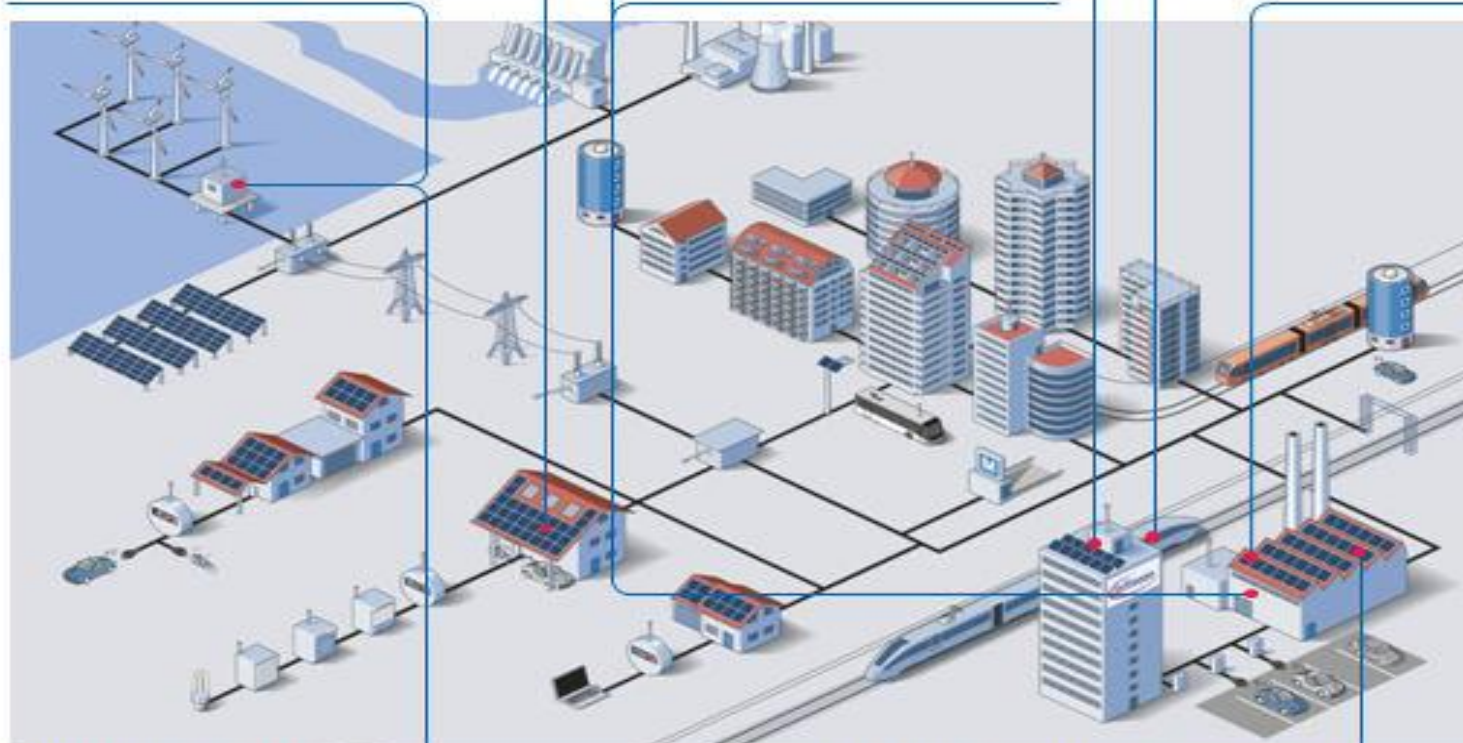
Control Elements



Gearwheel
Speed Sensor



Pneumatics



Barometric Pressure
Sensing



Absolute & Incremental
Rotary Encoder



Vehicle Sensors

Lane departure system

Night vision

Front object CCD
camera

Front airbag
sensors

ASCD

Nighttime pedestrian
warning

Drowsiness sensors

Front object
laser radar

Nighttime pedestrian
warning IR sensor

Active park assist

Tire pressure sensor

Rear object monitor
CCD camera

Rear camera

Side curtain sensor

Blind spot
detection

Cross traffic
alert

Central
computer

Rear object
laser radar

Wheel speed sensor

Tire pressure sensor

Collision sensor

Side airbag SRS

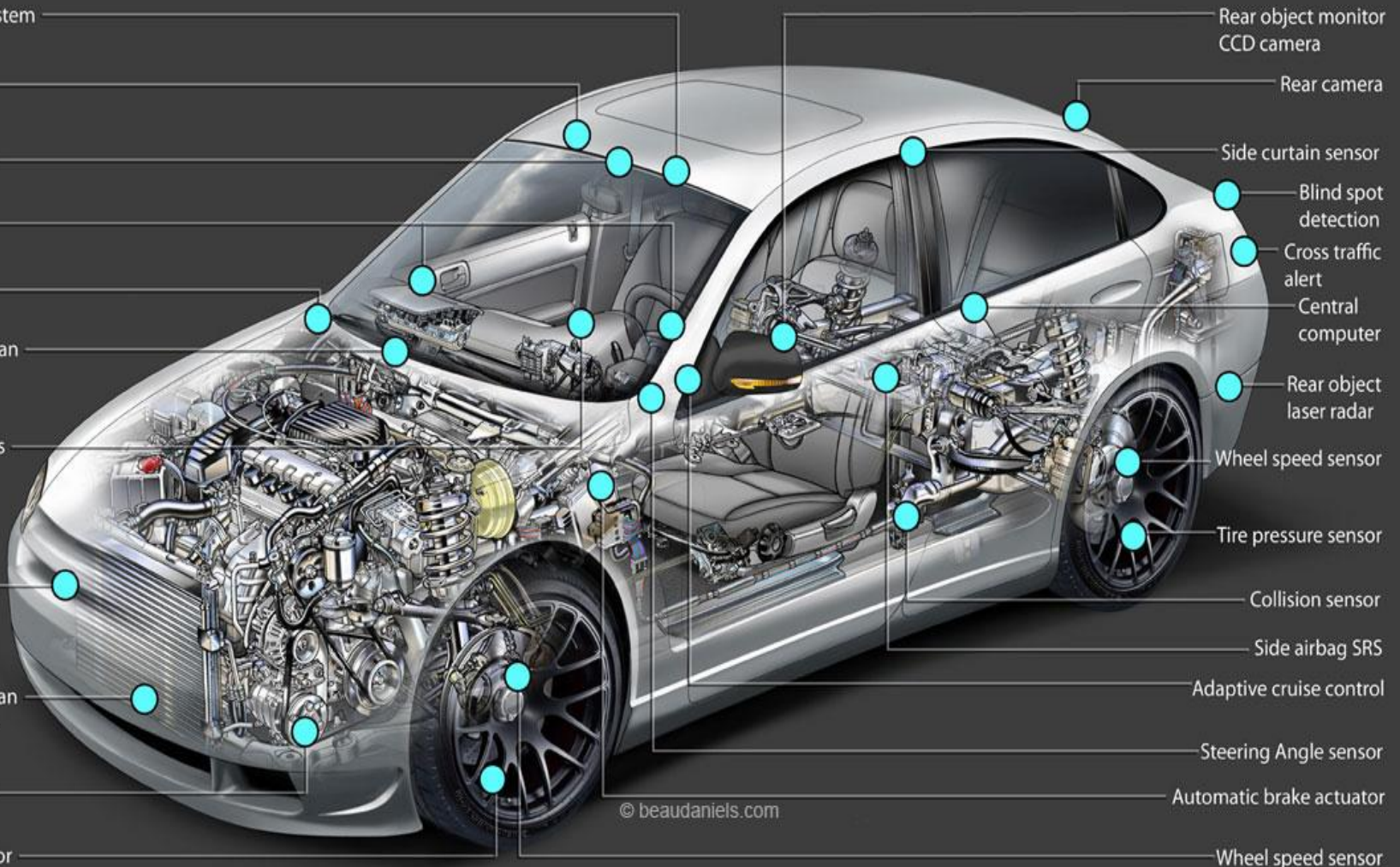
Adaptive cruise control

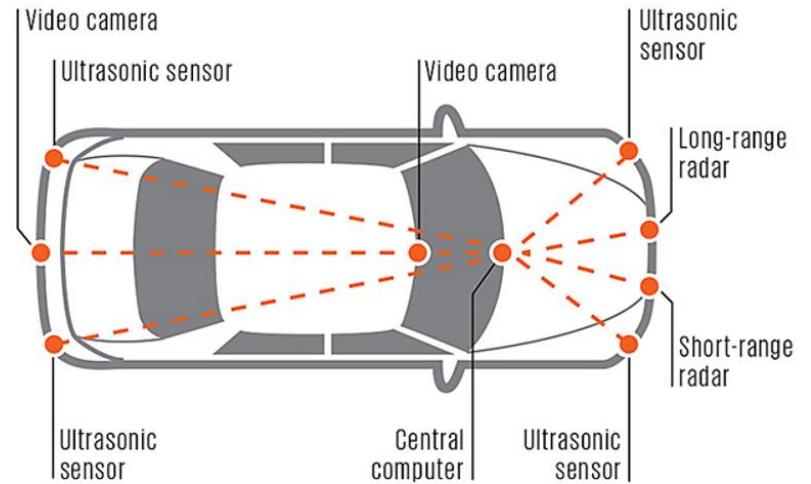
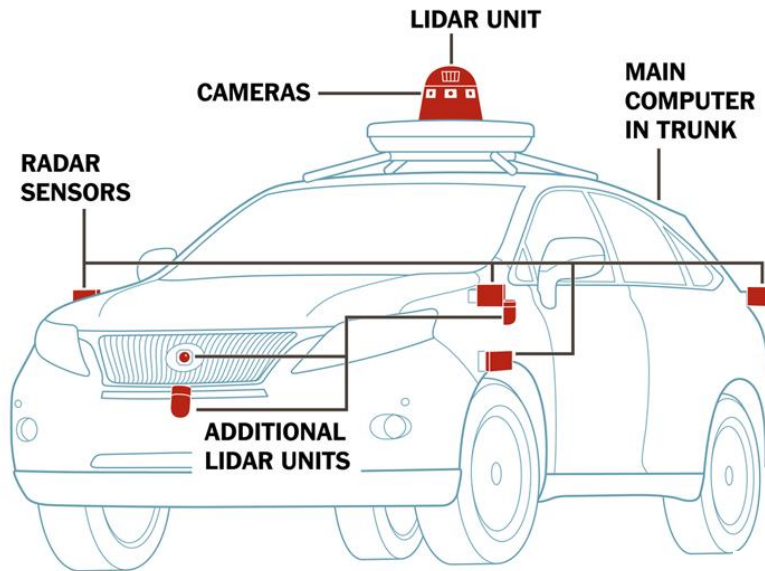
Steering Angle sensor

Automatic brake actuator

Wheel speed sensor

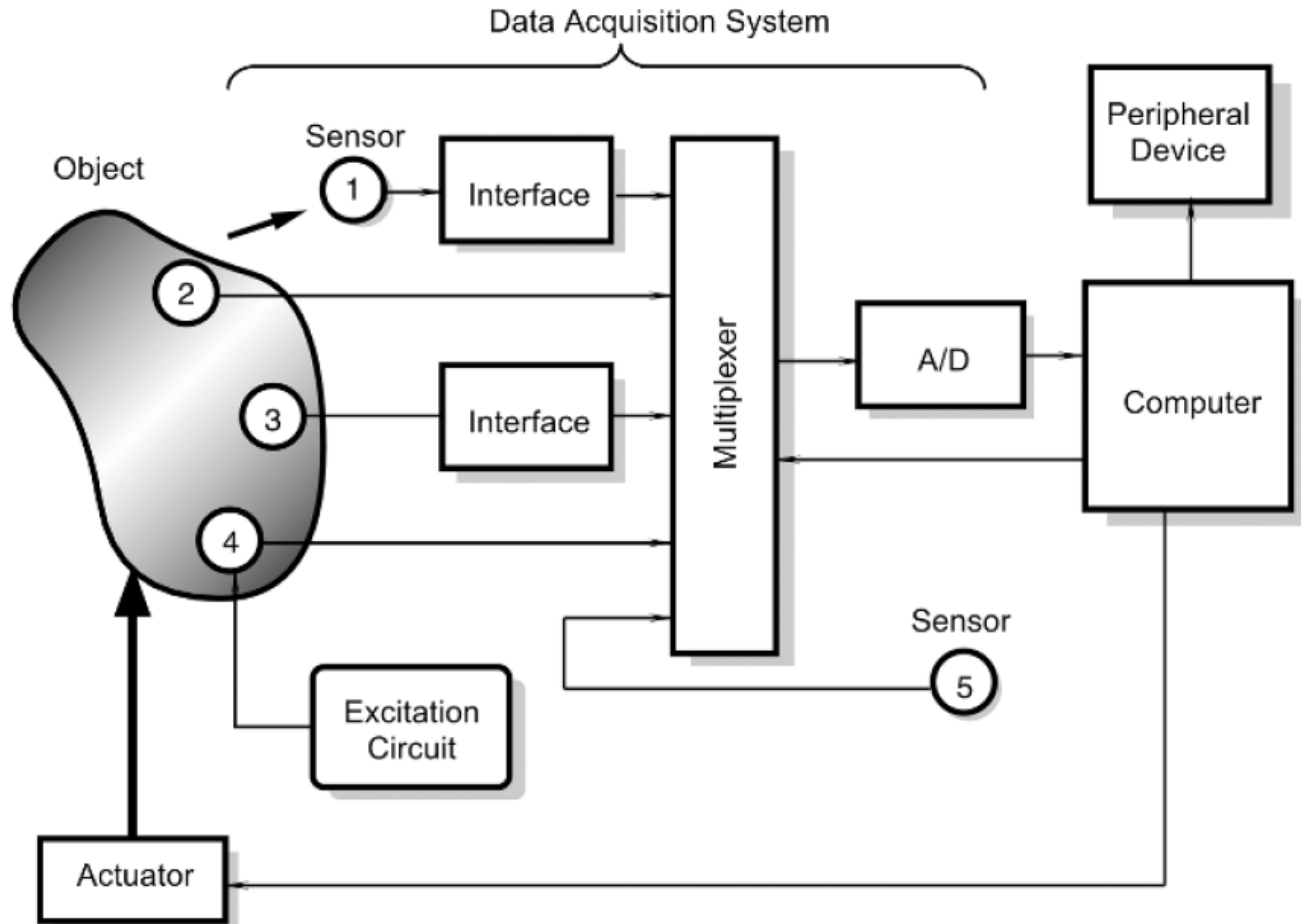
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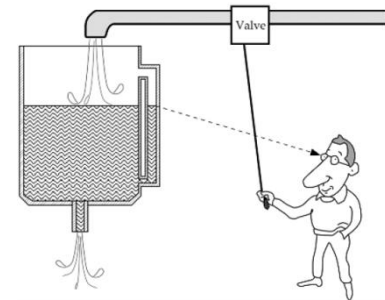
Active safety systems collect data from computer sensors, radar, video cameras, and ultrasonic distance detectors. The computer can activate alerts and brakes automatically based on sensor input. — Institute of Electrical & Electronics Engineers

Position of sensor in Data Acquisition system



Sensors

- Sensor or Transducer is a device which provides a usable output in response to the specified measurement.
 - Instrument society of America
- Sensor is an device that receives a stimulus and responds with an electrical signal.





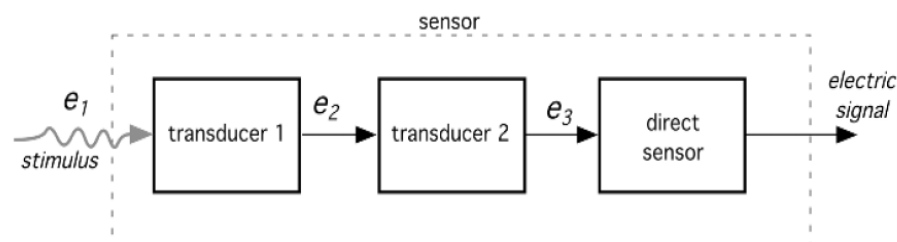
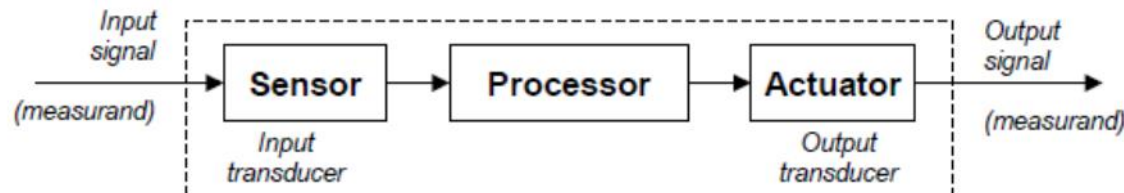
Sensor & transducer

- **Sensor**:-Convert any type of signal to electrical(Photo effect & seeback effect) .
- **Transducer**:-Convert one type of energy into another type of energy. Transducers may be used as actuators.
- Example for an transducer
 - loud speaker (act as Transducer and actuator).
 - Chemical sensor(Chemical reaction generate heat + Thermopile sense heat) combination gives chemical sensor with electrical output.



Sensors classification

- Broadly classified into
 - Direct sensor (stimulus converted to electrical signal)
 - Complex sensor (sensor may incorporate several transducers to convert stimulus to electrical signal)





Sensor Types



Active Sensor & Passive Sensor

- **Passive Sensor:** A passive sensor does not need any additional energy source and directly generates an electric signal in response to an external stimulus; that is, the input stimulus energy is converted by the sensor into the output signal
 - Eg. Thermocouple, Photodiode, Piezoelectric sensor
- **Active Sensor:** The active sensors require external power for their operation, which is called an excitation signal. That signal is modified by the sensor to produce the output signal.
 - Eg: Strain gauge, thermistor

Active Sensor & Passive Sensor

PROPERTY	SENSOR	ACTIVE/PASSIVE	OUTPUT
Temperature	Thermocouple	Passive	Voltage
	Silicon	Active	Voltage/Current
	RTD	Active	Resistance
	Thermistor	Active	Resistance
Force/Pressure	Strain Gage	Active	Resistance
	Piezoelectric	Passive	Voltage
Acceleration	Accelerometer	Active	Capacitance
Position	LVDT	Active	AC Voltage
Light Intensity	Photodiode	Passive	Current

Ref: Sensor Technology Handbook –Jon S
Wilson-Elsevier

Comparison	Active Transducer	Passive Transducer
What is	The transducer which generate the output in the form of voltage or current, without any external energy source is known as active transducer.	The passive transducer means the transducer whose internal parameters like capacitance, resistance & inductance changes because of the input signal.
Additional Energy Source	Not Require	Require
Working Principle	Draw energy from the measurand source.	Take power from the external source which changes the physical properties of transducer.
Design	Simple	Complicated
Resolution	Low	High
Output signal	Produces from the signal to be measured.	Output obtains by receiving the signal from the external power source.
Examples	Tachogenerator, Thermocouple, Photovoltaic cell etc.	Thermistor, Differential transformer, Photomultiplier tube, Photovoltaic cell.



Absolute and Relative sensor

Based on selected reference

- **Absolute Sensor:** An *absolute* sensor detects a stimulus in reference to an absolute physical scale that is independent on the measurement conditions.
 - Eg: a thermistor: a temperature-sensitive resistor
- **Relative Sensor:** A *relative* sensor produces a signal that relates to some special case.
 - Eg: thermocouple: It produces an electric voltage that is function of temperature gradient across the thermocouple wires



Example

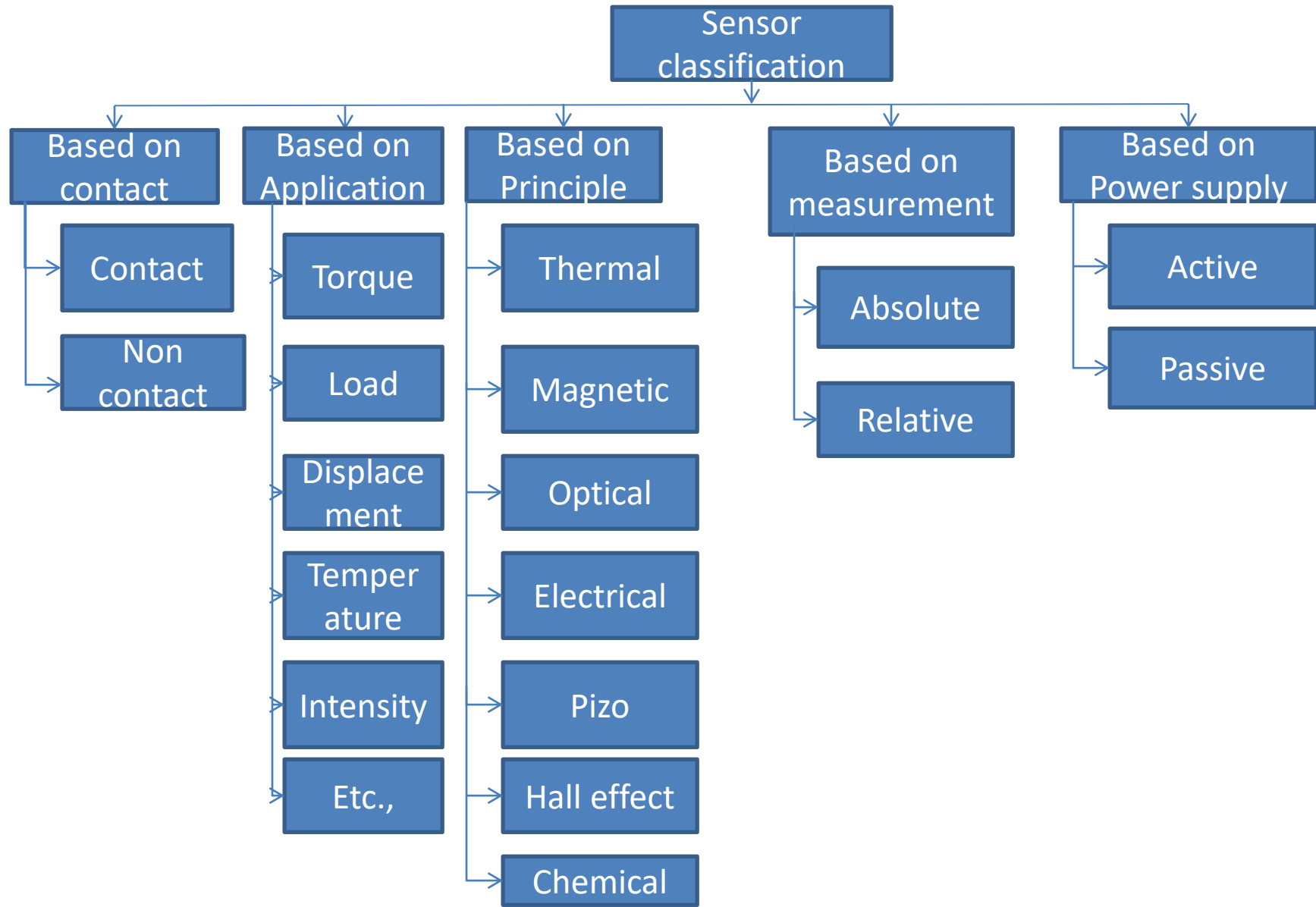
- An absolute-pressure sensor produces signal in reference to vacuum—an absolute zero on a pressure scale.
- A relative-pressure sensor produces signal with respect to a selected baseline that is not zero pressure (e.g., to the atmospheric pressure)



Different perspective.....

- Consider all of its property
 - What physical phenomenon it is sensitive to?
 - What conversion mechanism is employed?
 - What material it is fabricated from?
 - What its field of application?

Sensor Classification(summary)





Field of application

- Agriculture
- Automotive
- Civil engineering, construction Domestic, appliances
- Distribution, commerce, finance Environment, meteorology, security
- Energy, power Information, telecommunication
- Health, medicine Marine
- Manufacturing Recreation, toys
- Military Space
- Scientific measurement Other
- Transportation (excluding automotive)



Sensor characteristics

- Static
- Dynamic characteristics

Sensors Characteristics

- Static characteristics:
 - Static characteristics are values given when steady state condition occurs, i.e. the values given when the transducer has settled down after having received some input.
- Dynamic characteristics:
 - Dynamic characteristics refer to the behaviour between the time that the input value changes and the time that the value given by the transducer settles down to the steady-state value.



Static Characteristics

- Range
- Span
- Error
- Accuracy
- Sensitivity
- Hysteresis
- Linearity
- Non-Linearity
- Repeatability/Reproducibility
- Stability
- Dead band/time
- Resolution
- Zero Drift
- Output Impedance



Dynamic Characteristics

- Response Time
- Time constant
- Rise time
- Settling time



Sensor materials

- Inorganic
 - Conductor
 - Semiconductor
 - Biological substance
- organic
 - Insulator
 - Liquid, gas and plasma
 - Others...



Detection means used in sensor

- Biological
- Chemical
- Electric, magnetic, or electromagnetic wave
- Heat, temperature
- Mechanical displacement or wave
- Radioactivity, radiation
- Other

Conversion phenomenon

Physical

Thermoelectric
Photoelectric
Photo magnetic
Magnetoelectric
Thermoelastic
Electroelastic
Thermomagnetic
Thermooptic
Photoelastic
Other

Chemical

Chemical transformation
Physical transformation
Electrochemical process
Spectroscopy
Electromagnetic
Other

Biological

Biochemical transformation
Physical transformation
Effect on test organism
Spectroscopy
Other

Measurand (stimulus)

Table 1.6. Stimulus

Acoustic	Mechanical
Wave amplitude, phase, polarization	Position (linear, angular)
Spectrum	Acceleration
Wave velocity	Force
Other	Stress, pressure
Biological	Strain
Biomass (types, concentration, states)	Mass, density
Other	Moment, torque
Chemical	Speed of flow, rate of mass transport
Components (identities, concentration, states)	Shape, roughness, orientation
Other	Stiffness, compliance
Electric	Viscosity
Charge, current	Crystallinity, structural integrity
Potential, voltage	Other
Electric field (amplitude, phase, polarization, spectrum)	Radiation
Conductivity	Type
Permittivity	Energy
Other	Intensity
Magnetic	Other
Magnetic field (amplitude, phase, polarization, spectrum)	Thermal
Magnetic flux	Temperature
Permeability	Flux
Other	Specific heat
Optical	Thermal conductivity
Wave amplitude, phase, polarization, spectrum	Other
Wave velocity	
Refractive index	
Emissivity	
reflectivity, absorption	
Other	



Sensor characteristics

Lecture-2

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Static Characteristics

- Range
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Range and Span

- Range: The range of a transducer defines the limits between which the input can vary.
- Span: The span is the maximum value of the input minus the minimum value (Dynamic range of stimuli which may be converted by a sensor).

Range and Span

- Range :- the difference between the largest and the smallest reading of the instrument is called range of instrument.
- Span: the algebraic difference between the upper and lower range values of instruments.

Example –

1) Range : 2 KN/m² to 50 KN/m²

Span : $50 - 2 = 48 \text{ KN/m}^2$

2) Range : -5°C to 90°C

Span: $90 - (-5) = 95^\circ\text{C}$

Error

- Error is the difference between the result of the measurement and the true value of the quantity being measured.
- $\text{Error} = \text{Measured value} - \text{True value}$

DPI 811 and DPI 812

Measure and Simulate	Standard	*Accuracy	Range
Pt 50 (385)	IEC 751	0.9°F (0.5°C)	-328°F to 1562°F (-200°C to 850°C)
Pt 100 (385)	IEC 751	0.45°F (0.25°C)	-328°F to 1562°F (-200°C to 850°C)
Pt 200 (385)	IEC 751	1.08°F (0.6°C)	-328°F to 1562°F (-200°C to 850°C)
Pt 500 (385)	IEC 751	0.72°F (0.4°C)	-328°F to 1562°F (-200°C to 850°C)
Pt 1000 (385)	IEC 751	0.36°F (0.2°C)	-328°F to 752°F (-200°C to 400°C)
D 100 (392)	JIS 1604-1989	0.45°F (0.25°C)	-328°F to 1202°F (-200°C to 650°C)
Ni 100	DIN 43760	0.36°F (0.2°C)	-76°F to 482°F (-60°C to 250°C)
Ni 120	MINCO 7-120	0.36°F (0.2°C)	-112°F to 500°F (-80°C to 260°C)
Ohms		0 to 4000	0.1 to 1.3 Ω

- *Accuracy includes operation over 50°F to 86°F (10°C to 30°C), one year stability and calibration uncertainty.
- Excitation: 0.2 to 0.5 mA measure 0.05 to 3 mA simulate
- Pulse excitation currents minimum duration 10 ms

DPI 812 Only

Measure	Accuracy
0 to 55.000 mA	0.02% reading + 3 counts
Temperature coefficient	14°F to 50°F, 86°F to 122°F, 0.0011% FS/°F (30°C to 50°C, -10°C to 10°C, 0.002% FS °C)
Switch detection	Open and closed, 2 mA current
Loop power output	24V ±10% (35 mA maximum)
HART mA loop resistor	250 Ω (menu selection)
Electrical connectors	4 mm sockets

Accuracy



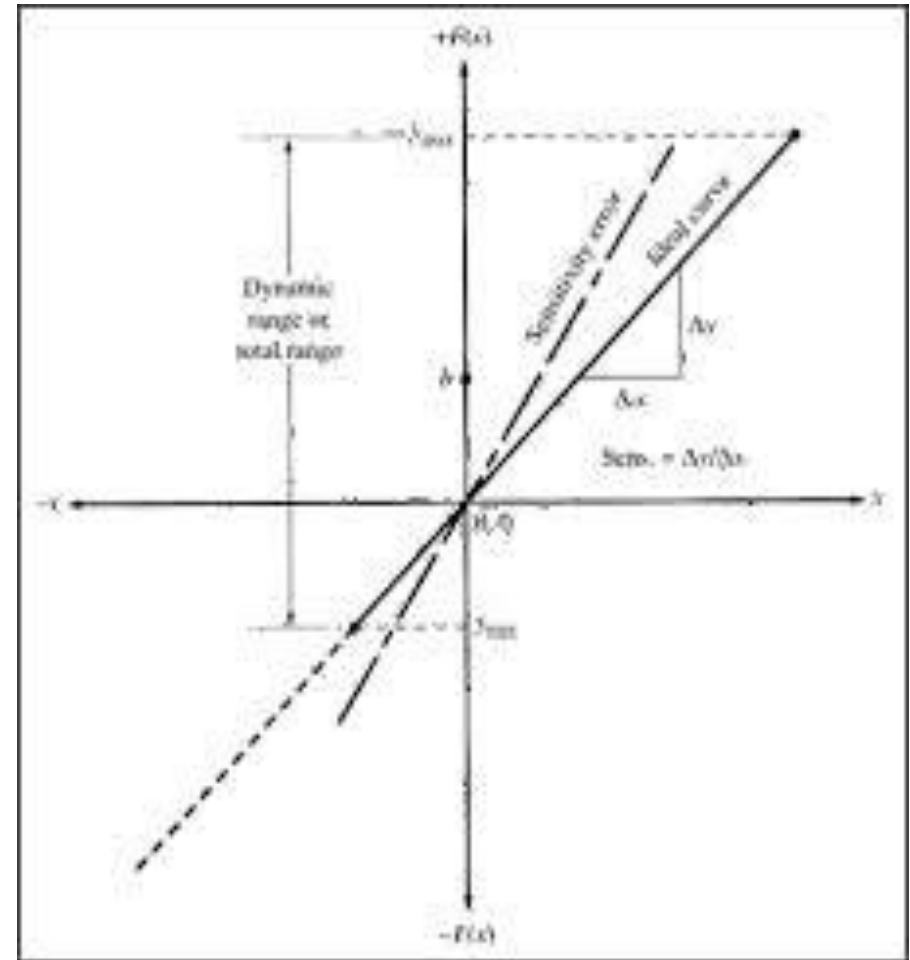
- Accuracy is the extent to which the value indicated by a measurement system might be wrong.
- Degree of closeness to the true value



precision

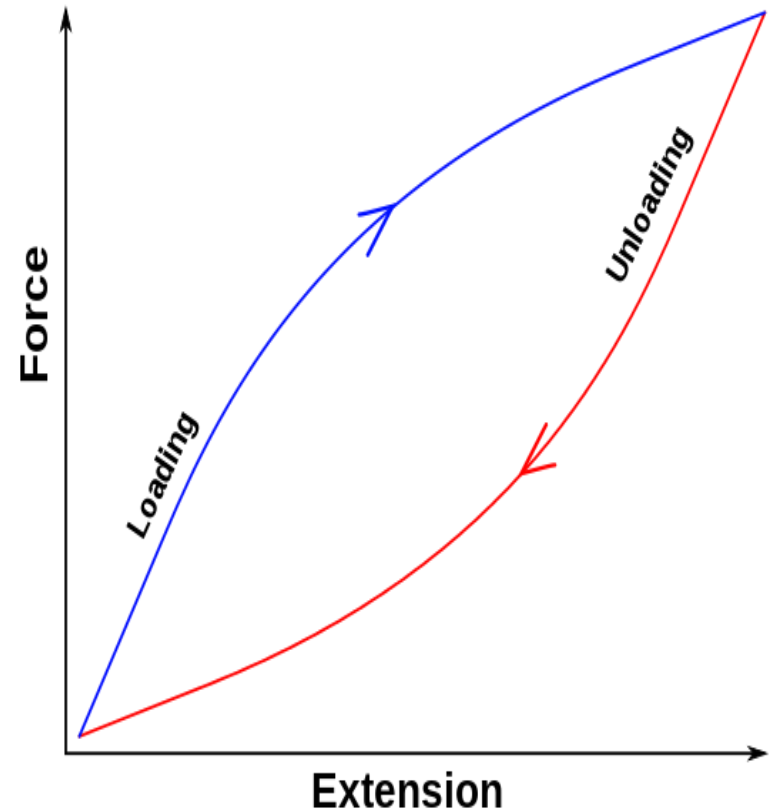
Sensitivity

- The Sensitivity is the relationship indicating how much output there is per unit input.



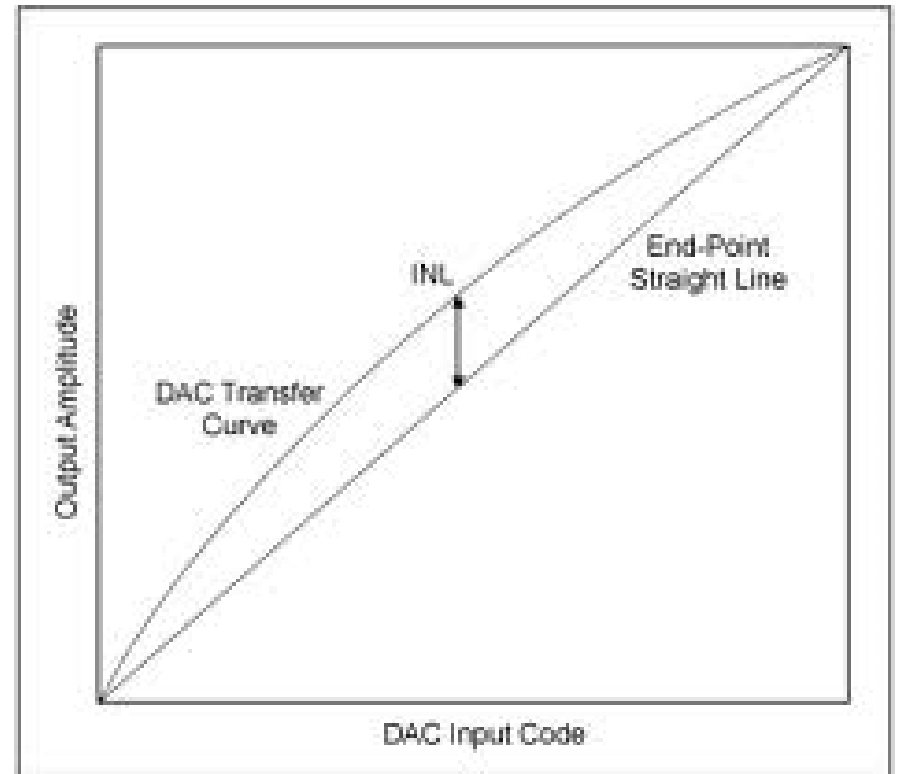
Hysteresis error

- Transducers can give different outputs from the same value of quantity being measured according to whether that value has been reached by a continuously increasing change or a continuously decreasing change.



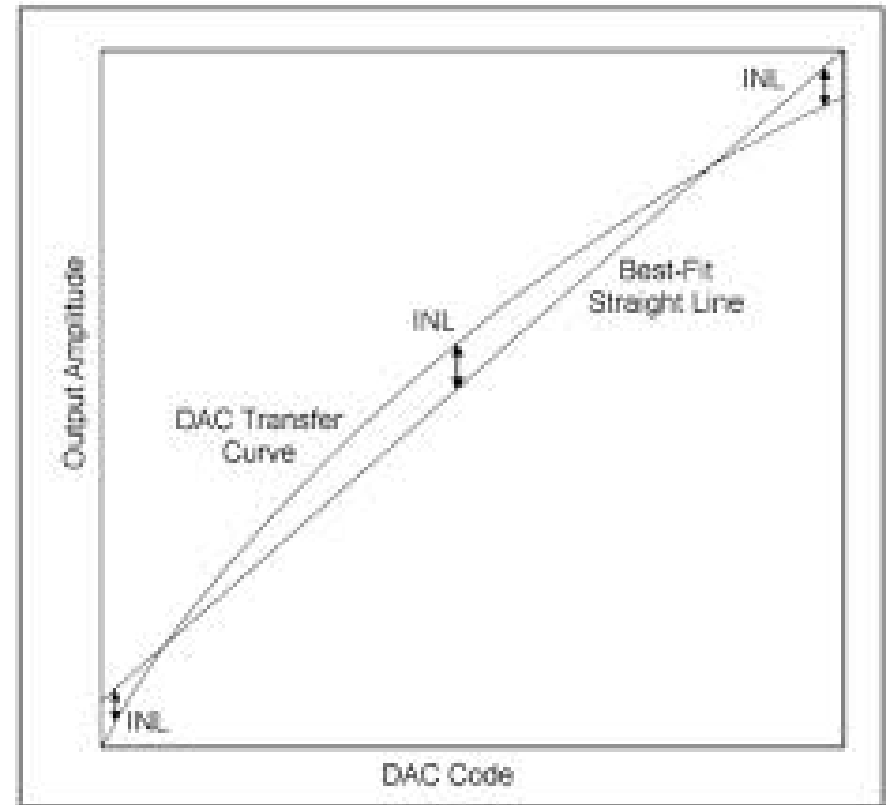
Non-linearity Error

- The error is defined as the maximum difference from the straight line.



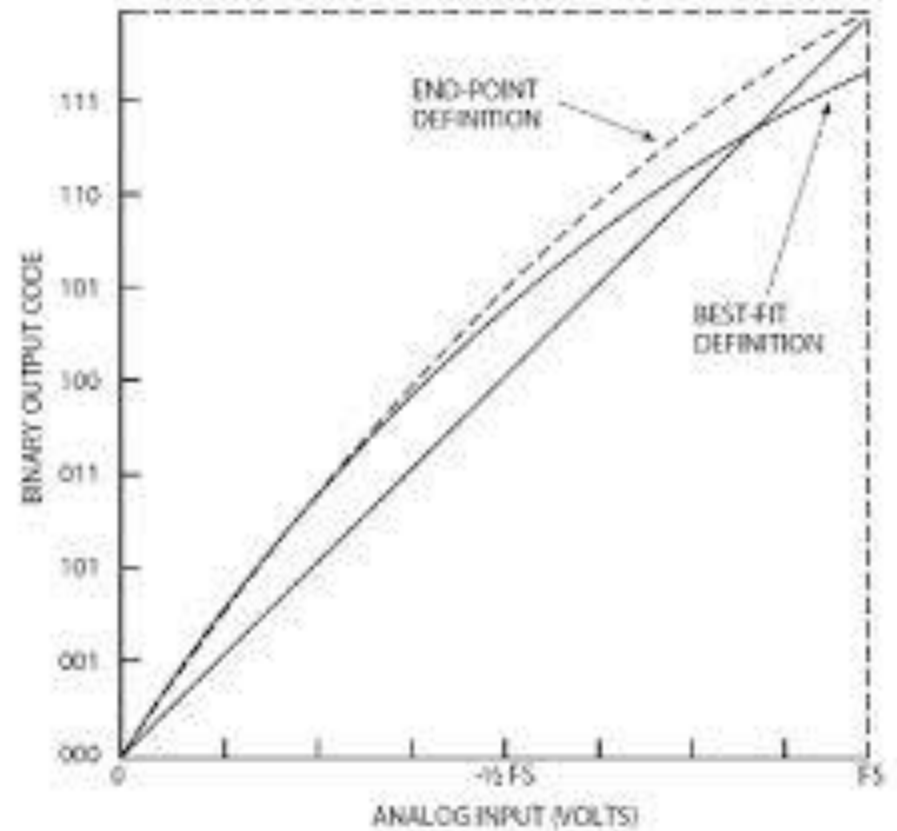
Non-linearity Error

- Least square method to find the best fit line .

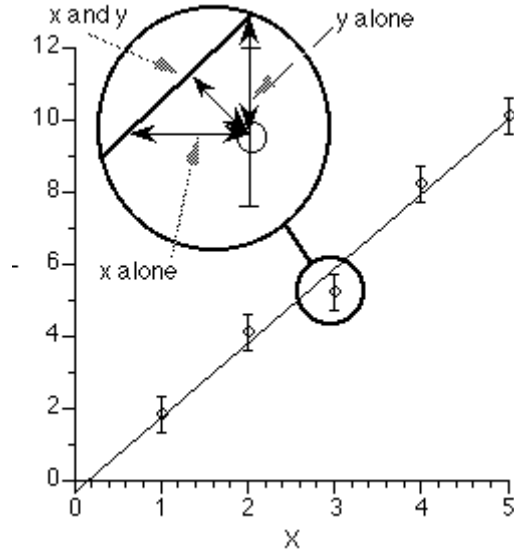


Non-linearity Error

- Least square method to find the best fit line which passes through the zero point.



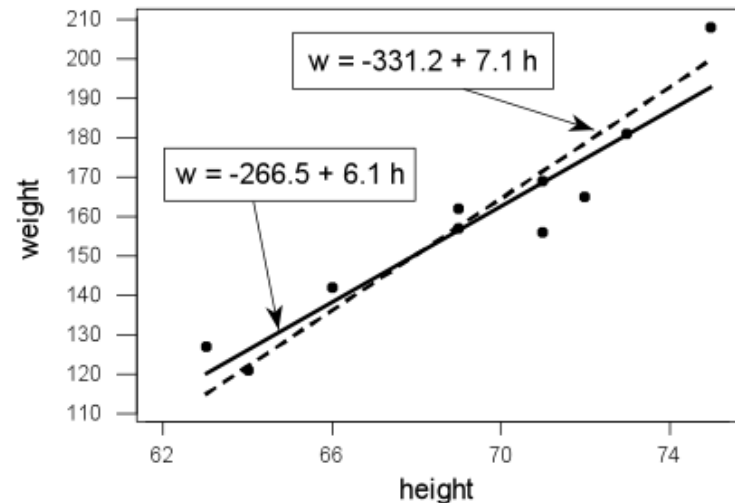
Least Square criterion



- Residual = $Y_{\text{observed}} - Y_{\text{calculated}}$
- Residual = $(Y_{\text{observed}} - Y_{\text{calculated}})^2$
- $SS = \sum_{i=1}^{i=n} (Y_{\text{observed},i} - Y_{\text{calculated},i})^2$
- $WSS = \sum_{i=1}^{i=n} (Y_{\text{observed},i} - Y_{\text{calculated},i})^2 \cdot W_i$

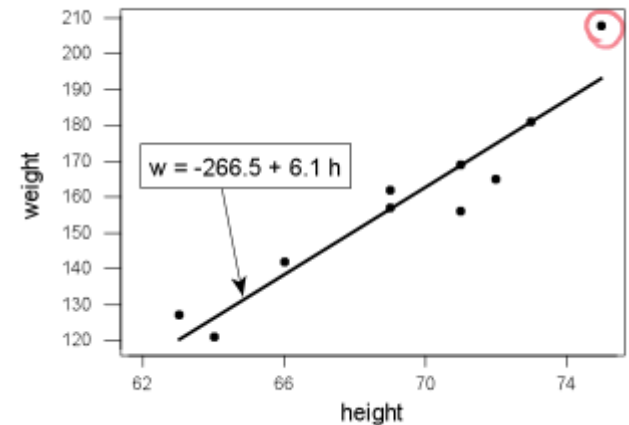
Example

- A student was interested in quantifying the (linear) relationship between height (in inches) and weight (in pounds), so she measured the height and weight of ten randomly selected students in her class. After taking the measurements, she created the adjacent scatterplot of the obtained heights and weights. Wanting to summarize the relationship between height and weight, she eyeballed what she thought were two good lines (solid and dashed), but couldn't decide between:
- $\text{weight} = -266.5 + 6.1 \times \text{height}$
- $\text{weight} = -331.2 + 7.1 \times \text{height}$
- Which is the "best fitting line"?





- Solution. In order to facilitate finding line, let's define some notation. Recall that the response variable is the thing being measured (in this case, a student's weight):
- let y_i denote the observed response for the i th experimental unit
- let x_i denote the predictor value for the i th experimental unit
- let \hat{y}_i denote the predicted response (or fitted value) for the i th experimental unit
- Therefore, for the data point circled in red:





- we have:
- $x_i=75$ and $y_i=208$
- And, using the unrounded version of the proposed line, the predicted weight of a randomly selected 75-inch tall student is:
- $\hat{y}_i=-266.534+6.13758(75)=193.8$
- pounds. Now, of course, the estimated line does not predict the weight of a 75-inch tall student perfectly. In this case, the prediction is 193.8 pounds, when the reality is 208 pounds. We have made an error in our prediction. That is, in using \hat{y}_i to predict the actual response y_i we make a prediction error (or a residual error) of size:
- $e_i=y_i-\hat{y}_i$



Line of best fit

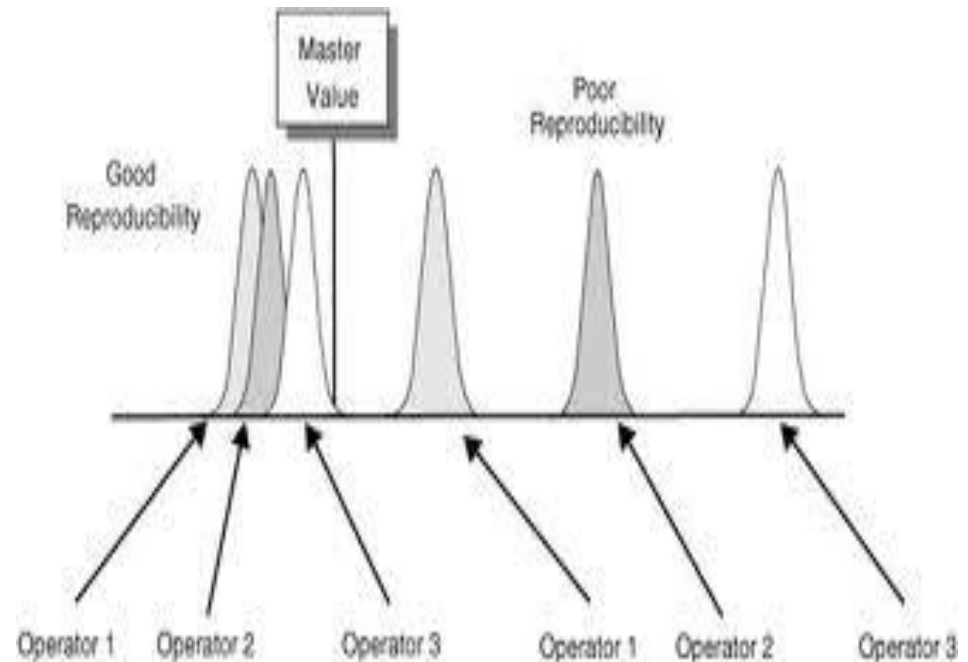
- A **line of best fit** is a straight line that is the best approximation of the given set of data
- It is used to study the nature of the relation between two variables. (We're only considering the two-dimensional case, here.)
- A line of best fit can be roughly determined using an eyeball method by drawing a straight line on a [scatter plot](#) so that the number of points above the line and below the line is about equal (and the line passes through as many points as possible).
- A more accurate way of finding the line of best fit is the **least square method** .



- Use the following steps to find the equation of line of best fit for a set of ordered pairs $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$.
- Step 1: Calculate the mean of the x -values and the mean of the y -values.
-

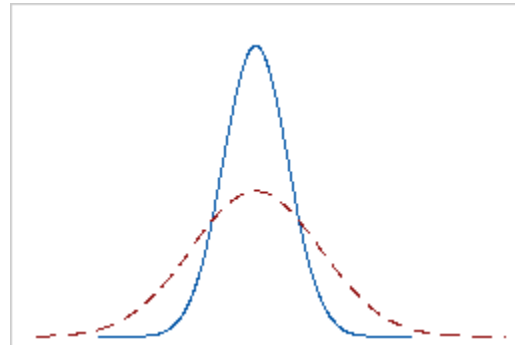
Repeatability/Reproducibility

- Ability to give the same output for repeated applications of the same input value.
- $\text{Repeatability} = (\text{Max} - \text{Min. values given}) / \text{full range} * 100$



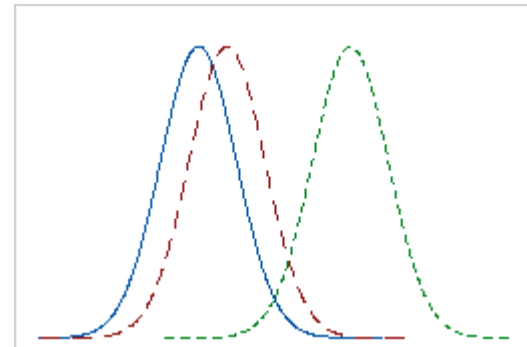
Repeatability

- The ability of an operator to consistently repeat the same measurement of the same part, using the same gage, under the same conditions. Operator 1 measures a single part with Gage A 20 times, and then measures the same part with Gage B. The solid line is the measurements from Gage A. The dashed line is the measurements from Gage B. Gage A has less variation, so it is more repeatable than Gage B.



Reproducibility

- The ability of a gage, used by multiple operators, to consistently reproduce the same measurement of the same part, under the same conditions. Operators 1, 2, and 3 measure the same part 20 times with the same gage. The three lines are the measurements from Operator 1, 2, and 3. The variation in average measurements between Appraisers 1 and 2 is much less than the variation between Appraisers 1 and 3. Therefore, the gage's reproducibility is too low.



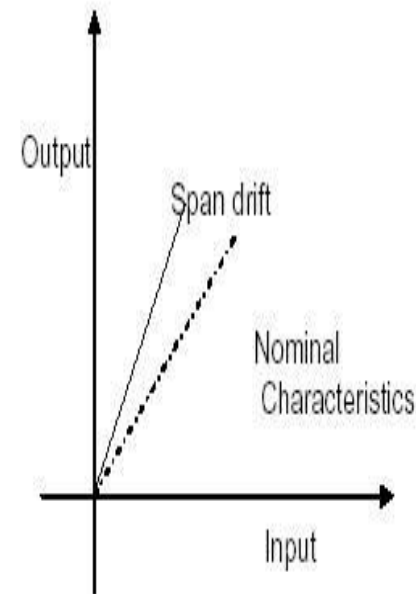


Stability

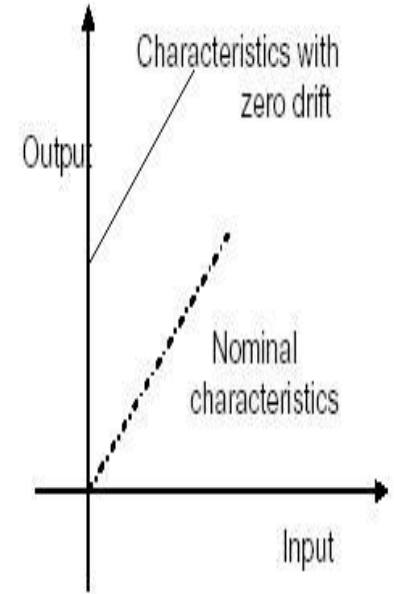
- Ability of a transducer to give the same output when used to measure a constant input over a period of time

Drift and Zero Drift

- Drift:
 - Change in output occurs over a period of time.
 - It may be expressed in % of full range output.
- Zero Drift:
 - Changes that Occur in output when there is zero input.



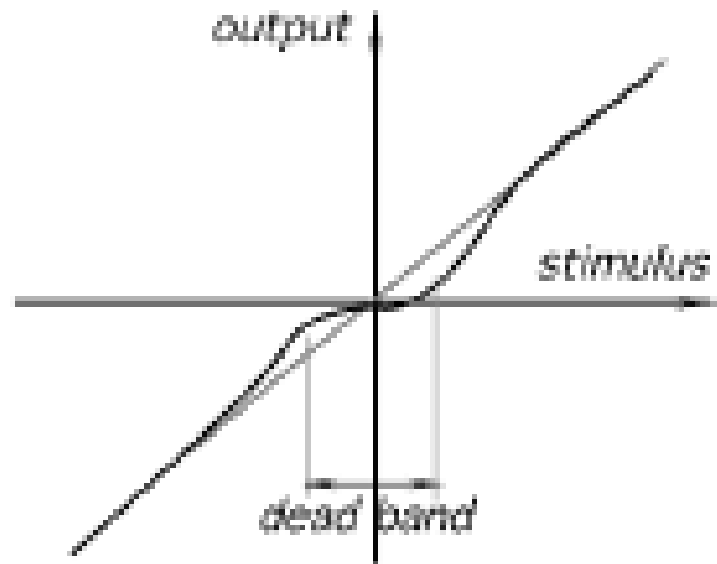
(Fig) span drift



(fig) zero drift

Dead Band/Time

- The Dead band or dead space of a transducer is the range of input values for which there is no output.
- Dead time is the length of time from the application of an input until the output begins to respond and change.



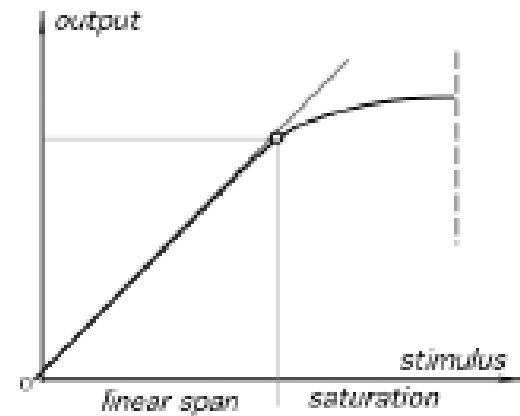


Resolution

- When the input varies continuously over a range, the output signals for some sensors may change in small steps.
- Eg: Thus for a sensor giving a data word of N bits, i.e. a total of 2^N bits, the resolution is generally expressed as $1/2^N$

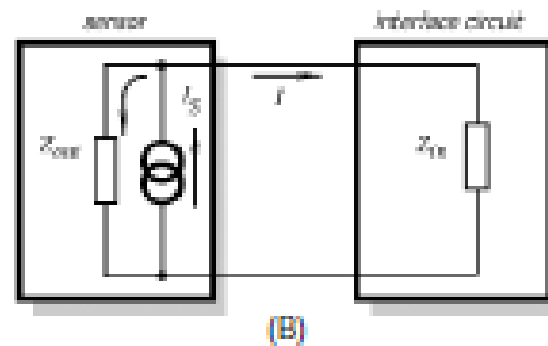
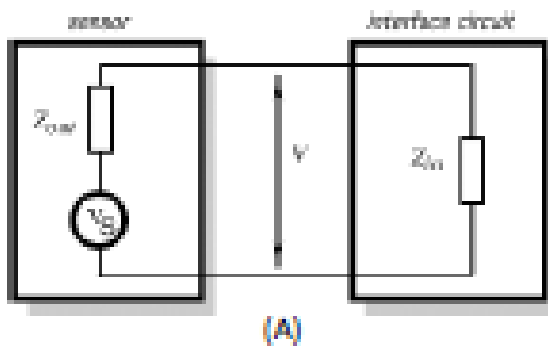
Saturation

- Every sensor has its operating limits. Even if it is considered linear, at some levels of the input stimuli, its output signal no longer will be responsive.
- A further increase in stimulus does not produce a desirable output



Output Impedance

- When a sensor giving an electrical output is interfaced with an electronic circuit it is necessary to know the output impedance since this impedance is being connected in either series or parallel with that circuit.





Output Impedance

- To minimize the output signal distortions, a current generating sensor(B) should have an output impedance as high as possible and the circuit's input impedance should be low.
- For the voltage connection (A), a sensor is preferable with lower Z_{out} and the circuit should have Z_{in} as high as practical.

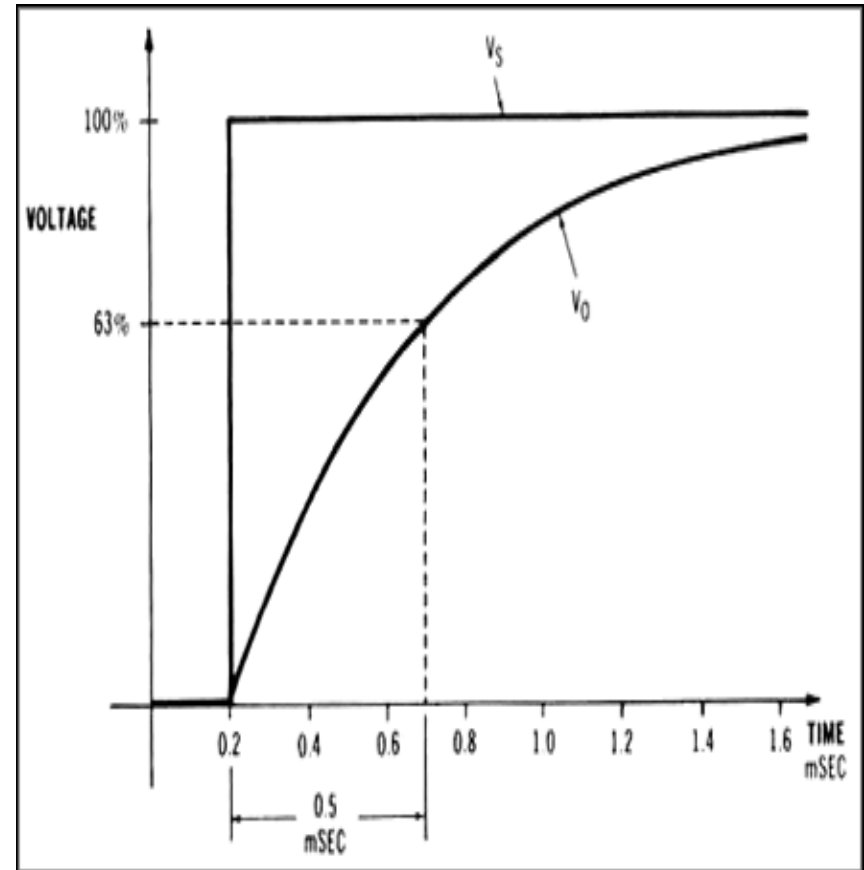


Dynamic Characteristics

- Response Time
- Time constant
- Rise time
- Settling time

Response Time

- This is the time which elapses after a constant input, a step input is applied to the transducer up to the point at which the transducer gives an output corresponding to some specified percentage.
- The time taken by the system to react to a given stimulus





Time Constant

- This is the 63.2% response time.
- The time constant is a measure of the inertia of the sensor and so how fast it will react to changes in its input: the bigger the time constant , the slower the reaction to a changing input signal.



Rise Time

- This is the time taken for the output to rise to some specified percentage of the steady-state output.
- Often the rise time refers to the time taken for the output to rise from 10% of the steady-state value to 90 or 95% of the steady state value.
- the time required for a pulse to rise from 10 per cent to 90 per cent of its steady value.



Settling time

- This is the time taken for the output to settle to within some percentage.

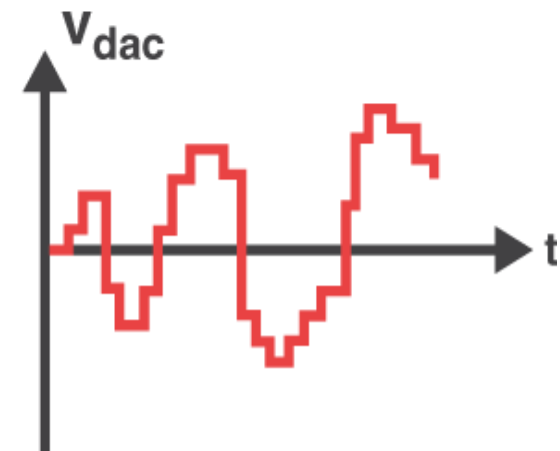
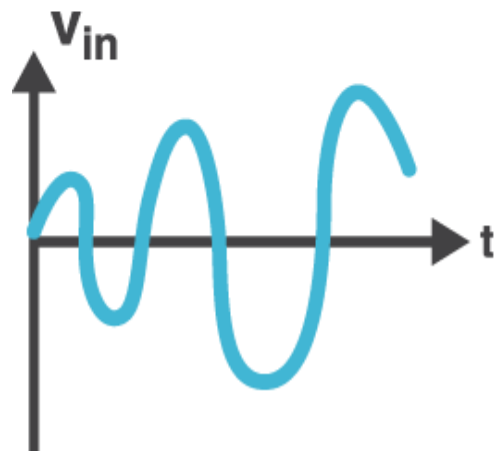
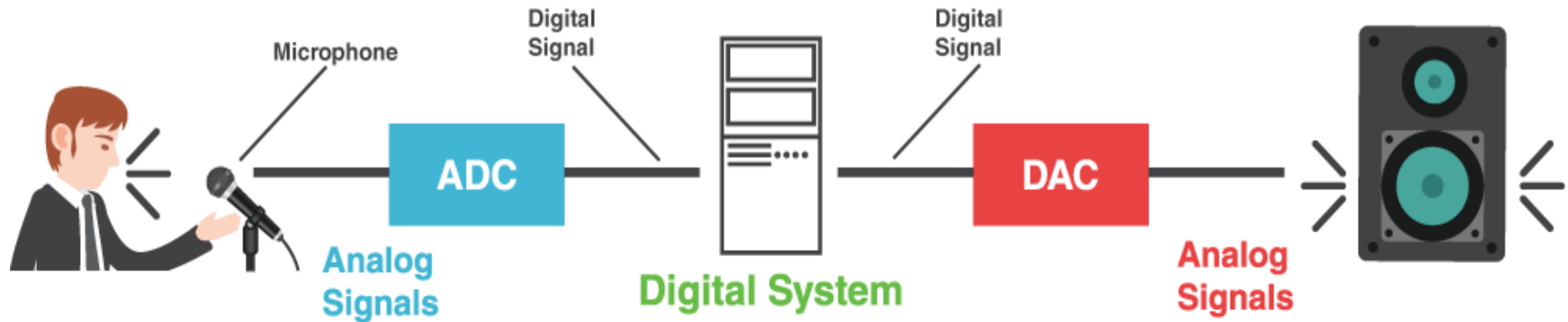


Errors

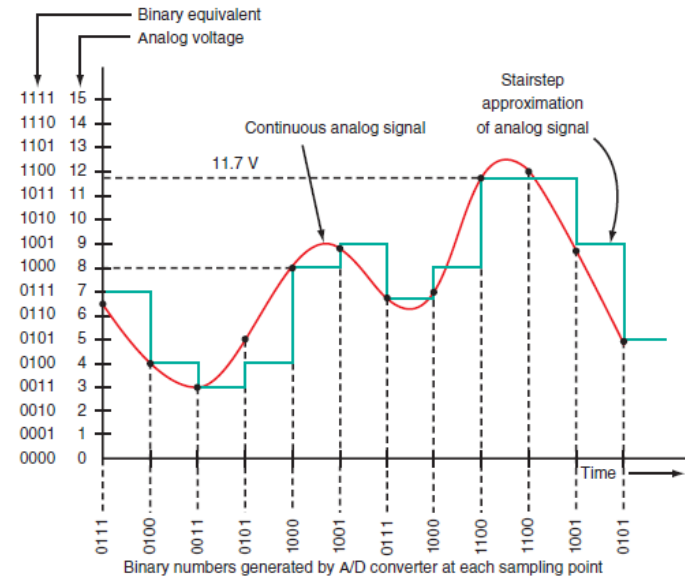
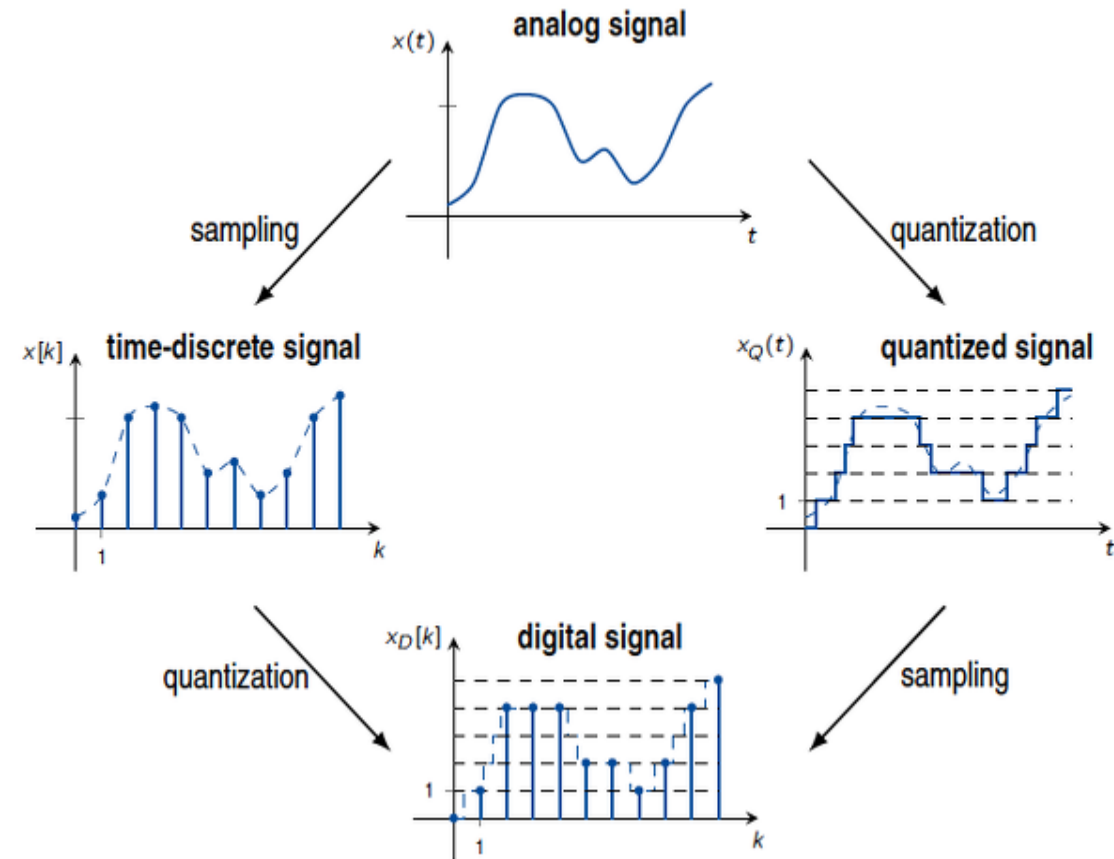
$$\begin{aligned} \text{Absolute Error} &= |\text{Measured value} - \text{True value}| \\ \Rightarrow E_a &= |X_m - X_t| \end{aligned}$$

$$\begin{aligned} \text{Relative error} &= \frac{\text{Absolute error}}{\text{True value}} \\ \Rightarrow E_r &= \frac{|X_m - X_t|}{X_t} \end{aligned}$$

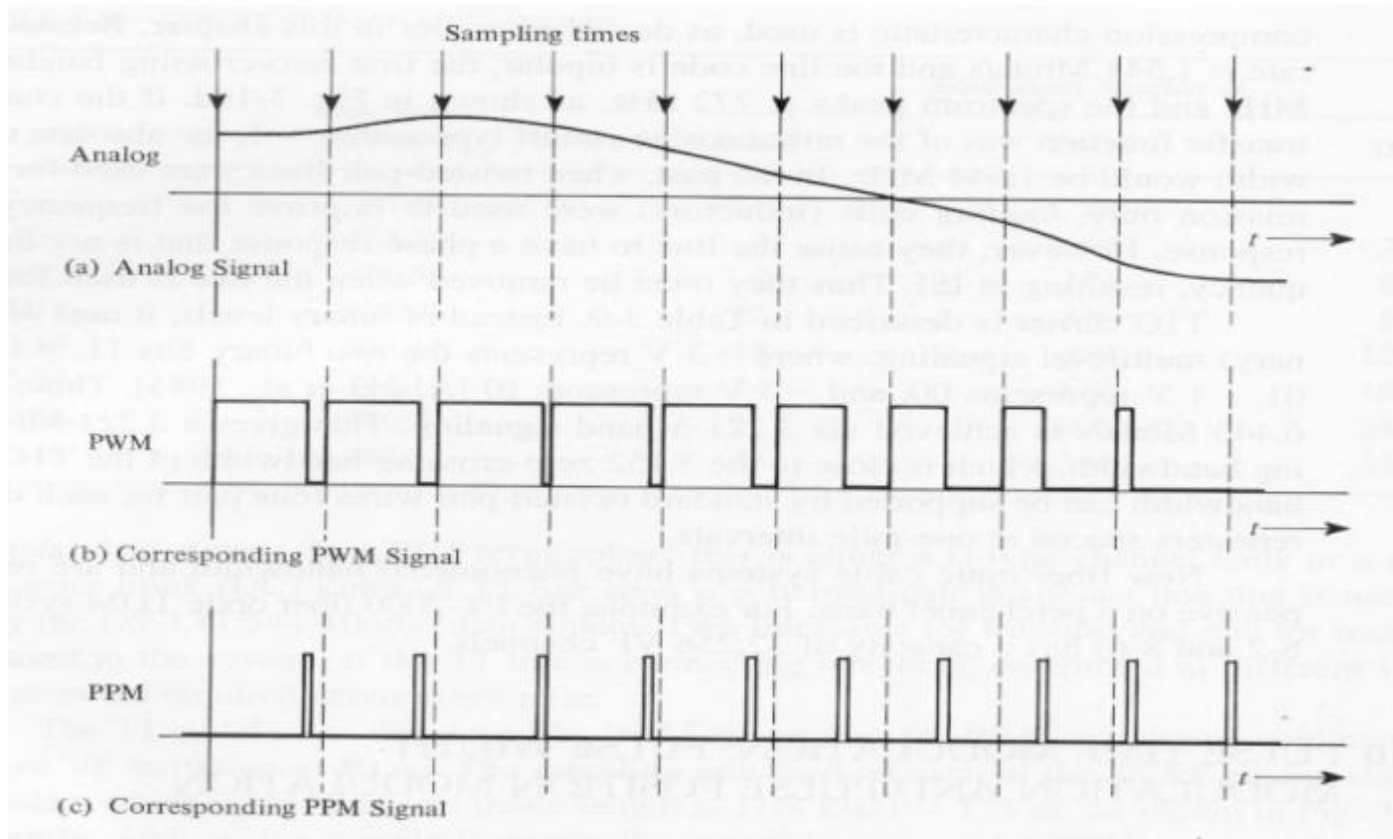
Signals



Analog and Digital Signal



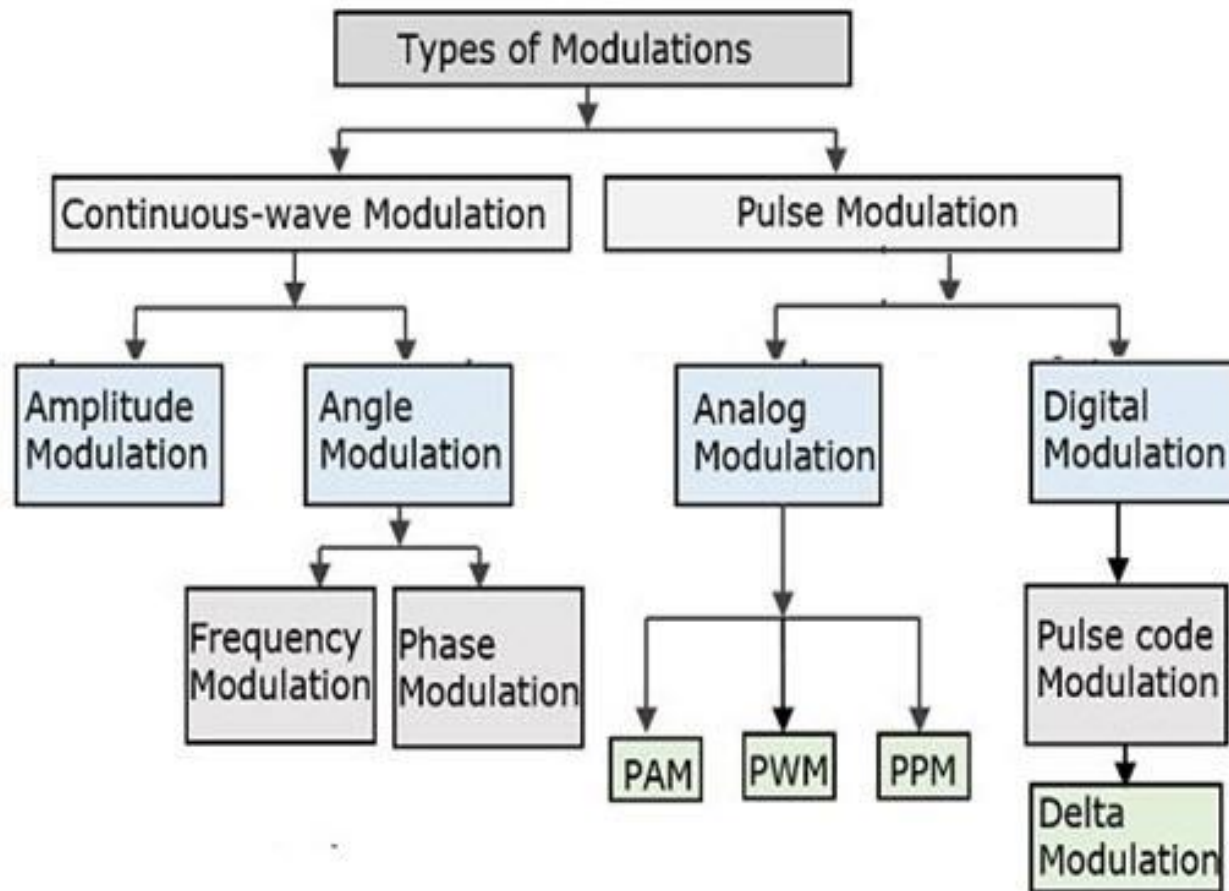
Signals



Difference between analog and digital signals

S. No.	Analog signal	Digital Signal
1	Analog signals are continuous signals	Digital signals are discrete signals.
2	Analog signal uses continuous values for representing the information.	A digital signal uses discrete values for representing the information.
3	Analog signals can be affected by the noise during the transmission.	Digital signals cannot be affected by the noise during transmission.
4	Accuracy of Analog signal is affected by the noise.	Digital signals are noise-immune hence their accuracy is less affected
5	Devices which are using analog signals are less flexible	Devices using digital signals are very flexible
6	Analog signals consume less bandwidth	Digital signals consume more bandwidth.
7	Analog signals are stored in the form of continuous wave form.	Digital signals are stored in the form of binary bits "0", "1".
8	Analog signals have low cost.	Digital signals have high cost.
9	Analog signals are portable.	Digital signals are not Portable.
10	Analog signals give observation error	Digital Signals don't give observation error.

Modulation

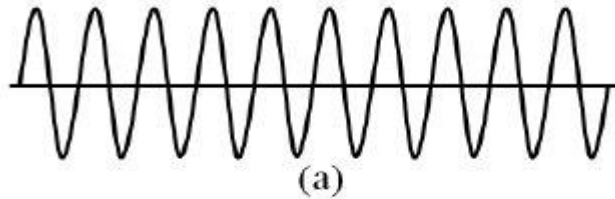




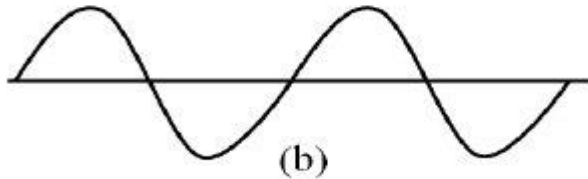
Modulation

- Modulation is a process through which audio, video, image or text information is added to an electrical or optical carrier signal to be transmitted over a telecommunication or electronic medium. Modulation enables the transfer of information on an electrical signal to a receiving device that demodulates the signal to extract the blended information.

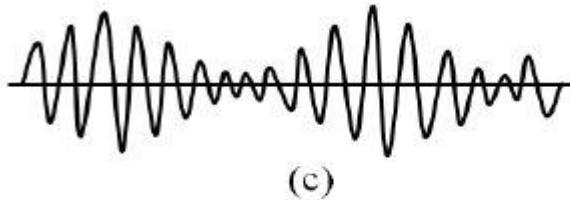
Amplitude Modulation (AM)



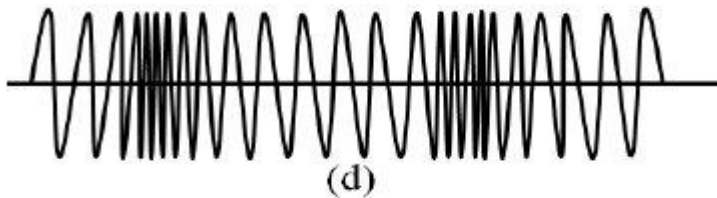
Carrier



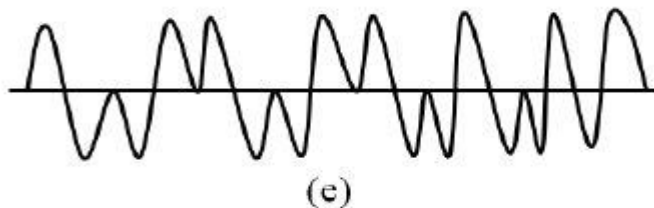
Signal



ASK



FSK

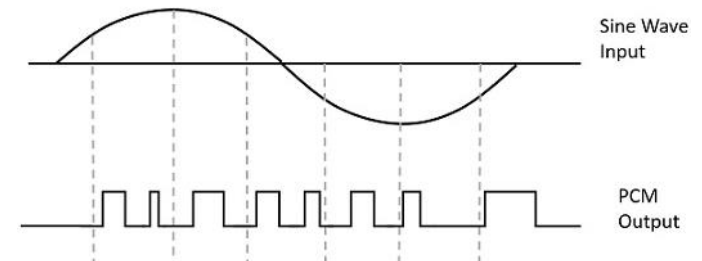


PSK

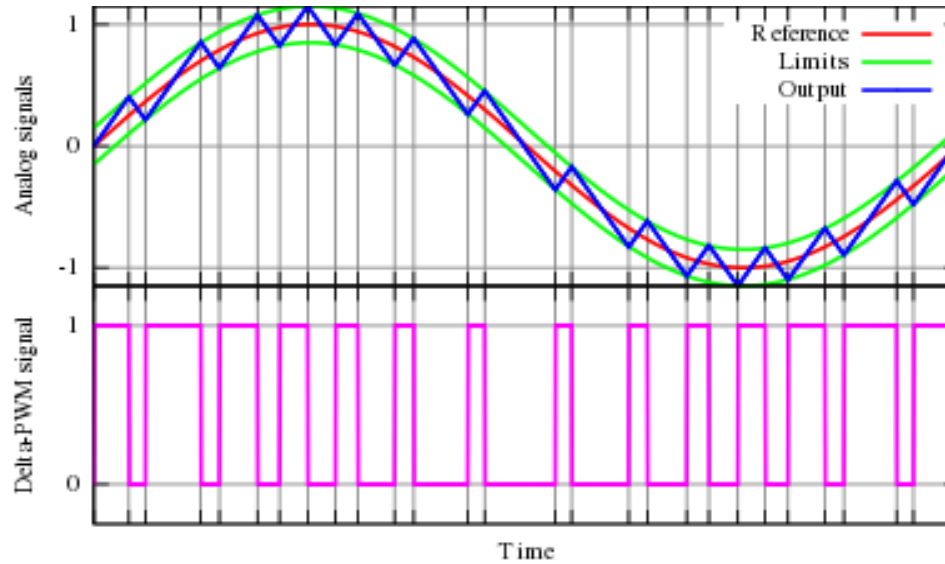
S.No	Pulse Amplitude Modulation (PAM)	Pulse Duration/Width Modulation (PDM/PWM)	Pulse Position Modulation (PPM)
1	Amplitude of the pulse proportional to amplitude of modulating signal	Width of the pulse is proportional to amplitude of modulating signal	The relative position of the pulse is proportional to amplitude of modulating signal
2	Bandwidth of the transmission channel depends on the pulse width	Bandwidth of the transmission channel depends on the rise time of the pulse	Bandwidth of the transmission channel depends on the rising time of the pulse
3	Instantaneous power of the transmitter varies	Instantaneous power of the transmitter varies	Instantaneous power of the transmitter remains constant
4	Noise interference is high	Noise interference is minimum	Noise interference is minimum
5	System is complex to implement	System is simple to implement	System is simple to implement
6	Similar to amplitude modulation	Similar to frequency modulation	Similar to phase modulation

Pulse Code Modulation

- Instead of a pulse train, PCM produces a series of numbers or digits, and hence this process is called as **digital**. Each one of these digits, though in binary code, represent the approximate amplitude of the signal sample at that instant.
- In Pulse Code Modulation, the message signal is represented by a sequence of coded pulses. This message signal is achieved by representing the signal in discrete form in both ~~time and~~ amplitude.



PCM



Principle of the delta PWM. The output signal (blue) is compared with the limits (green). The limits (green) correspond to the reference signal (red), offset by a given value. Every time the output signal reaches one of the limits, the PWM signal changes state.



research

- However, when a sensor is used for measuring or detecting a stimulus, an inversed function (output-to-input) needs to be employed. When a transfer function is linear, the inversed function is very easy to compute

Lecture-3

Calibration

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- Sensor output signal type
- Sensor calibration

Calibration

- Calibration means the determination of specific variables that describe the overall transfer function.
- Overall means of the entire circuit, including the sensor, the interface circuit, and the A/D converter.
- The mathematical model of the transfer function should be known before calibration.

Calibration

- If the sensor system(sensor, signal conditioning) is linear we need to find variables a and b.
- If exponential we need to find a and K.
- *Example: for temperature measurement, if it is linear.*
- *Then, $v = a + bt$.*

$$v_1 = a + bt_1,$$

$$v_2 = a + bt_2,$$

$$b = \frac{v_1 - v_2}{t_1 - t_2} \quad \text{and} \quad a = v_1 - bt_1$$

Calibration types

- To compute the temperature from the measured voltage.

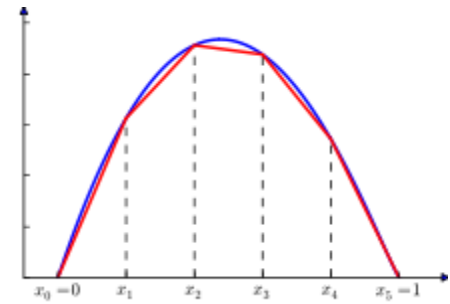
$$t = \frac{v - a}{b}.$$

- **One point calibration:** If one of the constant 'b' known already then single point calibration is needed to find out 'a'.
- Two point calibration:
- Piecewise calibration(for nonlinear systems)

Calibration types

- **Two point calibration:** For nonlinear functions, more than two points may be required, depending on a mathematical model of the transfer function.
- Any transfer function may be modeled by a polynomial, and depending on required accuracy, the number of the calibration points should be selected

Calibration types



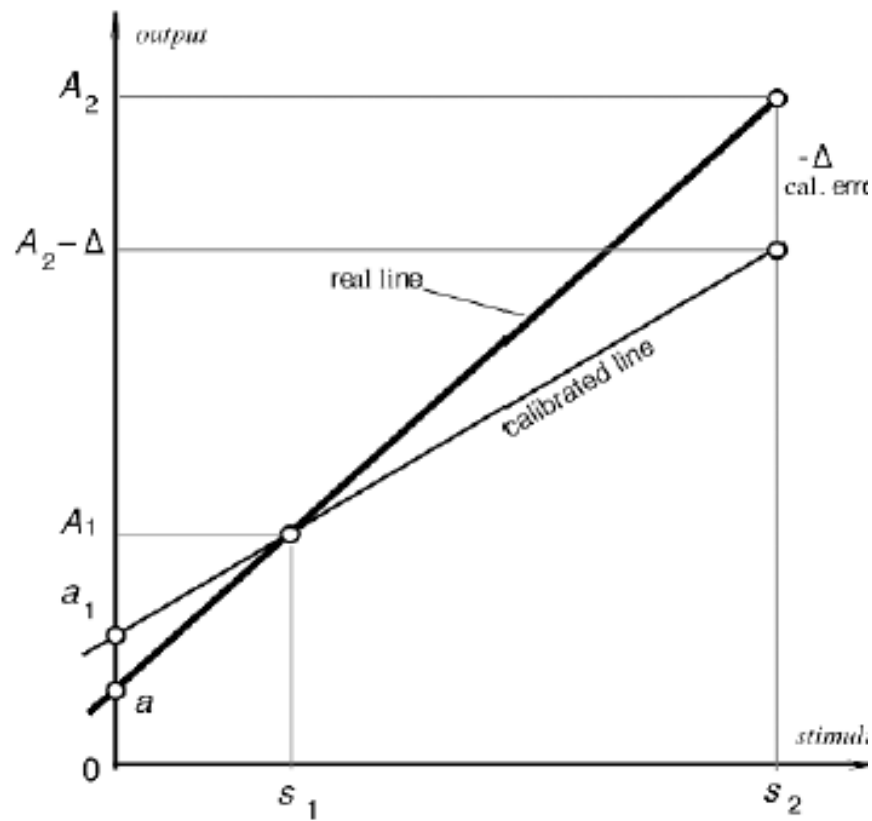
- Piecewise calibration(for nonlinear systems)
- piecewise approximation. As was mentioned earlier, any section of a curvature, when sufficiently small, can be considered linear and modeled by Eq. (2.1). Then, a curvature will be described by a family of linear lines where each has its own constants a and b .
- During the measurement, one should determine where on the curve a particular output voltage S is situated and select the appropriate set of constants a and b to compute the value of a corresponding stimulus s from an equation.

$$S = a + bs, \longrightarrow 2.1$$

Calibration error

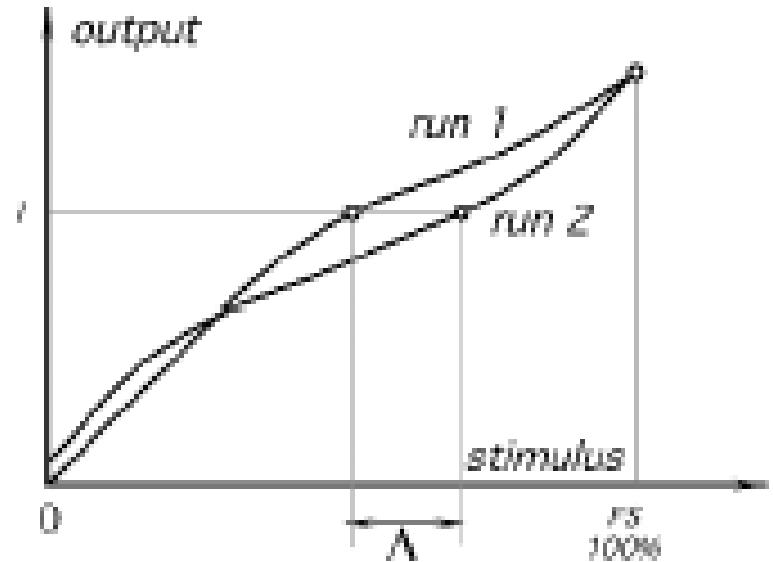
- The calibration error is inaccuracy permitted by a manufacturer when a sensor is calibrated in the factory.
- Eg: consider two point calibration of the real linear transfer function.
- This error is of a systematic nature, meaning that it is added to all possible real transfer functions. It shifts the accuracy of transduction for each stimulus point by a constant.
- To determine the slope and the intercept of the function, two stimuli, s_1 and s_2 , are applied to the sensor

Calibration error



Repeatability

- *Repeatability* (reproducibility) error is caused by the inability of a sensor to represent the same value under identical conditions



$$\delta_r = \frac{\Delta}{FS} \times 100\%$$



Lecture-4

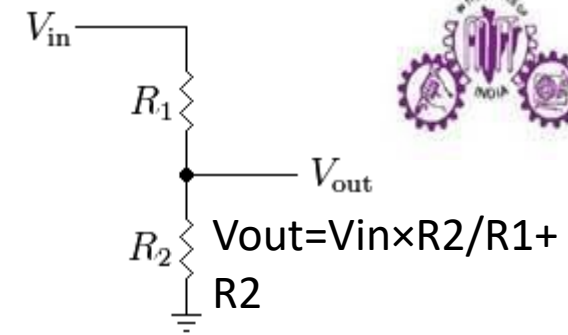
Displacement Sensor

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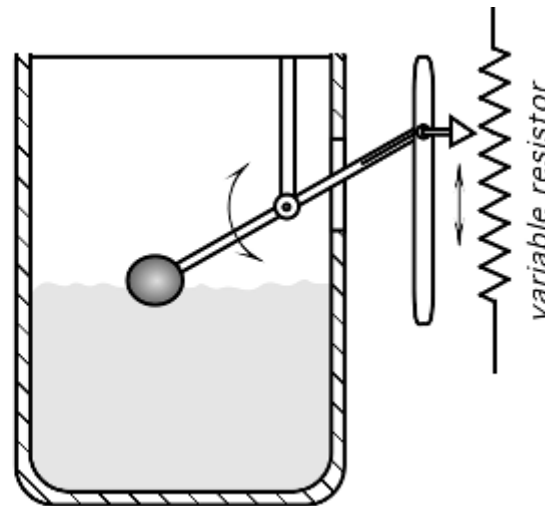
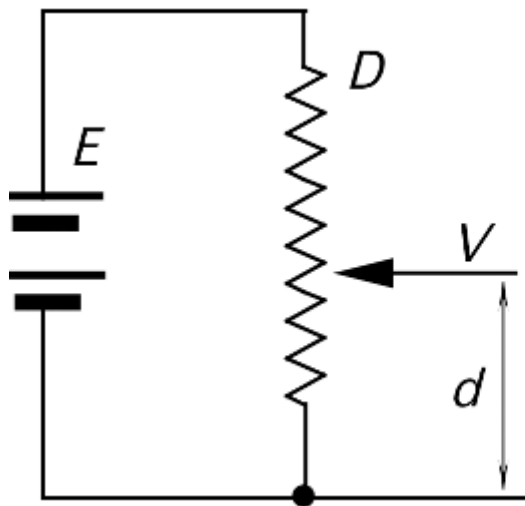
Resistive Type

- Potentiometer
- It is an active Device

$$R = \frac{\rho l}{A} \quad V = E \frac{d}{D}$$



V=Voltage across wiper of the linear pot
D=full scale displacement
d=displacement



RESOLUTION

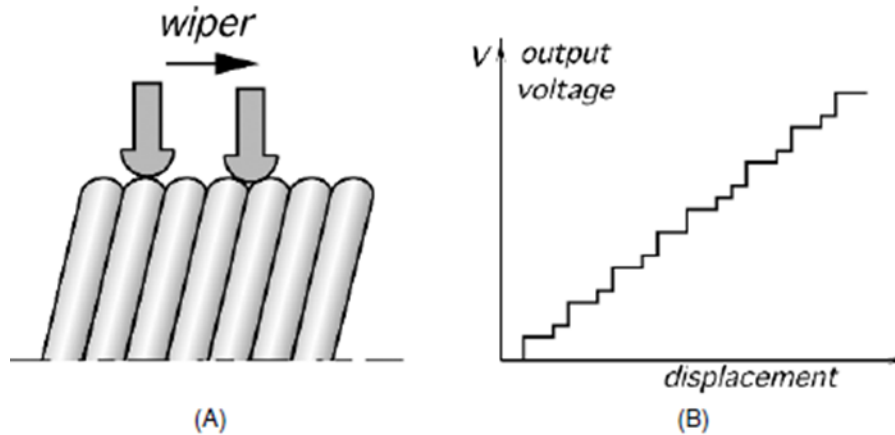
$$n = \frac{100}{N\%}$$



Materials

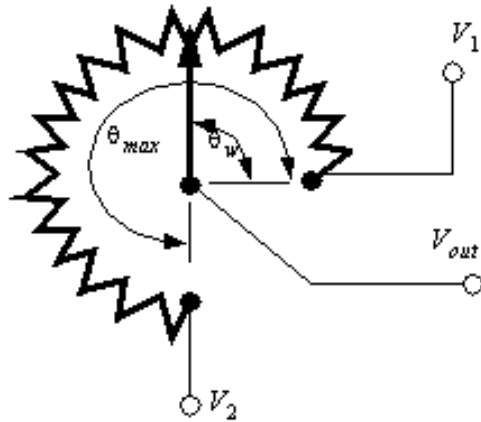
- The continuous-resolution pots are fabricated with conductive plastic, carbon film, metal film, or a ceramic–metal mix which is known as *cermet*.
- The wiper of the precision potentiometers are made from precious metal alloys

drawbacks



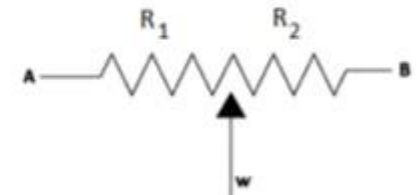
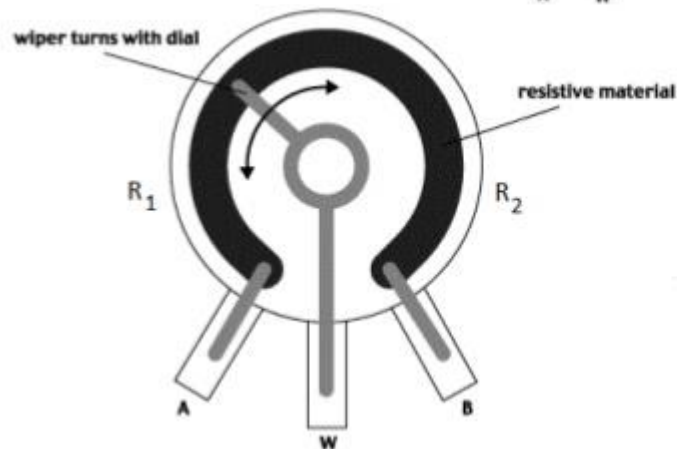
1. Noticeable mechanical load (friction)
2. Need for a physical coupling with the object
3. Low speed
4. Friction and excitation voltage cause heating of the potentiometer
5. Low environmental stability

Rotary potentiometer



$$V_{out} = (V_2 - V_1) \left(\frac{\theta_w}{\theta_{max}} \right) + V_1$$

Potentiometer



Potentiometer

- R_1 and R_2 vary linearly with θ between the two extremes:

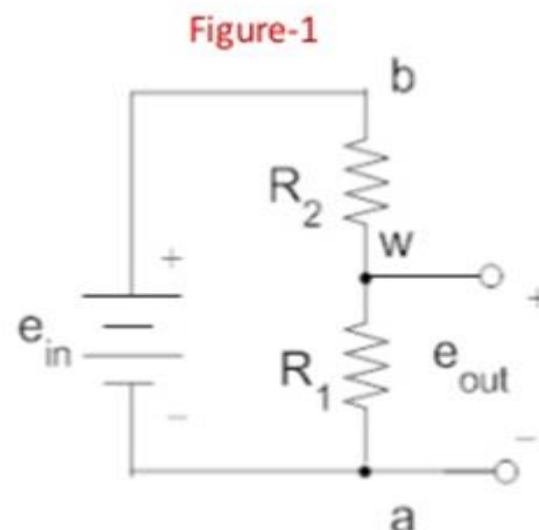
$$R_1 = \frac{\theta}{\theta_{\max}} R_{\text{tot}}$$

$$R_2 = \frac{\theta_{\max} - \theta}{\theta_{\max}} R_{\text{tot}}$$



Potentiometer

- Potentiometer can be used to sense angular position, consider the circuit of **figure-1**.
- Using the voltage divider principle we can write:

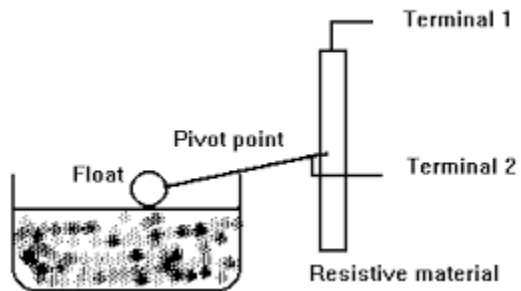


$$e_{out} = \frac{R_1}{R_1 + R_2} e_{in} = \frac{R_1}{R_{tot}} e_{in}$$

$$e_{out} = \frac{\theta}{\theta_{max}} e_{in}$$

$$R_1 = \frac{\theta}{\theta_{max}} R_{tot}$$

Application





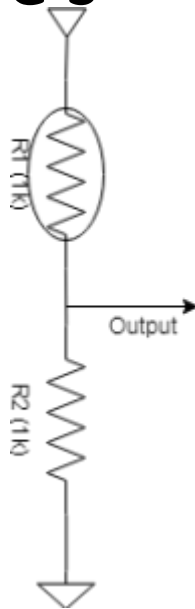
Converting resistance to voltage

- Converting resistance to voltage in electronics sometimes are so important. This happens because many electronics device such as microcontroller only can read voltage as analog input signal. Analog signal then will be converted to digital using ADC. But before we talk about ADC or microcontroller, how if our sensor has resistance output instead of voltage?
- **Voltage Divider as resistance to voltage converter**
- The only thing we can do to make our sensor readable by microcontroller is convert resistance to voltage. Converting a resistance to voltage is far more easier than converting to other quantity. So, how we do that?
- The answer is very simple. Use voltage divider !
- Voltage divider has capability to divide the voltage by comparison of two resistance. You can read more details about voltage divider here.



Application Example

I use an LDR for a light sensor. LDR has linear resistance to the light that exposed to it surface. When light getting brighter, the resistance will decreased. Otherwise when light brightness dercreases the resistance will increases. Here's my schematic example:





The output voltage will be :

- *Voltage divider*

$$V_1 = \frac{R_1}{R_1 + R_2} V_s$$

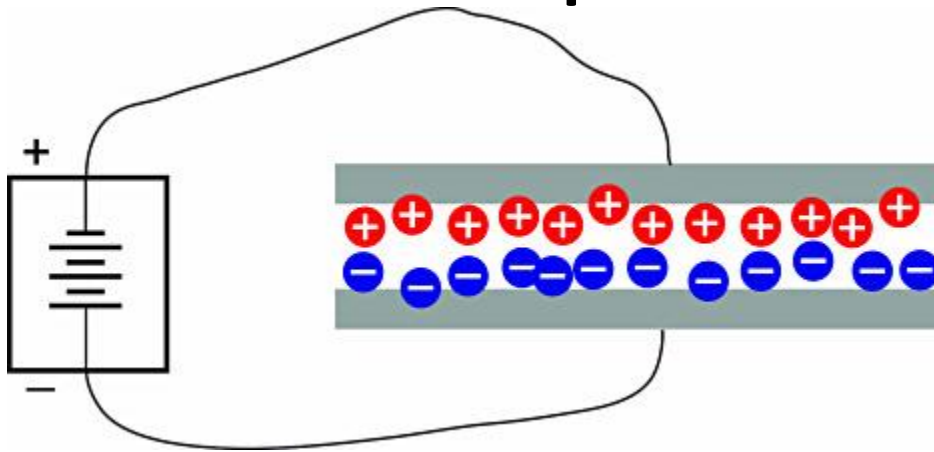
In this example, when light density is changed, the LDR resistance will changed too and of course Voltage output will changed accordingly.

Since the voltage will change in every change of light density, then you can connect this voltage output to an microcontroller ADC.

Little Tips:

Pick the right R2 has a little trick. You have to choose the closest one to LDR resistance range to make the voltage output difference better. For example, if your LDR resistance will vary between 800 ohm to 1k ohm then used 1k ohm resistor as R2 will be ok. But if you has LDR with resistance output vary from 8k-10k don't use 1k as R2, using 10k as R2 will better.

Capacitive sensor



$$\text{Capacitance} \propto \frac{\text{Area} \times \text{Dielectric}}{\text{Distance}}$$

$$X_c = \frac{1}{2 \pi f C}$$



$$C = \frac{\epsilon A}{d}$$

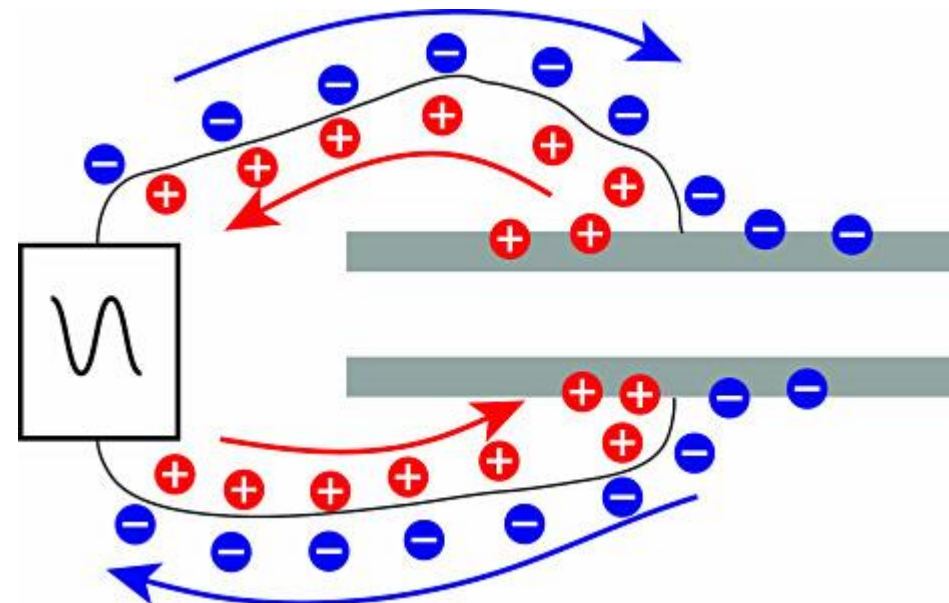
Where,

C = Capacitance in Farads

ϵ = Permittivity of dielectric (absolute, not relative)

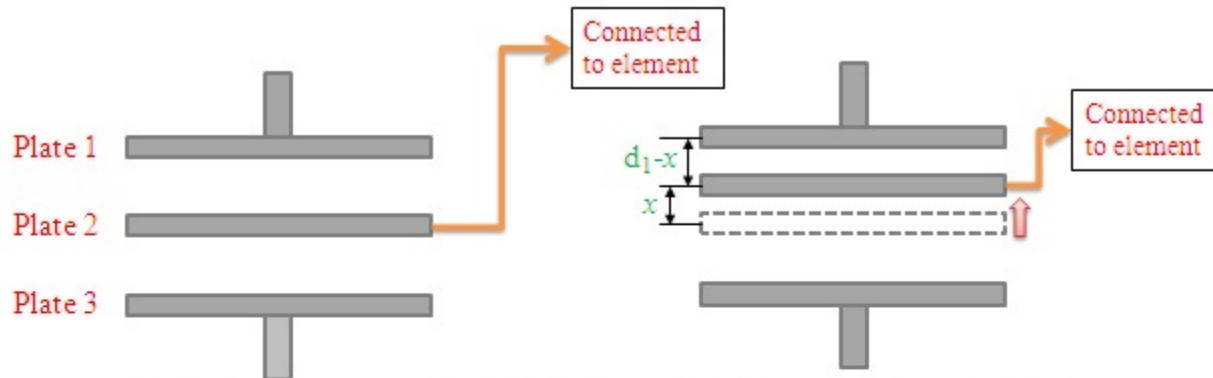
A = Area of plate overlap in square meters

d = Distance between plates in meters



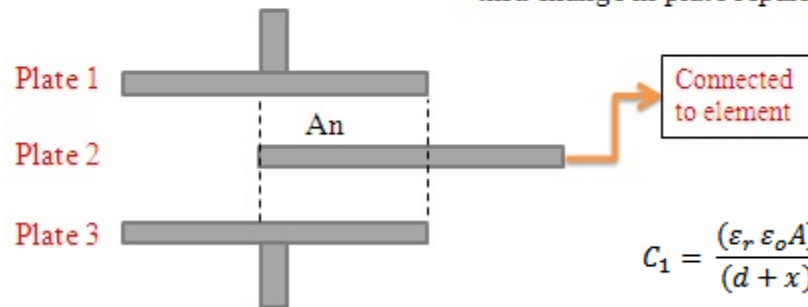
Capacitive sensor

<http://nptel.ac.in/courses/112103174/5>



(a) Three-plates capacitive element sensor

(b) Displacement measurement thru change in plate separation



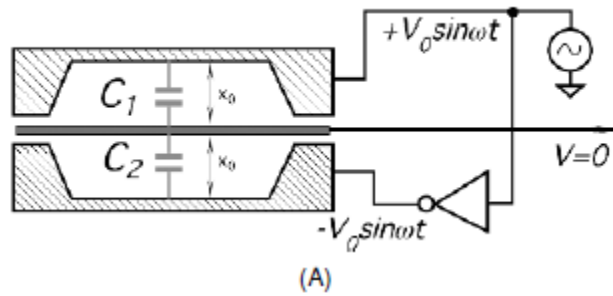
(c) Displacement measurement thru change in area of overlap

$$C = \frac{\epsilon_r \epsilon_o A}{d}$$

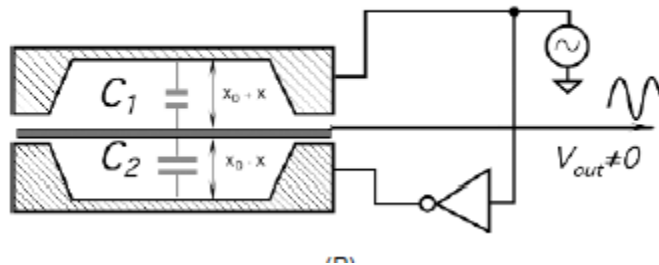
$$C_1 = \frac{(\epsilon_r \epsilon_o A)}{(d + x)}$$

$$C_2 = \frac{(\epsilon_r \epsilon_o A)}{(d - x)}$$

Capacitive

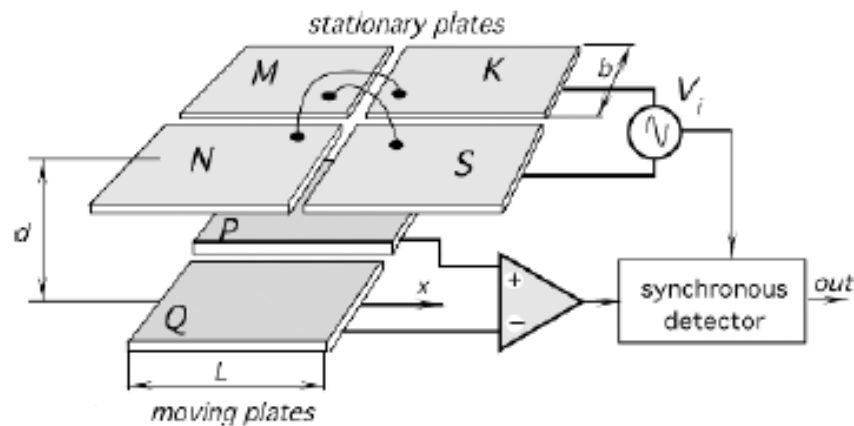


$$C_1 = \frac{\epsilon A}{x_0 + x} \quad \text{and} \quad C_2 = \frac{\epsilon A}{x_0 - x},$$

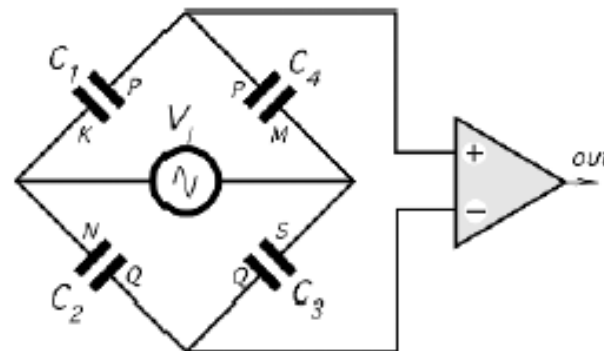


$$V_{out} = V_0 \left(-\frac{x}{x_0 + x} + \frac{\Delta C}{C} \right).$$

Parallel plate capacitor bridge sensor



$$C_1 = \frac{\epsilon_0 b}{d} \left(\frac{L}{2} + x \right).$$

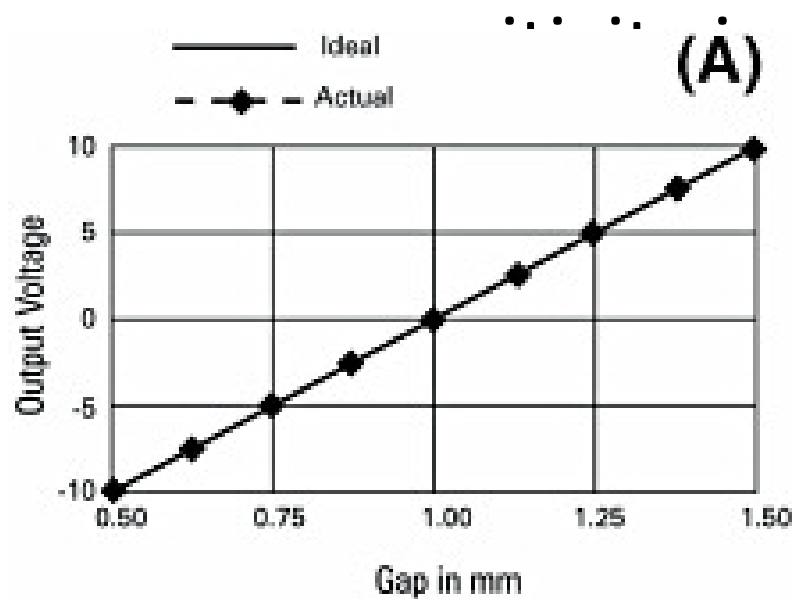


(A)

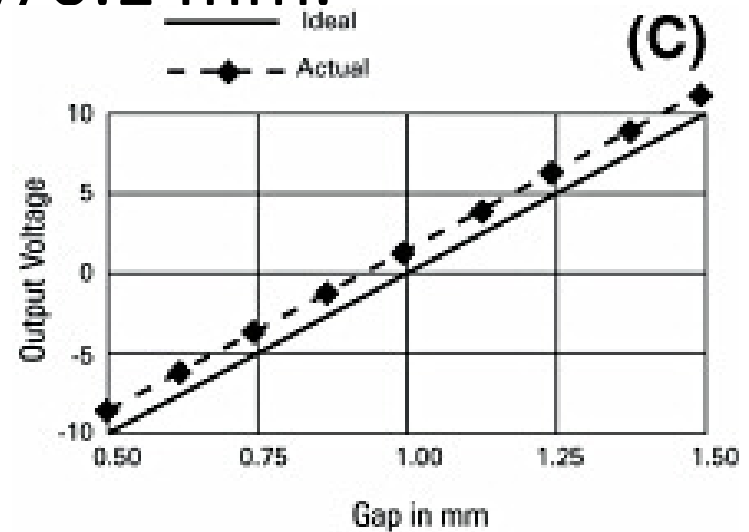
(B)

Response

- Sensitivity* indicates how much the output voltage changes as a result of a change in the gap between the target and the probe. A

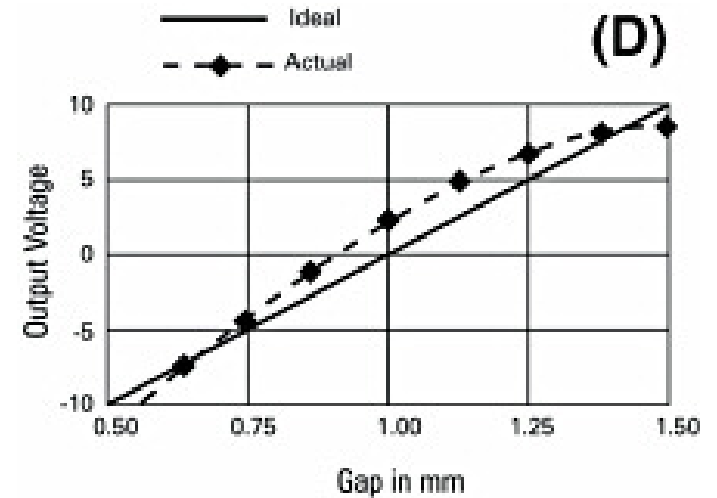
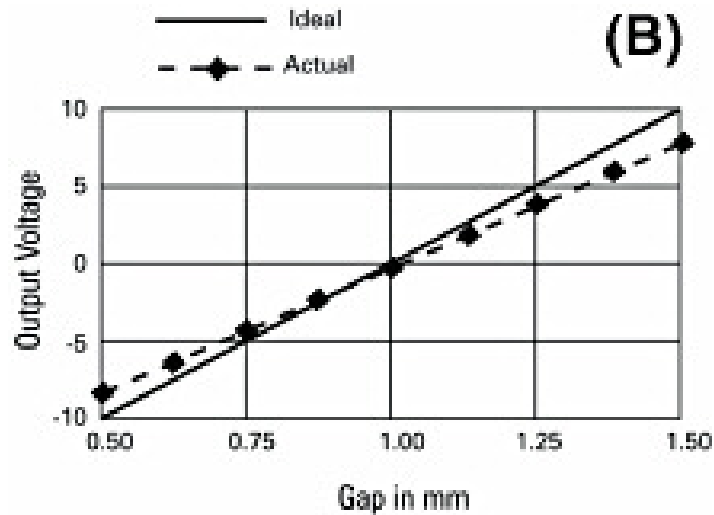


Sensitivity A is slope of the line



Offset error

Response



Actual measurement
deviates from ideal
slope

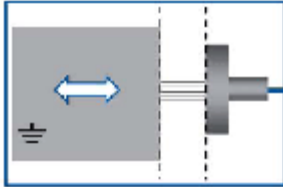
Linearity error



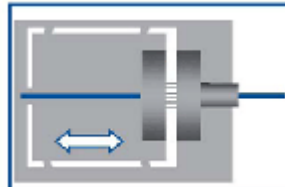
Bandwidth

- *Bandwidth* is defined as the frequency at which the output falls to -3 dB, a frequency that is also called the *cutoff frequency*. A -3 dB drop in the signal level is an approximately 30% decrease. With a 15 kHz bandwidth, a change of ± 1 V at low frequency will only produce a ± 0.7 V change at 15 kHz. Wide-bandwidth sensors can sense high-frequency motion and provide fast-responding outputs to maximize the phase margin when used in servo-control feedback systems; however, lower-bandwidth sensors will have reduced output noise which means higher resolution. Some sensors provide selectable bandwidth to maximize either resolution or response time.

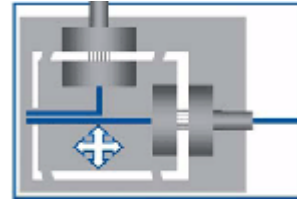
Application



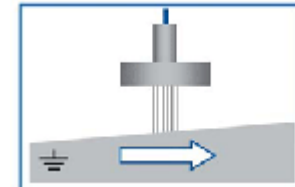
Displacement measurement



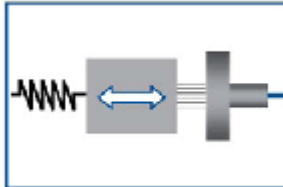
Nano positioning



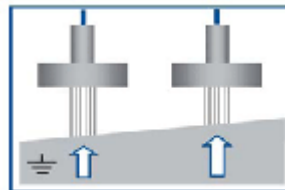
Parallel metrology



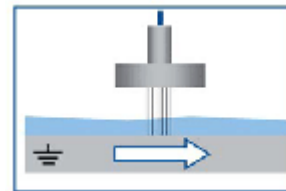
Measuring straightness & flatness



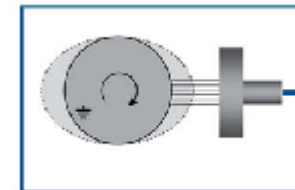
Force sensor with micronewton sensitivity



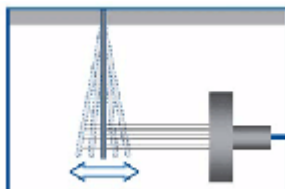
Tilt measurement and compensation



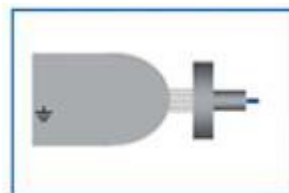
Layer thickness



Out of plane/out of round measurement

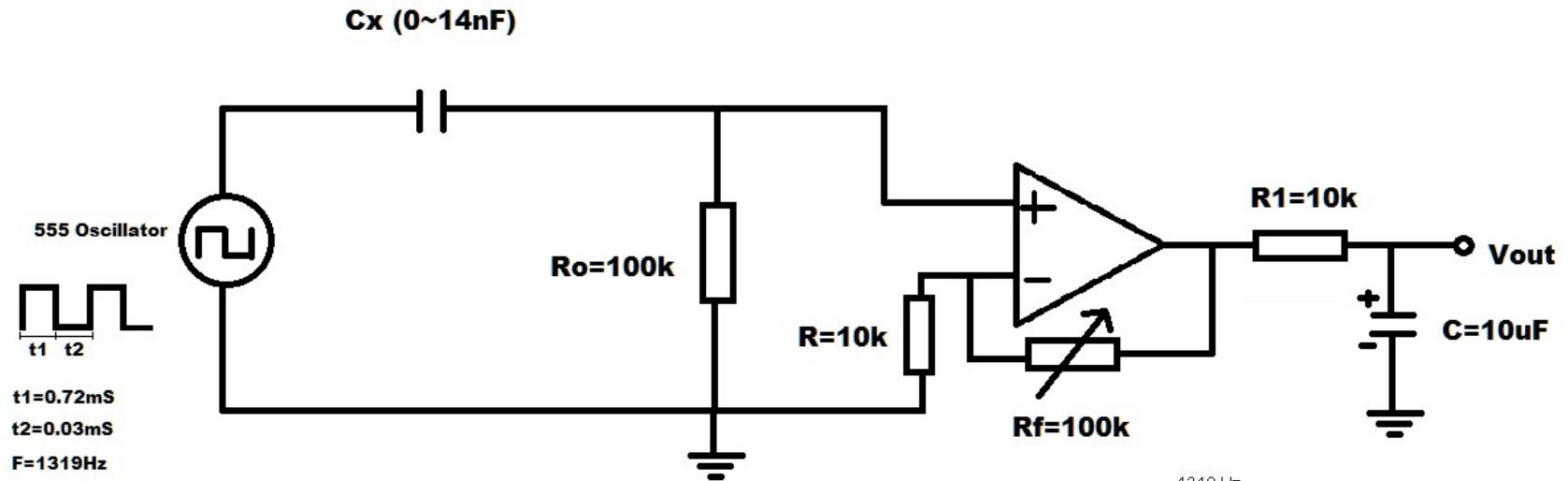


Vibration, flatness & Thickness

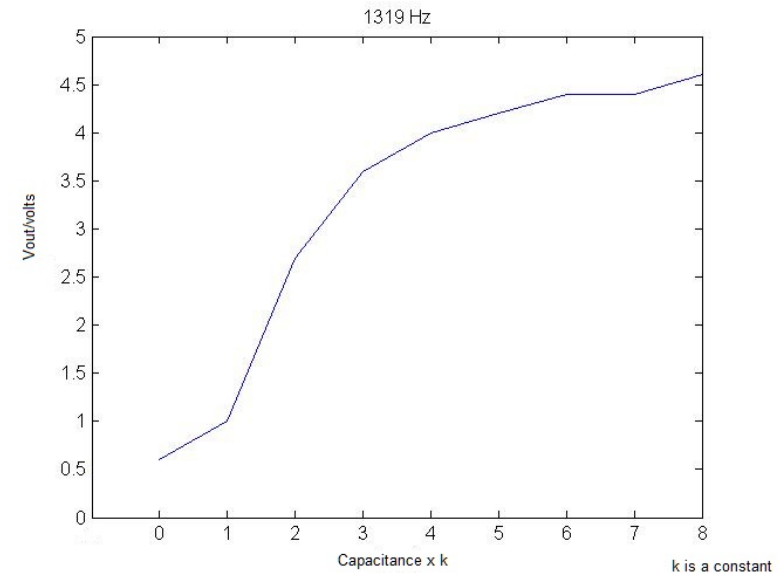


Effects of environmental condition

Vout from different Cx



<https://www.zhinst.com/others/en/blogs/impedance-characterisation-wearable-capacitive-sensors>





Inductance

- In electromagnetism and electronics, **inductance** is the property of an electrical conductor by which a change in current flowing through it induces an electromotive force in both the conductor itself and in any nearby conductors by mutual inductance

$$v(t) = L \frac{di}{dt} \quad M_{21} = N_1 N_2 P_{21}$$

Mutual inductance

Self Inductance



Variable Inductance Displacement Sensor

- In an electric circuit
 - $e.m.f = \text{current} * \text{resistance}$
- In an ferromagnetic material on which carrying the coil of n turns carrying current 'i'
- By analogy we can regard the coil as a source of magnetomotive force (m.m.f.) which drives a flux ϕ through the magnetic circuit
 - $m.m.f = \text{flux} * \text{reluctance} = \phi * \hat{R}$
- Reluctance \hat{R} limits the flux in a magnetic circuit just as resistance limits the current in an electrical circuit

- m.m.f. = ni , so that the flux in the magnetic circuit is

$$\phi = \frac{ni}{\mathcal{R}} \text{ weber}$$

- This is the flux linked by a single turn of the coil; the total flux N linked by the entire coil of n turns is

$$N = n\phi = \frac{n^2 i}{\mathcal{R}}$$

- By definition the self-inductance L of the coil is the total flux per unit current, i.e.

$$L = \frac{N}{i} = \frac{n^2}{\mathcal{R}}$$

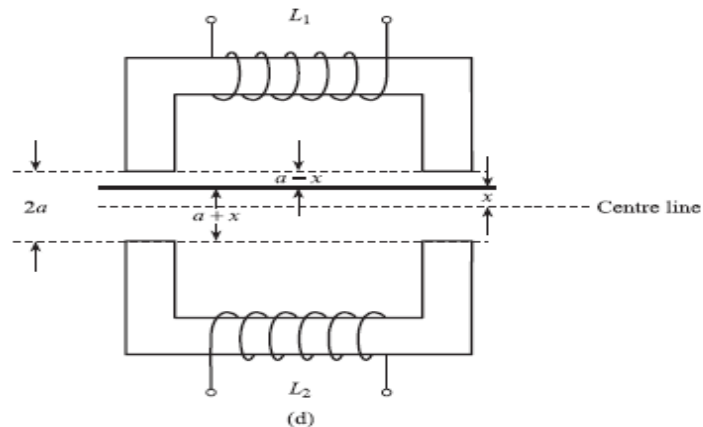
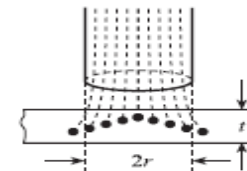
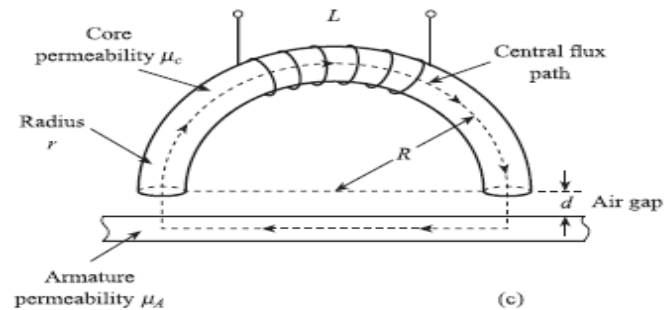
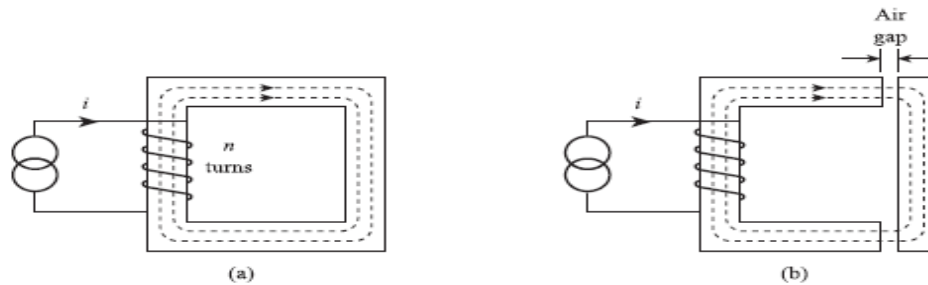
- The above equation enables us to calculate the inductance of a sensing element given the reluctance of the magnetic circuit. The reluctance of a magnetic circuit is given by

$$\mathcal{R} = \frac{l}{\mu\mu_0 A}$$

- where l is the total length of the flux path, μ is the relative permeability of the circuit material, μ_0 is the permeability of free space = $4\pi \times 10^{-7} \text{Hm}^{-1}$ and A is the

Variable reluctance elements

- (a)(b) Basic principle of reluctance sensing elements
- (c) Reluctance calculation for typical element
- (d) Differential or push/pull reluctance displacement sensor.



- The total reluctance of the magnetic circuit is the sum of the individual reluctances, i.e.

$$\mathcal{R}_{\text{TOTAL}} = \mathcal{R}_{\text{CORE}} + \mathcal{R}_{\text{GAP}} + \mathcal{R}_{\text{ARMATURE}}$$

- The length of an average, i.e. central, path through the core is πR and the cross sectional area is $A = \pi r^2$, giving

$$\mathcal{R}_{\text{CORE}} = \frac{\pi R}{\mu_0 \mu_C \pi r^2} = \frac{R}{\mu_0 \mu_C r^2}$$

- The total length of the flux path in air is twice the air gap, i.e. $2d$; also if there is little bending or fringing of the lines of flux in the air gap, then the cross-sectional area of the flux path in air will be close to that of the core. Assuming the relative permeability of air is unity,

$$\mathcal{R}_{\text{GAP}} = \frac{2d}{\mu_0 \pi r^2}$$

- The length of an average central flux path in the armature is $2R$; the calculation of the appropriate cross-sectional area is more difficult. A typical flux distribution is shown in Figure (c) and for simplicity we assume that most of the flux is concentrated within an area $2rt$, giving

$$\mathcal{R}_{\text{ARMATURE}} = \frac{2R}{\mu_0 \mu_A 2rt} = \frac{R}{\mu_0 \mu_A rt}$$

Thus

$$\mathcal{R}_{\text{TOTAL}} = \frac{R}{\mu_0 \mu_C r^2} + \frac{2d}{\mu_0 \pi r^2} + \frac{R}{\mu_0 \mu_A rt}$$

i.e.

$$\mathcal{R}_{\text{TOTAL}} = \mathcal{R}_0 + kd$$

where

$$\mathcal{R}_0 = \frac{R}{\mu_0 r} \left[\frac{1}{\mu_c r} + \frac{1}{\mu_a t} \right] = \text{reluctance at zero air gap}$$

$$k = \frac{2}{\mu_0 \pi r^2}$$

- *Inductance of reluctance displacement sensor*

$$L = \frac{n^2}{\mathcal{R}_0 + kd} = \frac{L_0}{1 + \alpha d}$$

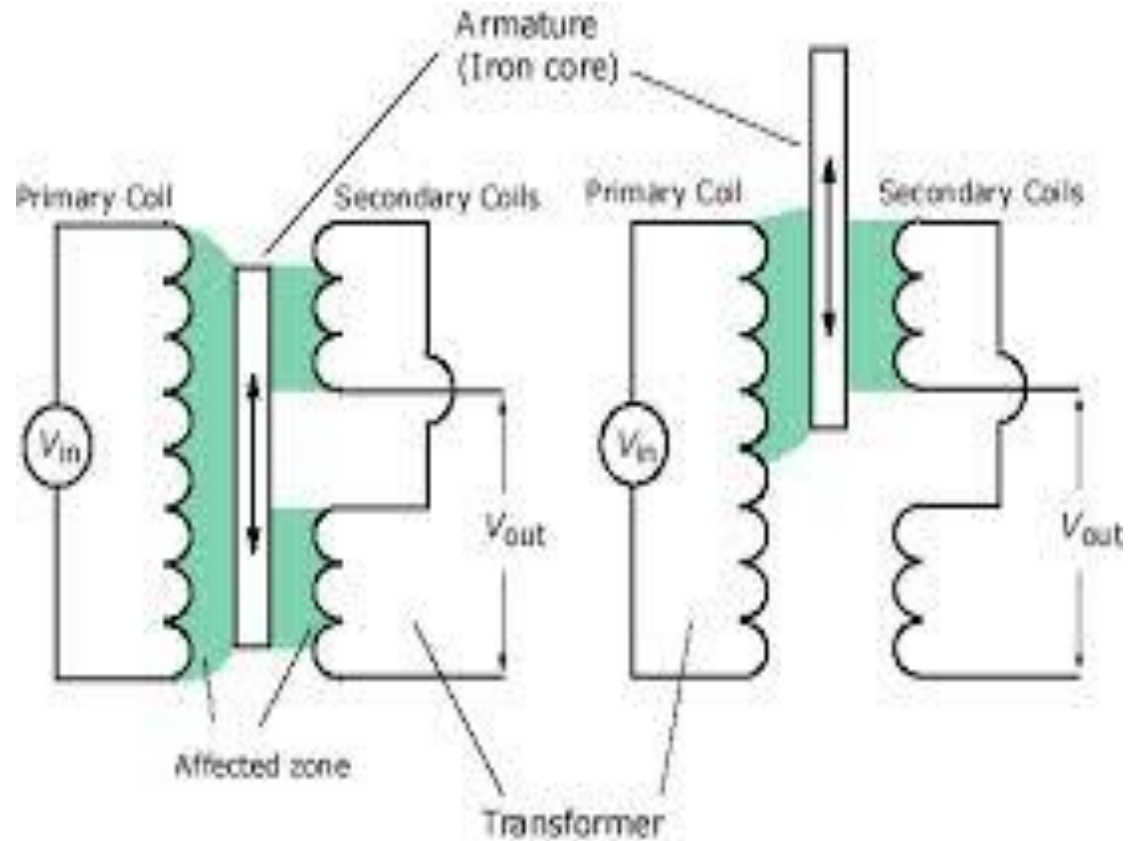
- *Differential reluctance displacement sensor*

$$L_1 = \frac{L_0}{1 + \alpha(a - x)}, \quad L_2 = \frac{L_0}{1 + \alpha(a + x)}$$

Linear Variable Differential Transformer

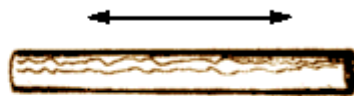
Open Wiring LVDT

- E.m.f induced
– $(e) = M \frac{di}{dt}$

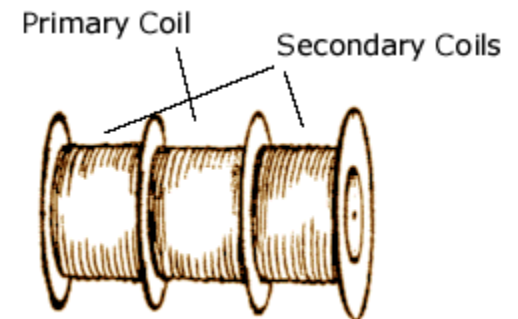




Transformer



Armature (Iron core)



Inside a Transformer

The basic transformer formula, which states that the voltage is proportional to the number of coil windings, is the backbone of the LVDT. The formula is,

$$\frac{V_{\text{Out}}}{V_{\text{In}}} = \frac{N_{\text{Out}}}{N_{\text{In}}}$$

where N is the number of coil windings and V is the voltage read out.

Most LVDT's are wired as shown in the schematic above. This wiring arrangement is known as open wiring. Since the number of coil windings is uniformly distributed along the transformer, the voltage output is proportional to the iron core displacement when the core slides through the transformer. This equation is,

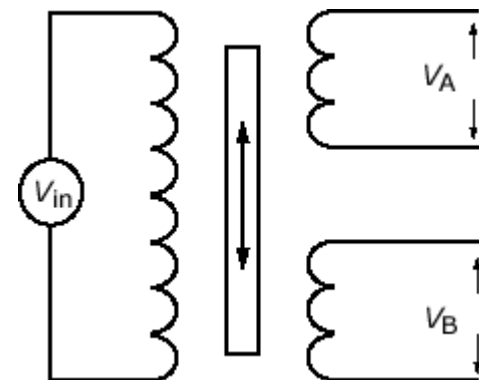
$$D = MV_{\text{Out}}$$

where D is displacement of the iron core with respect to the transformer, and M is the sensitivity of the transformer (slope of the displacement-voltage curve).

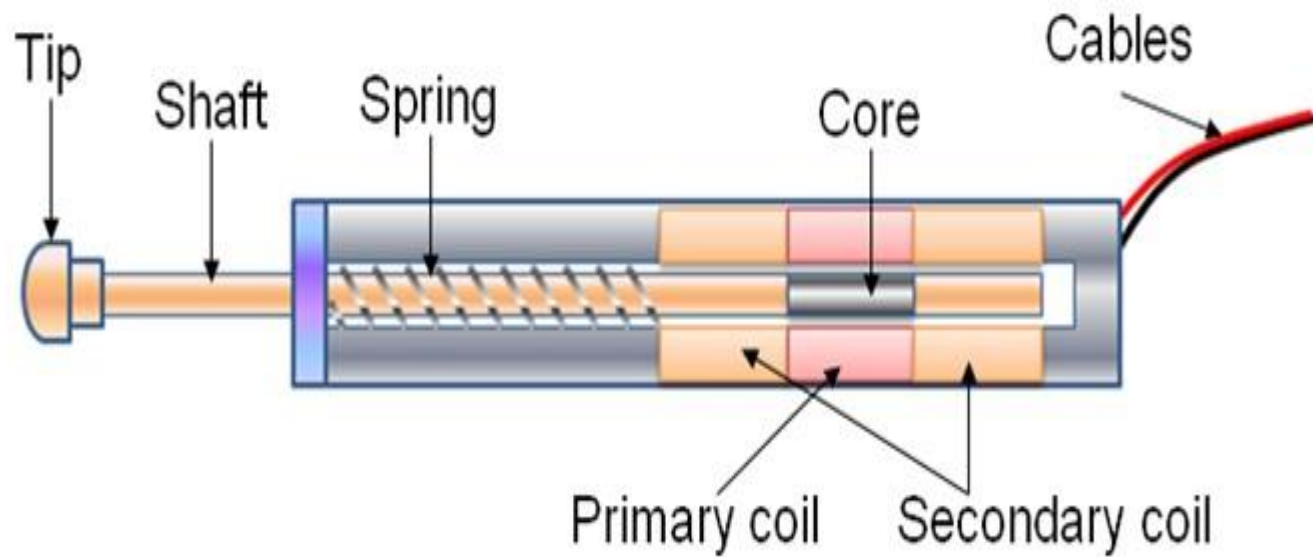
Ratiometric Wiring

The displacement for ratiometric LVDT's is given by the relation,

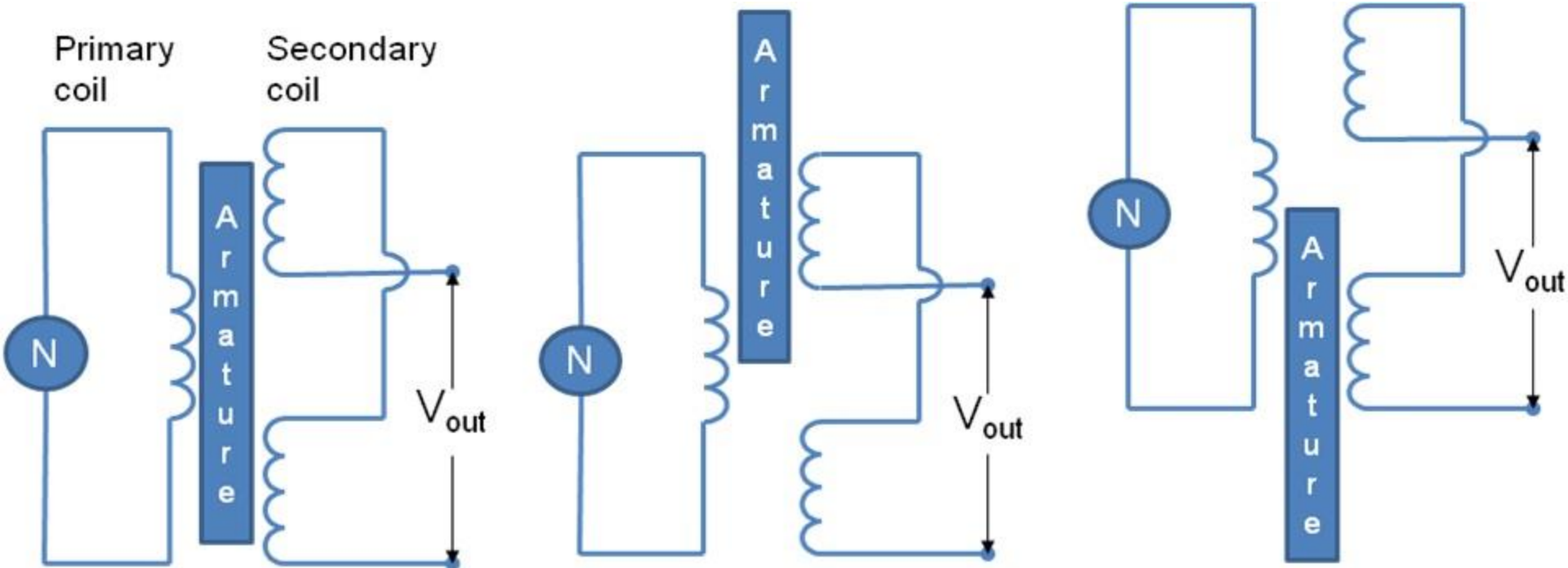
$$D = M \frac{V_A - V_B}{V_A + V_B}$$



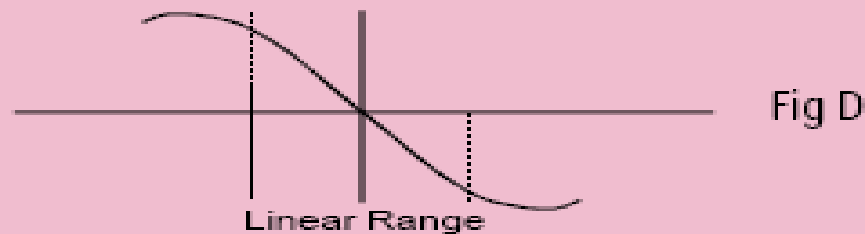
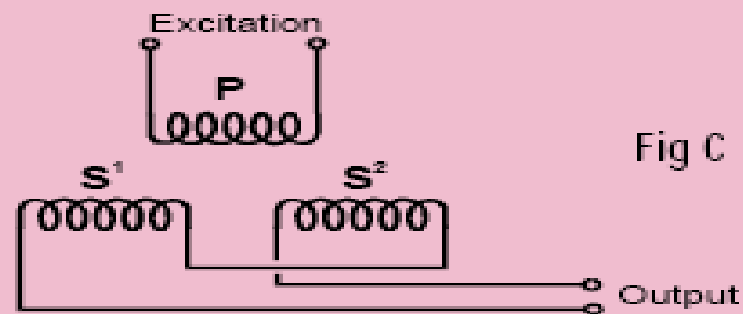
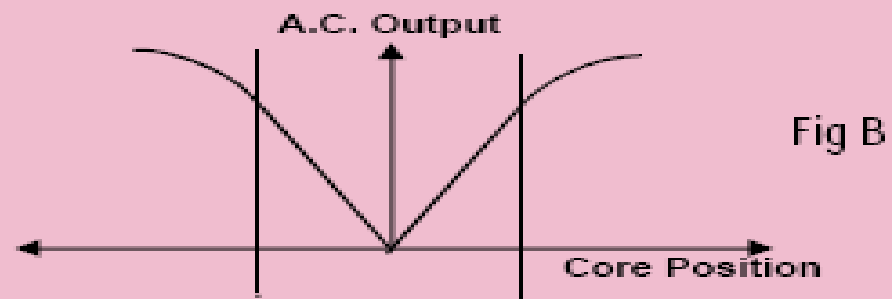
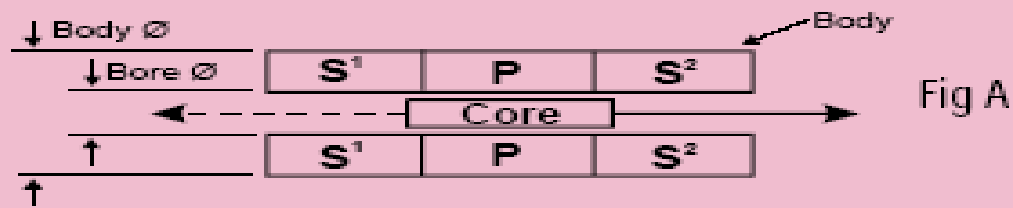
LVDT



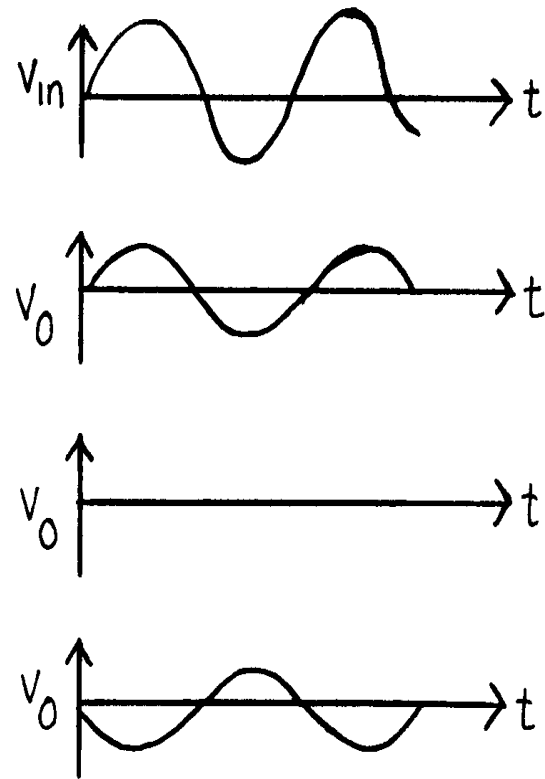
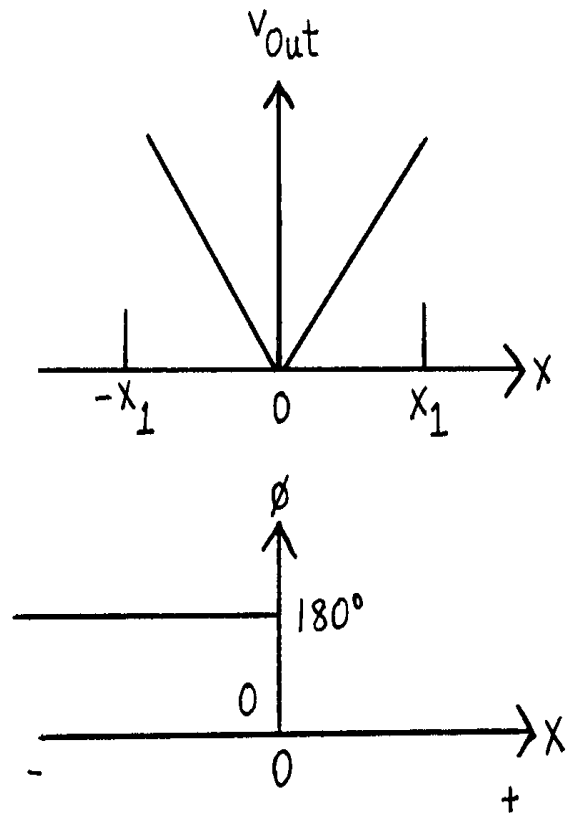
LVDT working



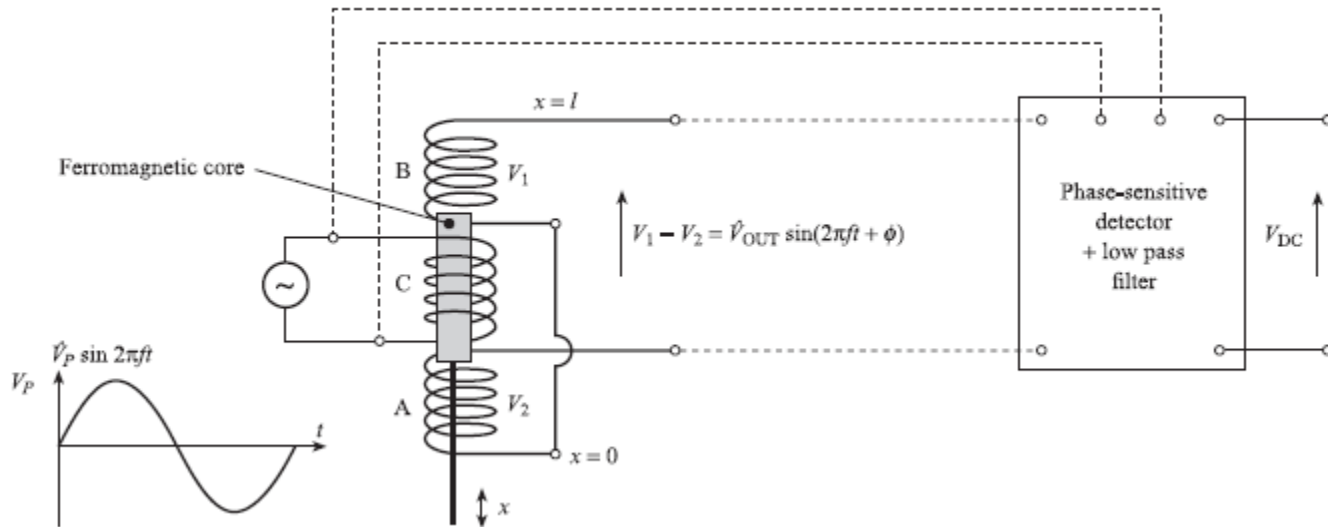
LVDT



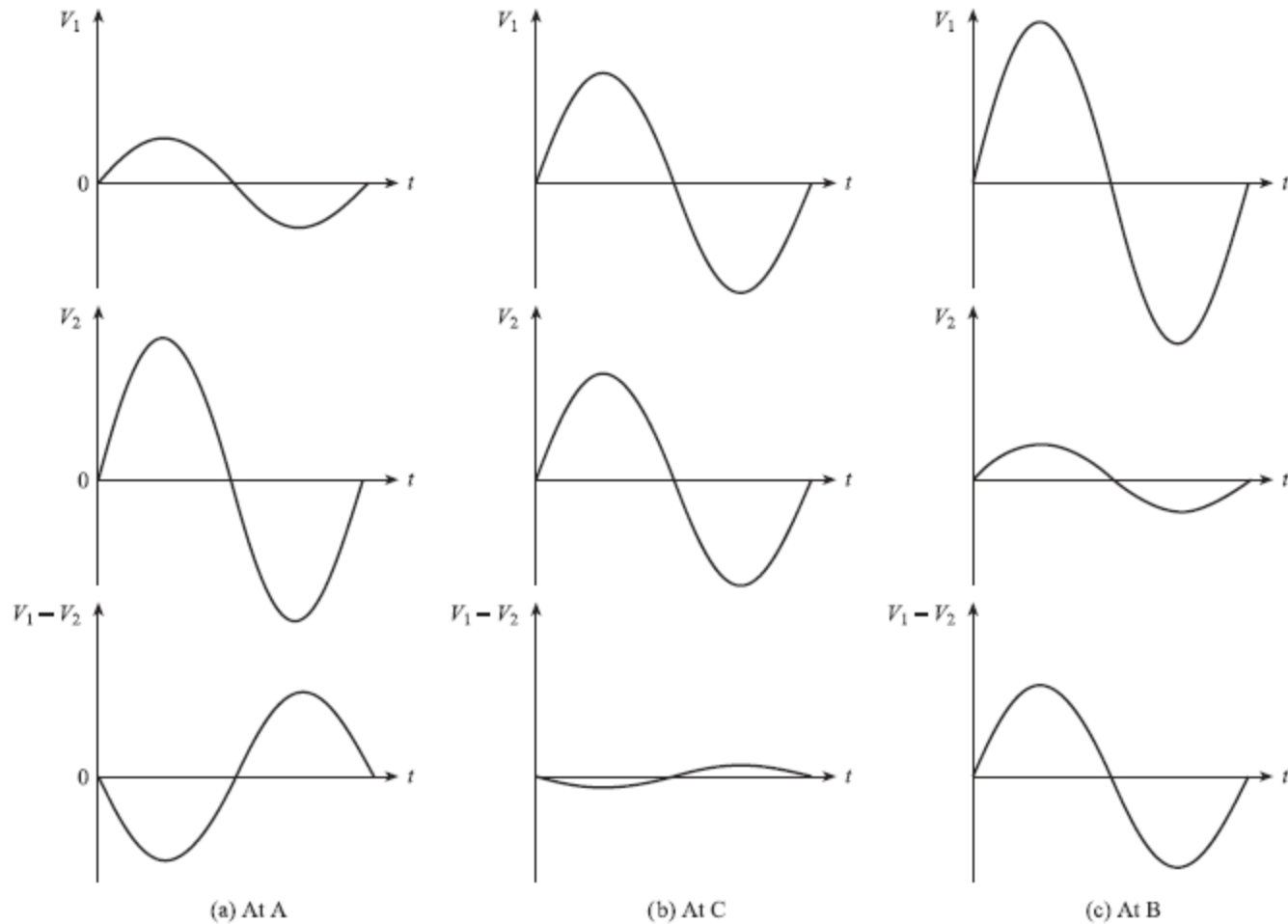
LVDT



LVDT and Connections to Phase Sensitive Detector

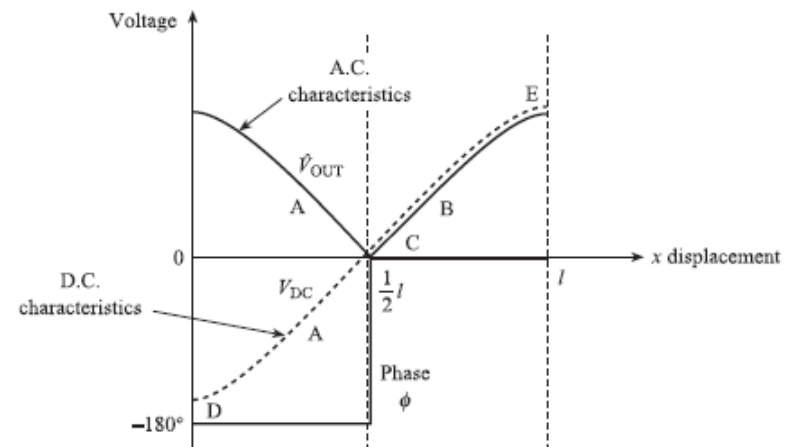


LVDT Secondary Waveform



A.C and D.C Characteristics of LVDT

- LVDT displacement sensors are available to cover ranges from $\pm 0.25\text{mm}$ to $\pm 25\text{cm}$.
- For a typical sensor of 2.5mm , the recommended V_p is 4 to 6 V and f is 5KHz (400Hz min to 50KHz Max).



Signal conditioning

– Sensor Technology(jon wilson)

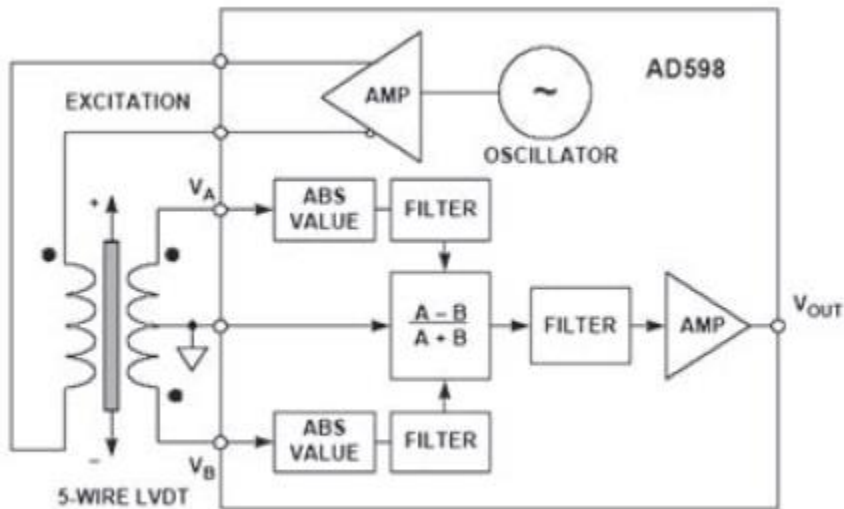


Figure 15.3.6: AD598 LVDT signal conditioner (simplified).

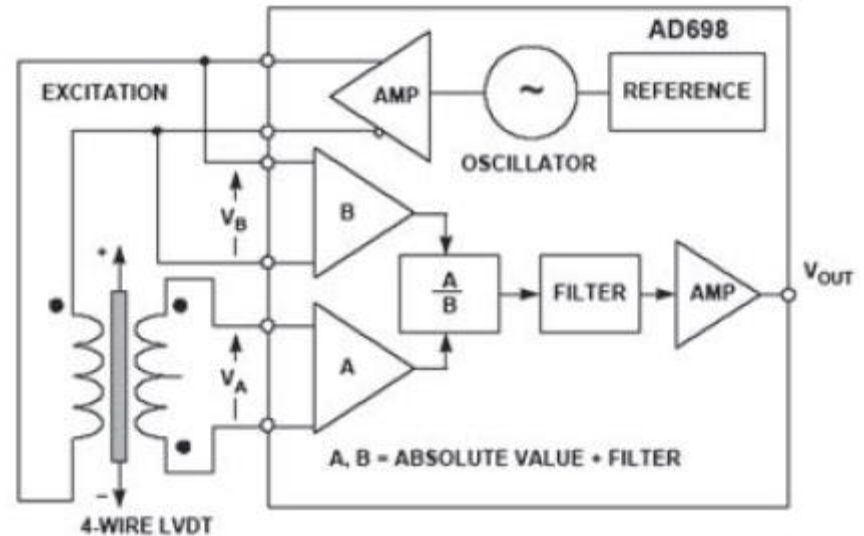
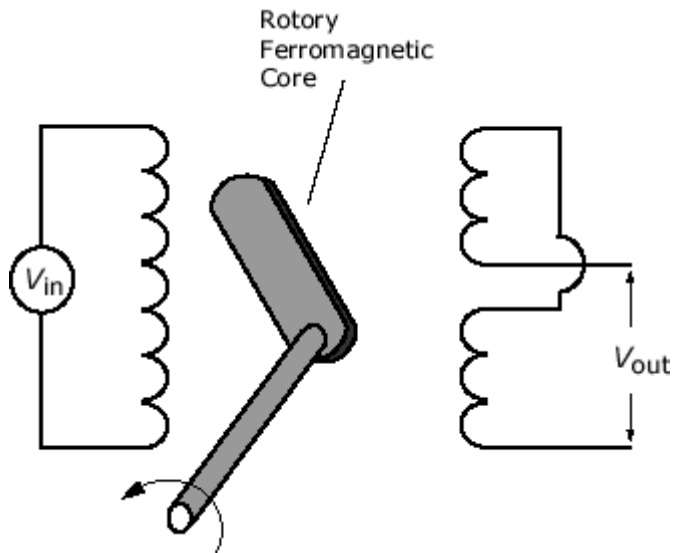


Figure 15.3.7: AD698 LVDT signal conditioner (simplified).

RVDT



http://www.efunda.com/designstandards/sensors/lvdt/rvdt_intro.cfm

http://as.flukecal.com/TCAL_tips_and_tricks



Lecture 4a

SYNCHROS

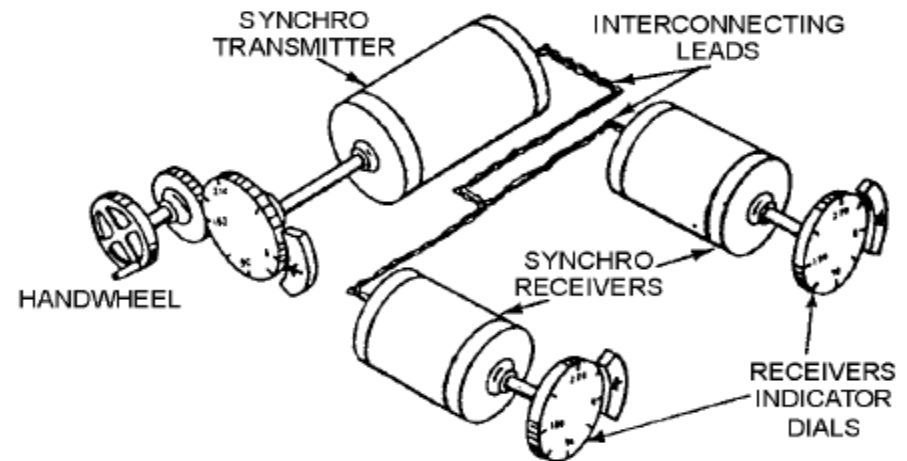
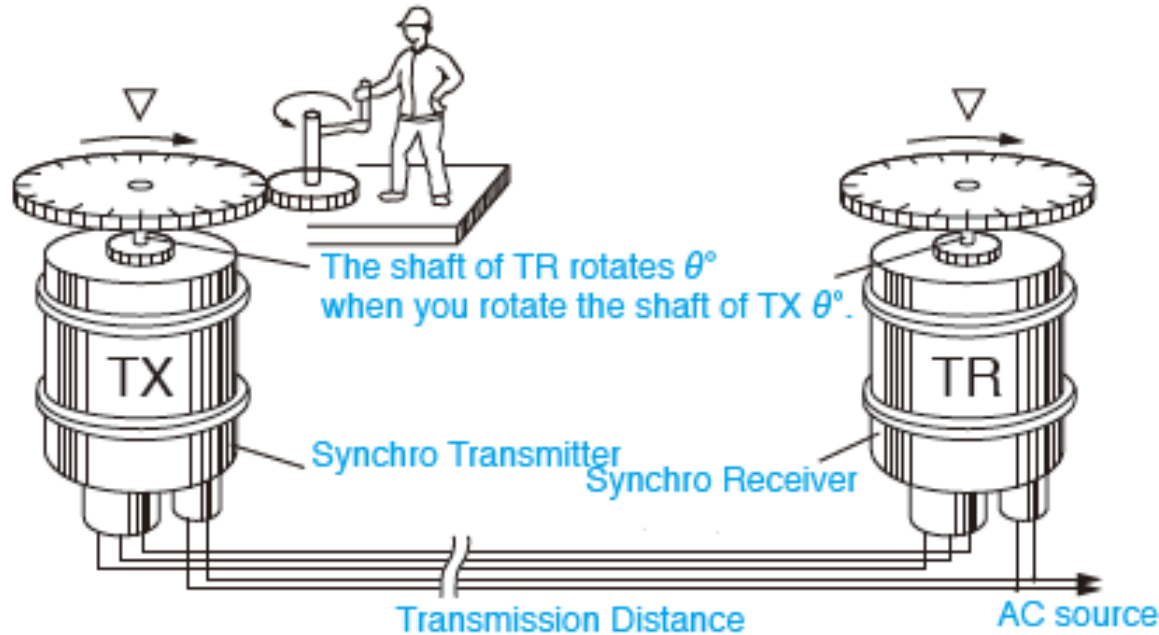
R.MATHIAZHAGAN
TEACHING FELLOW
DEPARTMENT OF PRODUCTION
TECHNOLOGY, MIT



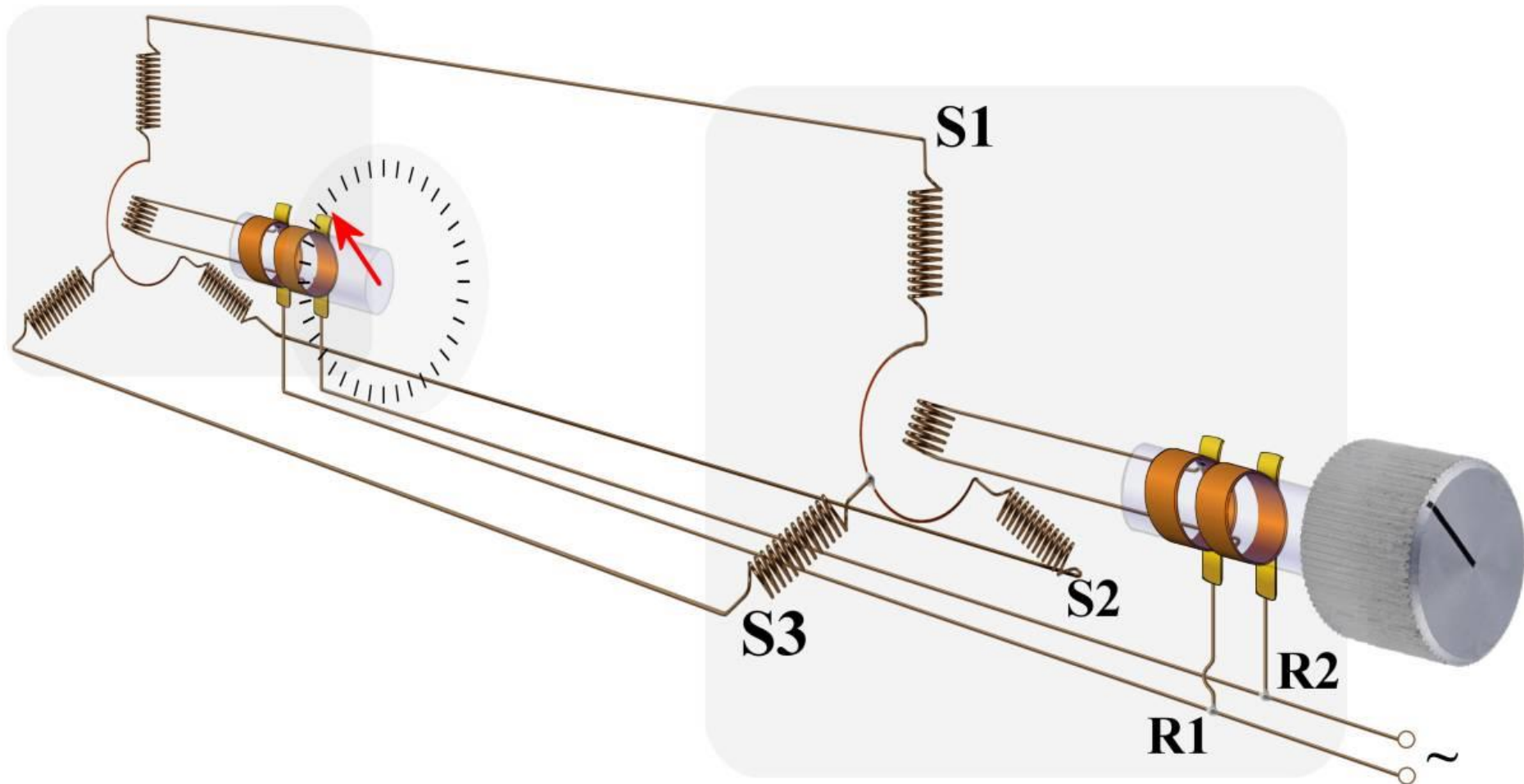
Introduction

- **Synchro is a type of rotary electrical transformer that is used** for measuring the angle of a rotating machine. Synchro is sometimes called selsyn with aliases. It is classified into two types ; Torque Synchro and Control Synchro. The principles of Synchro are similar to those of an electrical transformer except that the iron core of Synchro consists of a rotor and a stator. Output voltage of Synchro varies in accordance with a rotation angle of a shaft.
- Torque Synchro is used by connecting a torque transmitter (TX or G) with a torque receiver (TR or M) as illustrated in Fig.1. a
- shaft of the receiver rotates in unison with the rotation of a shaft of the transmitter. In other words, the receiver synchronizes exactly with the transmitter. So you can detect the shaft angle of the torque transmitter by measuring the shaft angle of the torque receiver.
- Control Synchro detects a rotation angle by reading output voltage. When a shaft of a control transmitter (CX) or of a brushless control transmitter (BCX) is rotated, 3-phase output voltage changes corresponding to the shaft angle. So the shaft angle can be determined by detecting the output voltage (fig.2).
- Structurally, Control Synchro is classified into two types : a brush type and a brushless type.

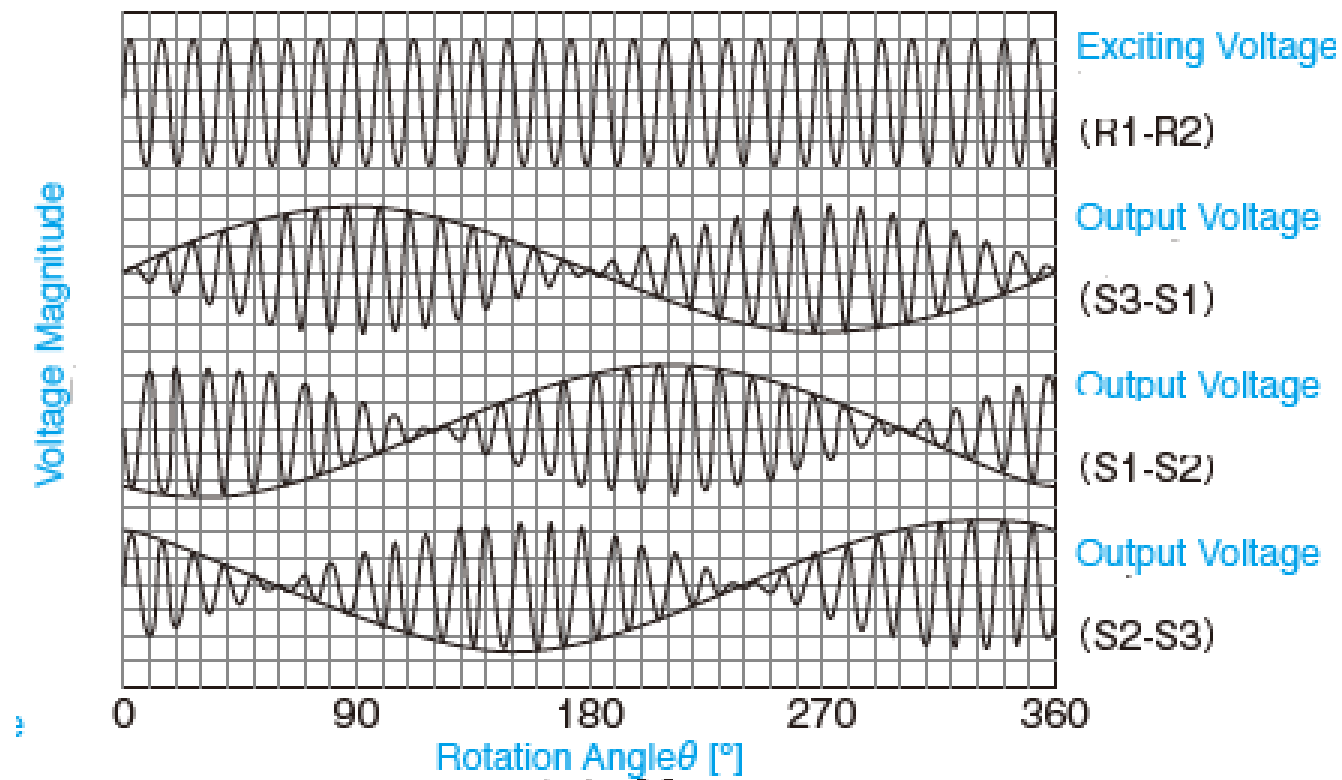
Data Transfer with synchros



synchros

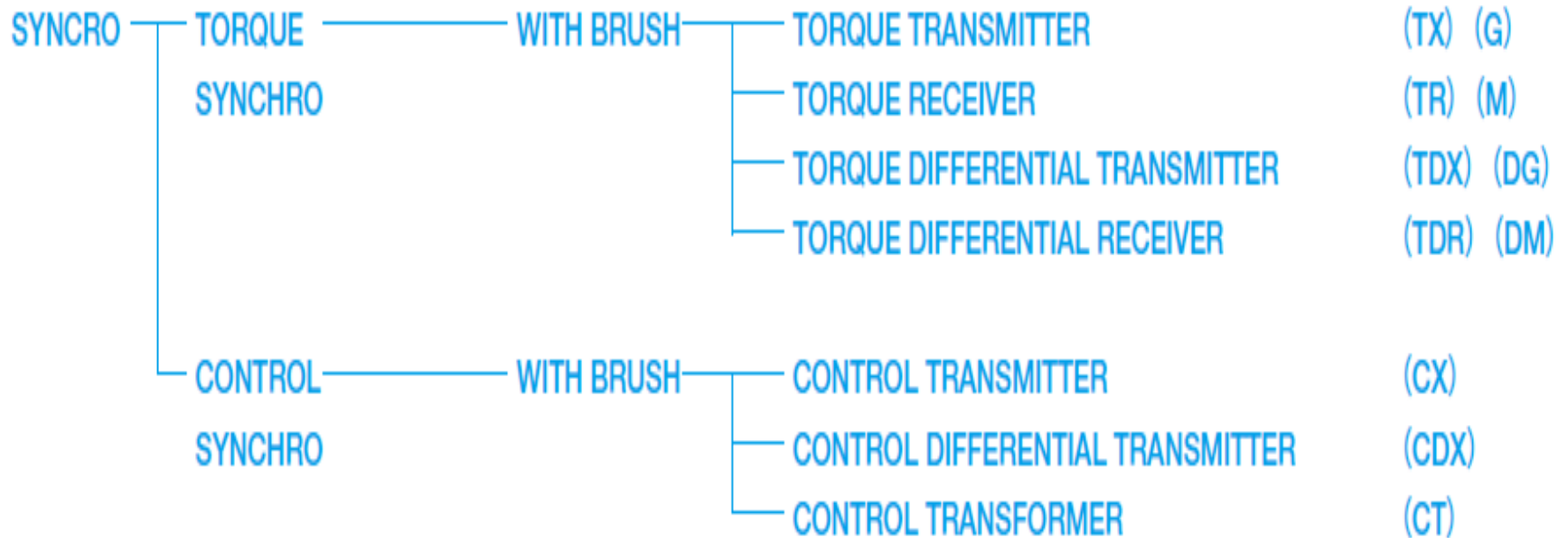


Output Voltage of control synchro





Classification



Functional Classification

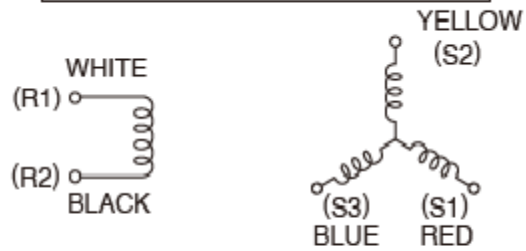
FUNCTIONAL CLASSIFICATION	ABBREVIATION	INPUT	OUTPUT
Torque transmitter	TX	Mechanical input to rotor (rotor energized from AC source)	Electrical output from stator representing angular position of rotor to TDX, TDR, or TR.
Control transmitter	CX	Same as TX	Same as TX except it is supplied to CDX or CT
Torque differential transmitter	TDX	Mechanical input to rotor, electrical input to stator from TX or another TDX.	Electric output from rotor representing algebraic sum or difference between rotor angle and angle represented by electrical input to TR, TDR, or another TDX.
Control differential transmitter	CDX	Same as TDX except electrical input is from CX or another CDX.	Same as TDX except output to CT or another CDX.
Torque receiver	TR	Electrical input to stator from TX or TDX. (Rotor energized from AC source)	Mechanical output from rotor. Note: Rotor has mechanical inertia damper.
Torque differential receiver	TDR	Electrical input to stator from TX or TDX, another electrical input to rotor from TX or TDX.	Mechanical output from rotor representing algebraic sum or difference between angles represented by electrical inputs. Has inertia damper.
Control transformer	CT	Electric input to stator from CX or CDX, mechanical input to rotor.	Electrical output from rotor proportional to the sine of the angle between rotor position and angle represented by electrical input to stator. Called error signal.
Torque receiver	TRX	Depending on application, same as TX.	Depending on application, same as TX or TR.



Specification

Model
Function
Input Voltage (Vrms)
Input Frequency (Hz)
Test Voltage (Vrms)
Test Frequency (Hz)
Output Voltage (Vrms)
Input Current (A Max)
Torque Grad. (N·m/deg. Min)
Receiver Error (deg. Max)
Synchronizing Time (sec. Max)
Temperature Rise (°C Max)
Insulation Resistance (M Ω Min)
Dielectric Strength (Vrms.1 min)
Mass (g)

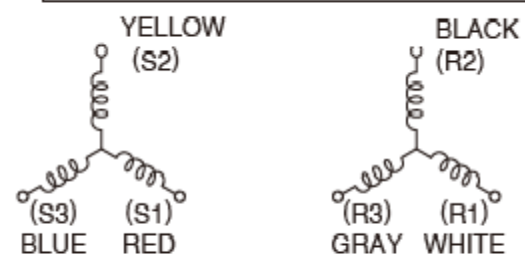
TX. TR. CX. CT. G. M



EXCITATION SIDE
(ROTOR)

OUTPUT SIDE
(STATOR)

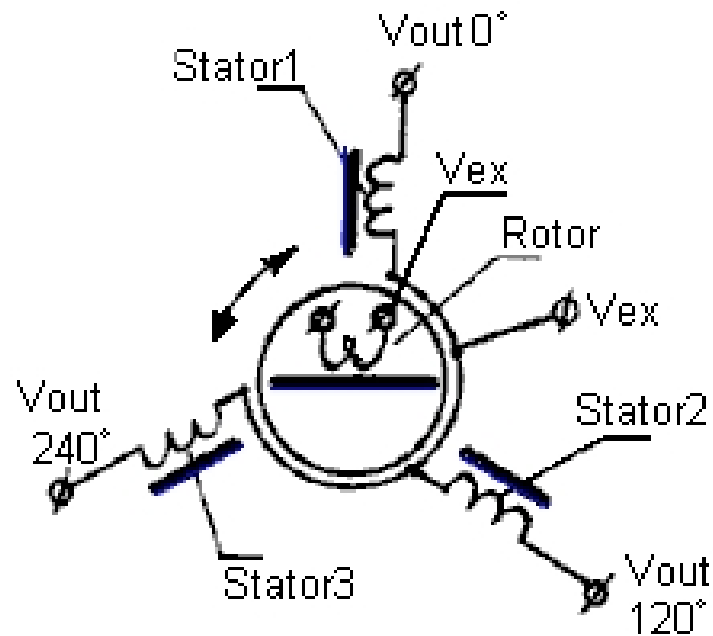
TDX. TDR. CDX. DG. DM



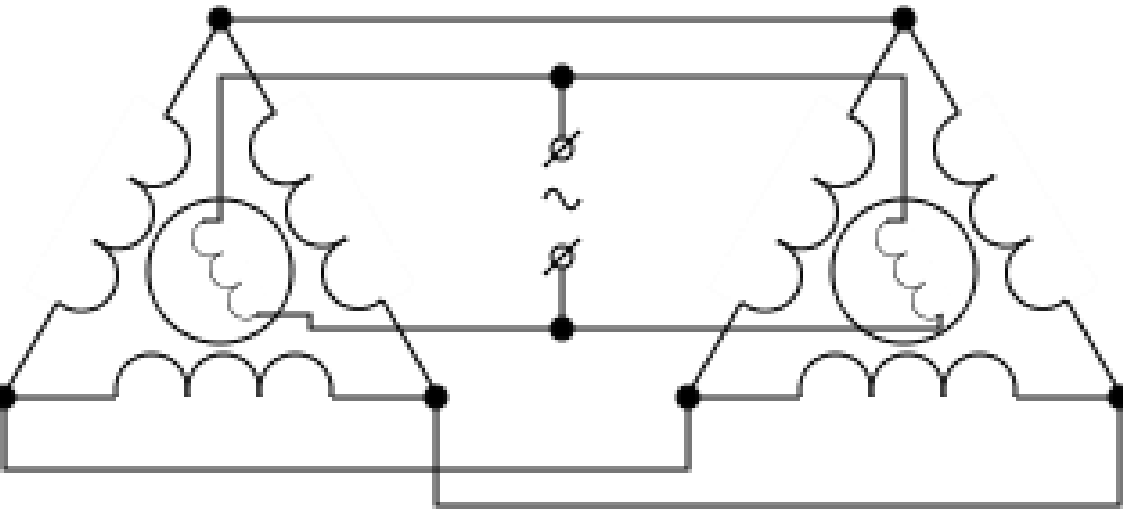
EXCITATION SIDE
(STATOR)

OUTPUT SIDE (ROTOR) ... TDX, CDX, DG

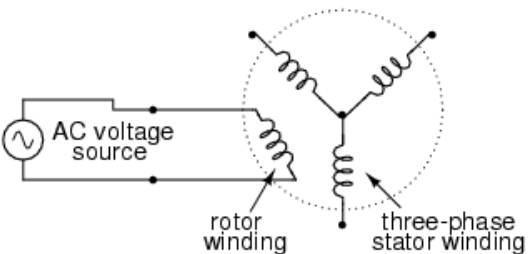
Circuit Diagram



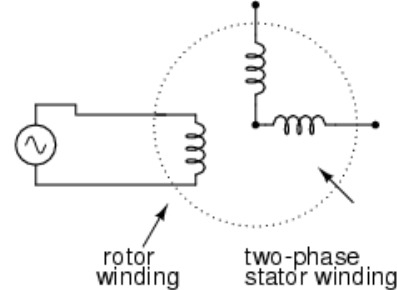
Connection of transmitter and receiver



Synchro (a.k.a "Selsyn")



Resolver

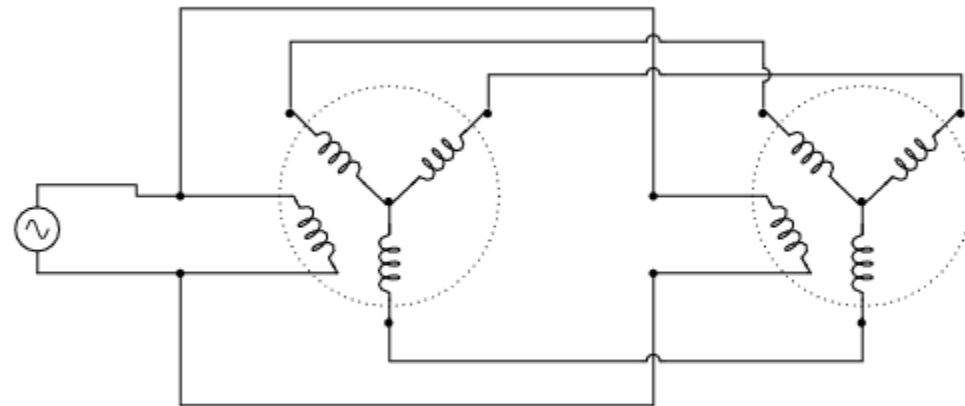


modern schematic symbol



Synchro "transmitter"

Synchro "receiver"



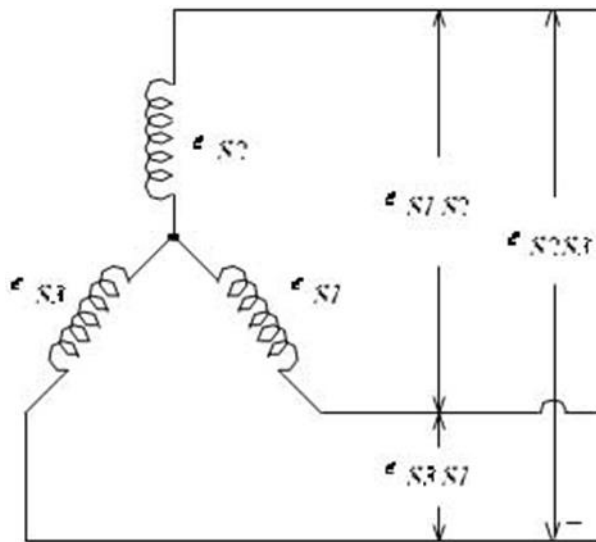
The receiver rotor will turn to match position with the transmitter rotor so long as the two rotors remain energized.



Working

- A synchro is, in effect, a transformer whose primary-to-secondary coupling may be varied by physically changing the relative orientation of the two windings. Synchros are often used for measuring the angle of a rotating machine such as an antenna platform. In its general physical construction, it is much like an electric motor. The primary winding of the transformer, fixed to the rotor, is excited by an alternating current, which by electromagnetic induction, causes currents to flow in three Y-connected secondary windings fixed at 120 degrees to each other on the stator. The relative magnitudes of secondary currents are measured and used to determine the angle of the rotor relative to the stator, or the currents can be used to directly drive a receiver synchro that will rotate in unison with the synchro transmitter. In the latter case, the whole device may be called a selsyn

Formula



$$e_{S_1S_2} = e_{S_1} - e_{S_2} = \sqrt{3} K E_r \sin (\theta + 240^\circ) \sin \omega t$$

$$e_{S_2S_3} = e_{S_2} - e_{S_3} = \sqrt{3} K E_r \sin (\theta + 120^\circ) \sin \omega t$$

$$e_{S_3S_1} = e_{S_3} - e_{S_1} = \sqrt{3} K E_r \sin \theta \sin \omega t$$

$$e_{S_1S_2} = e_{S_1} - e_{S_2} = K E_r \cos (\theta - 240^\circ) \sin \omega t - K E_r \cos \theta \sin \omega t$$

$$= K E_r [\cos \theta \cos 240^\circ + \sin \theta \sin 240^\circ - \cos \theta] \sin \omega t$$

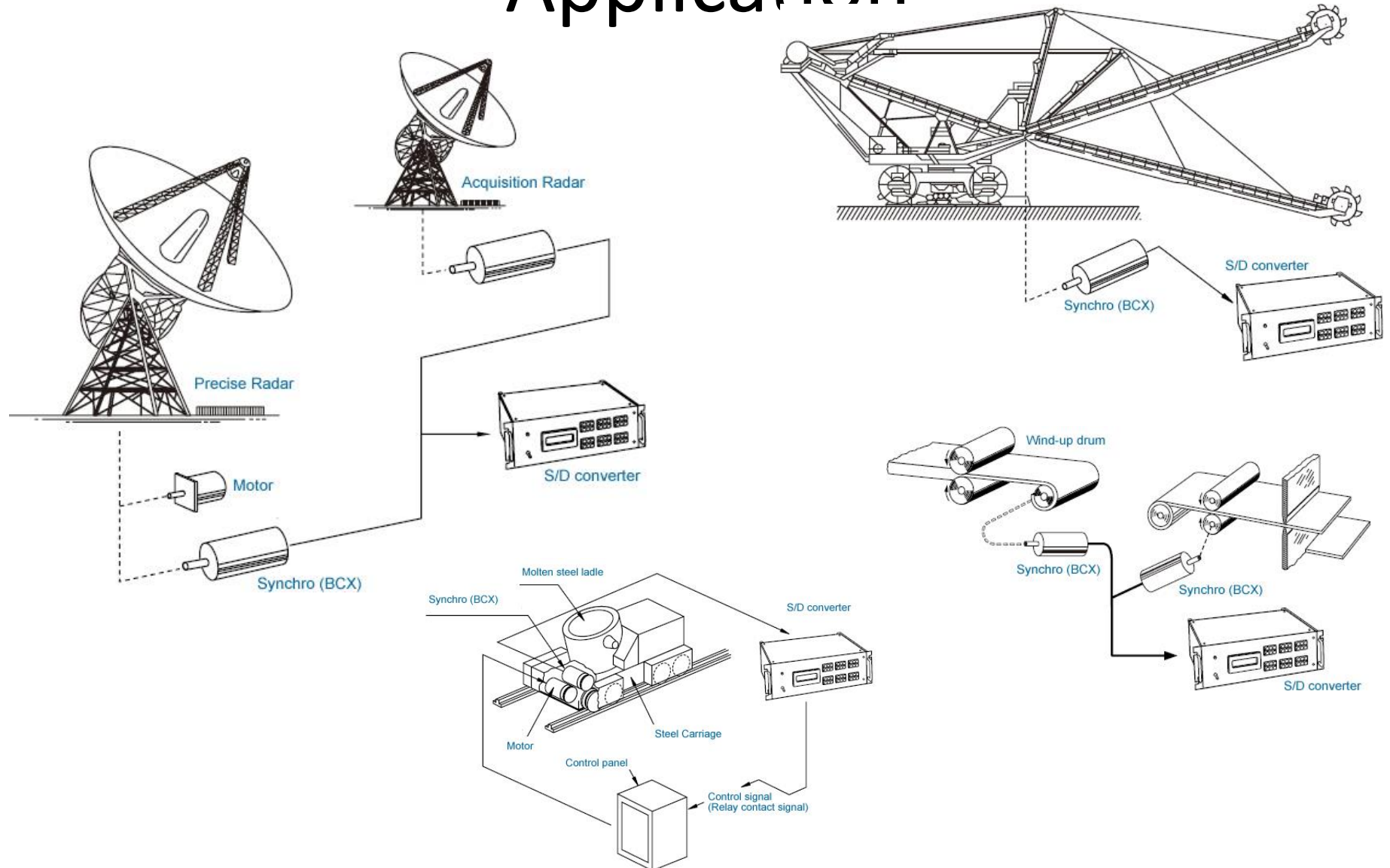
$$= K E_r \left[\cos \theta (-0.5) + \sin \theta \left(-\frac{\sqrt{3}}{2} \right) - \cos \theta \right] \sin \omega t$$

$$= \sqrt{3} K E_r \left[\sin \theta \left(-\frac{1}{2} \right) + \cos \theta \left(-\frac{\sqrt{3}}{2} \right) \right] \sin \omega t$$

$$= \sqrt{3} K E_r [\sin \theta \cos 240^\circ + \cos \theta \sin 240^\circ] \sin \omega t$$

$$= \sqrt{3} K E_r \sin (\theta + 240^\circ) \sin \omega t$$

Application



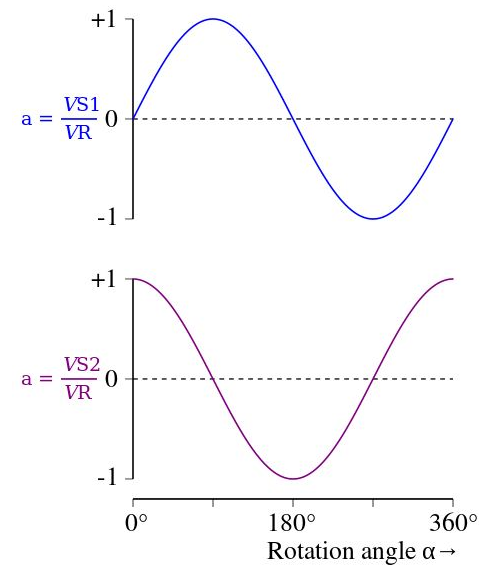


Application

- **Detection of winding length / Detection of roll interval**
- **Position detection of stackers / reclaimers**
Detection of boom swing angles and elevation angles
- **Angle detection : antenna bearing angles, and elevation angles**
- **Position detection of an automated carriage**

Difference between synchros and resolver

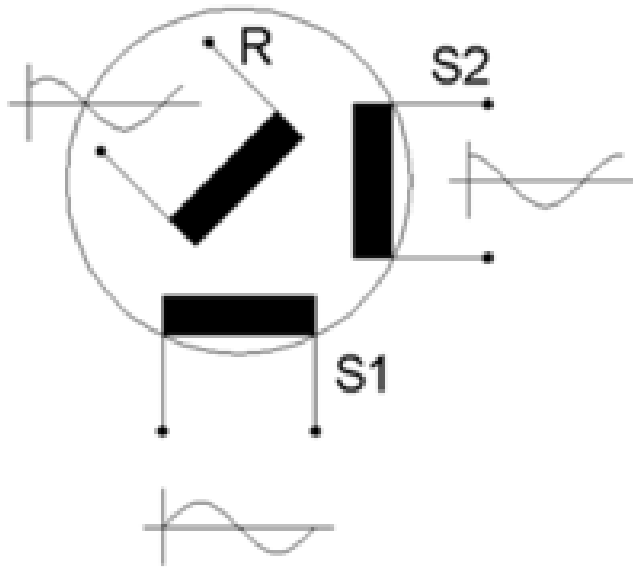
- They share the same rotor, stator, and shaft components. The primary difference between a synchro and a resolver is a synchro has three stator windings installed at 120 degree offsets, while the resolver has two stator windings installed at 90 degree angles.



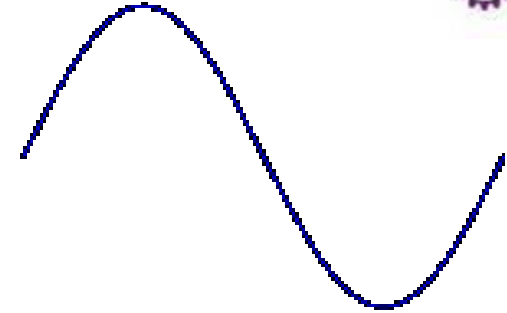


Resolver

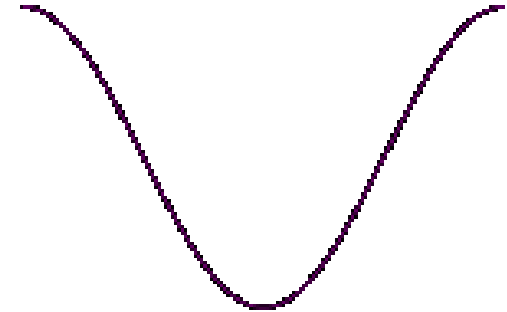
Resolver



$$V_S = \frac{V_{S1}}{V_R}$$



$$V_R = \frac{V_{S2}}{V_R}$$



The relative magnitudes of the two-phase voltages are measured and used to determine the angle of the rotor relative to the stator. Upon one full revolution, the feedback signals repeat their waveforms. This device may also appear in non-brushless type, i.e., only consisting in two lamination stacks, rotor and stator.



Types

- Two pole resolver
- Multiple pole resolver



Receiver resolver

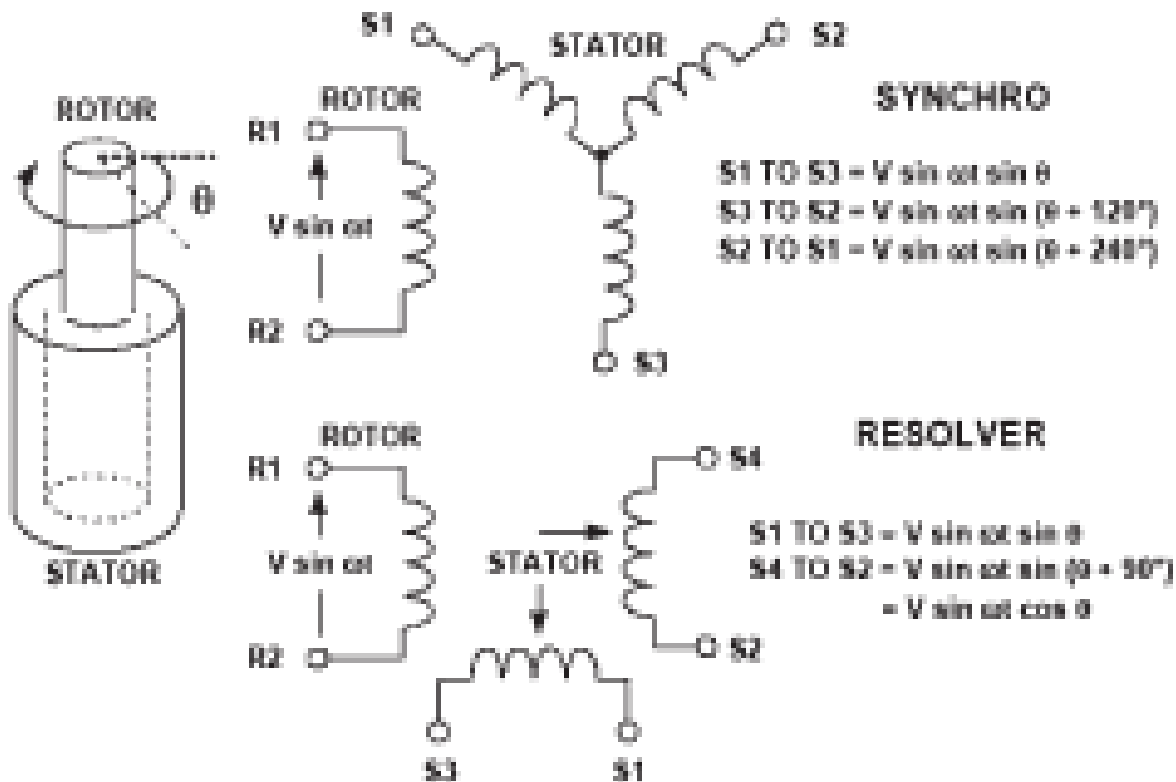
- These resolvers are used in the opposite way to transmitter resolvers. The two diphased windings are energized, the ratio between the sine and the cosine representing the electrical angle. The system turns the rotor to obtain a zero voltage in the rotor winding. At this position, the mechanical angle of the rotor equals the electrical angle applied to the stator



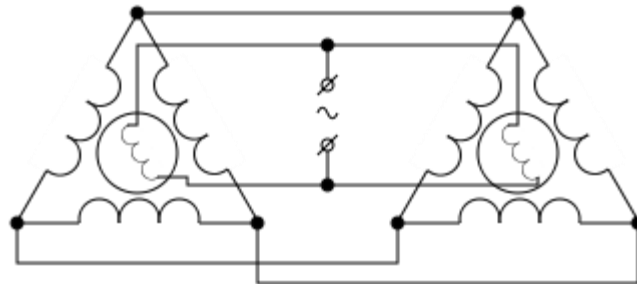
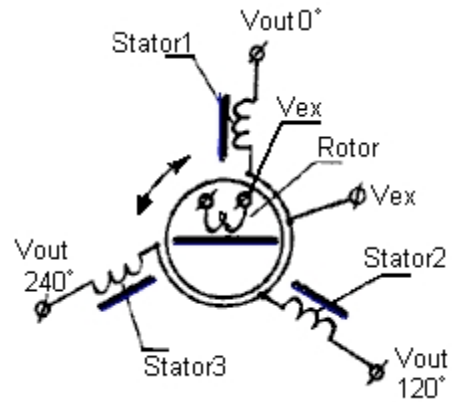
Application

- Rotary antenna
- Electrical antenna positioning

Resolver and synchros

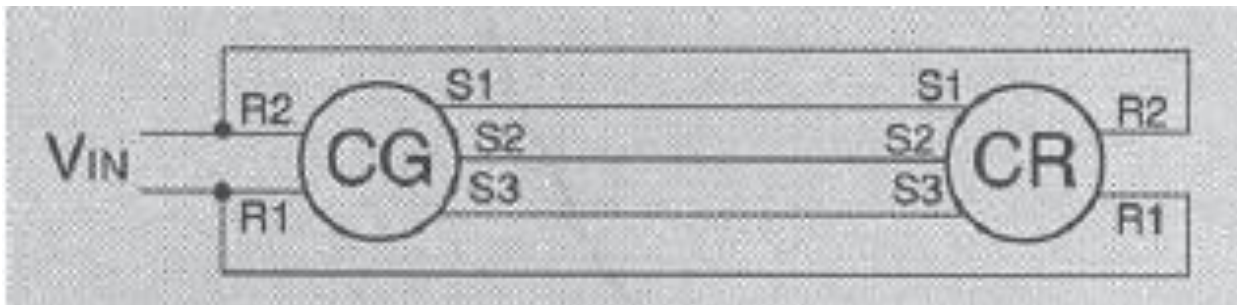


synchro

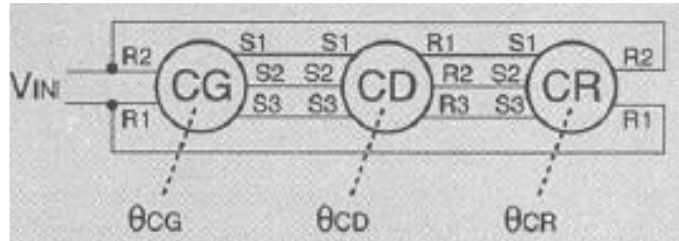


Transmitter & receiver

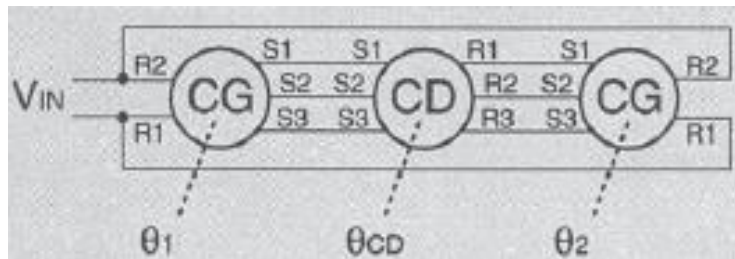
- $V_{S1-3} = K V_{R2-1} \sin \theta$
- $V_{S3-2} = K V_{R2-1} \sin (\theta + 120^\circ)$
- $V_{S2-1} = K V_{R2-1} \sin (\theta + 240^\circ)$



Differential

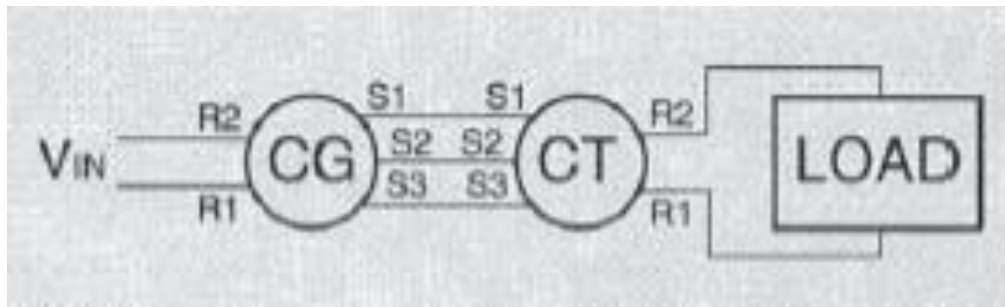


$$\theta_{CR} = \theta_{CG} \pm \theta_{CD},$$



$$\theta_{CD} = \theta_1 \pm \theta_2$$

Control Transformers





- <http://www.radartutorial.eu/01.basics/Radar%20Principle.en.html>



Lecture-5

Encoders

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Introduction

- Any transducer that generates a **coded reading** of a measurement can be termed an **encoder**.
- Shaft Encoders are digital transducers that are used for measuring angular displacements and velocities.
- Relative advantages of digital transducers over their analog counterparts:
 - High resolution (depending on the word size of the encoder output and the number of pulses per revolution of the encoder)
 - High accuracy (particularly due to noise immunity of digital signals and superior construction)



Continue....

- Relative ease of adaptation in digital control systems (because transducer output is digital) with associated reduction in system cost and improvement of system reliability
- Shaft Encoders can be classified into two categories depending on the nature and method of interpretation of the output:
 - Incremental Encoders
 - Absolute Encoders
- **Incremental Encoders**
 - Output is a pulse signal that is generated when the transducer disk rotates as a result of the motion that is being measured.



Continue....

- By counting pulses or by timing the pulse width using a clock signal, both angular displacement and angular velocity can be determined.
- –Displacement, however, is obtained with respect to some reference point on the disk, as indicated by a reference pulse (index pulse) generated at that location on the disk. The index pulse count determines the number of full revolutions.
- **Absolute Encoders**
- –An absolute encoder has many pulse tracks on its transducer disk.
- –When the disk of an absolute encoder rotates, several pulse trains –equal in number to the tracks on the disk –are generated simultaneously.



Continue...

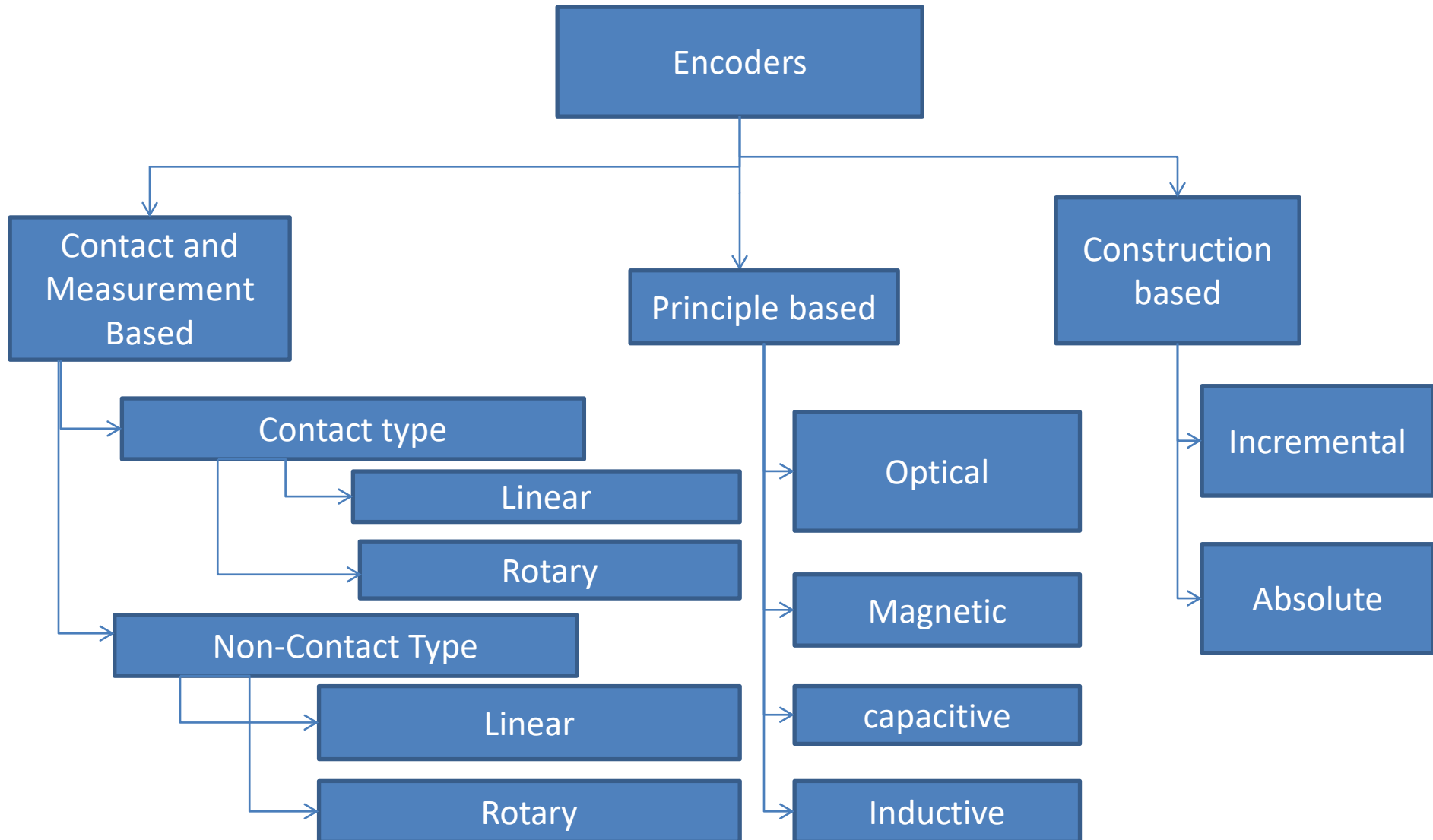
- At a given instant, the magnitude of each pulse signal will have one of two signal levels (i.e., a binary state) as determined by a level detector. This signal level corresponds to a binary digit (0 or 1). Hence, the set of pulse trains gives an encoded binary number at any instant.
- –The pulse windows on the tracks can be organized into some pattern (code) so that each of these binary numbers corresponds to the angular position of the encoder disk at the time when the particular binary number is detected.
- –Pulse voltage can be made compatible with some form of digital logic (e.g., TTL)
- –Direct digital readout of an angular position is possible.



Continue...

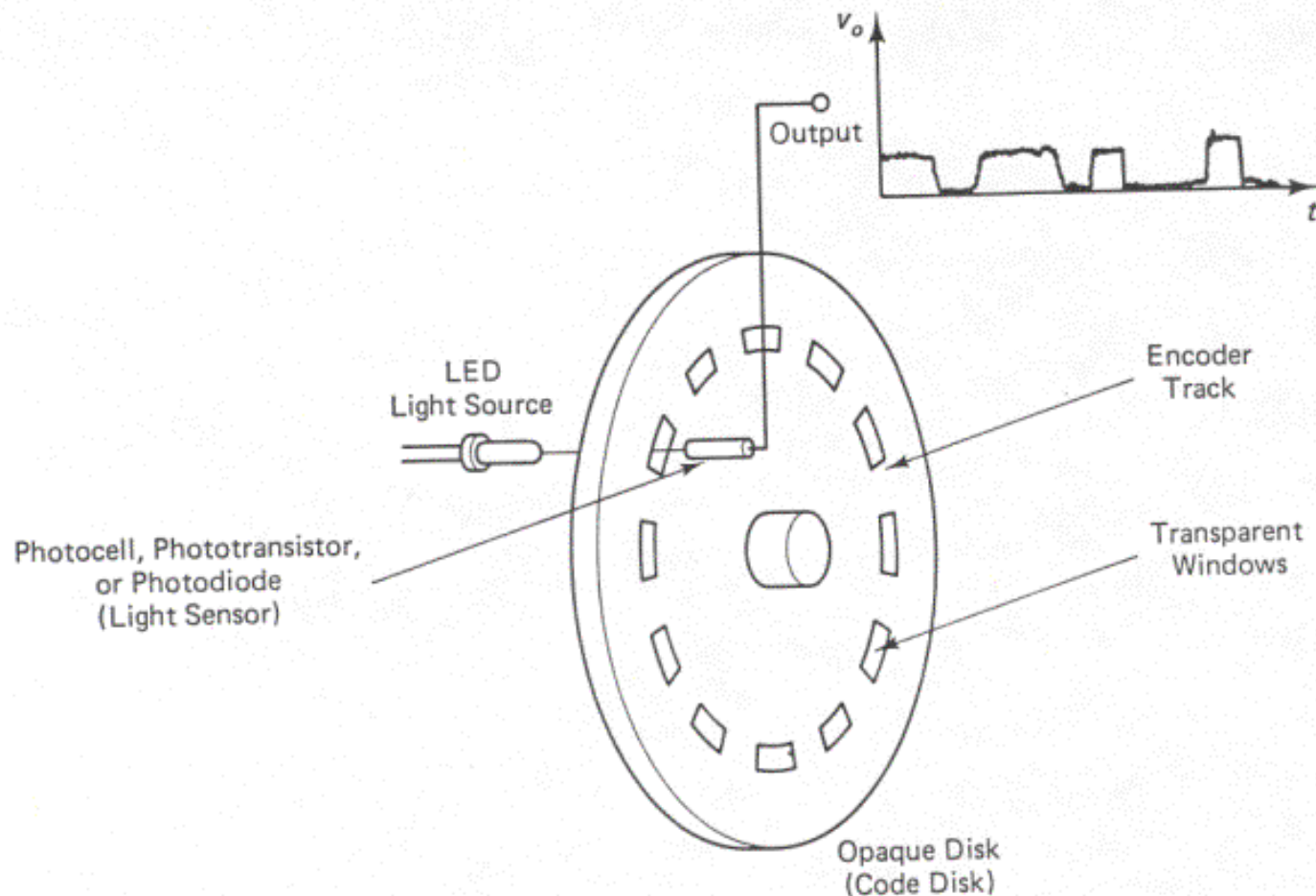
- Absolute encoders are commonly used to measure fractions of a revolution. However, complete revolutions can be measured using an additional track that generates an index pulse, as in the case of an incremental encoder.
- Signal Generation can be accomplished using any one of four techniques:
 - –Optical (photosensor) method
 - –Sliding contact (electrical conducting) method
 - –Magnetic saturation (reluctance) method
 - –Proximity sensor method
 - •Method of signal interpretation and processing is the same for all four types of signal generation.

Classification

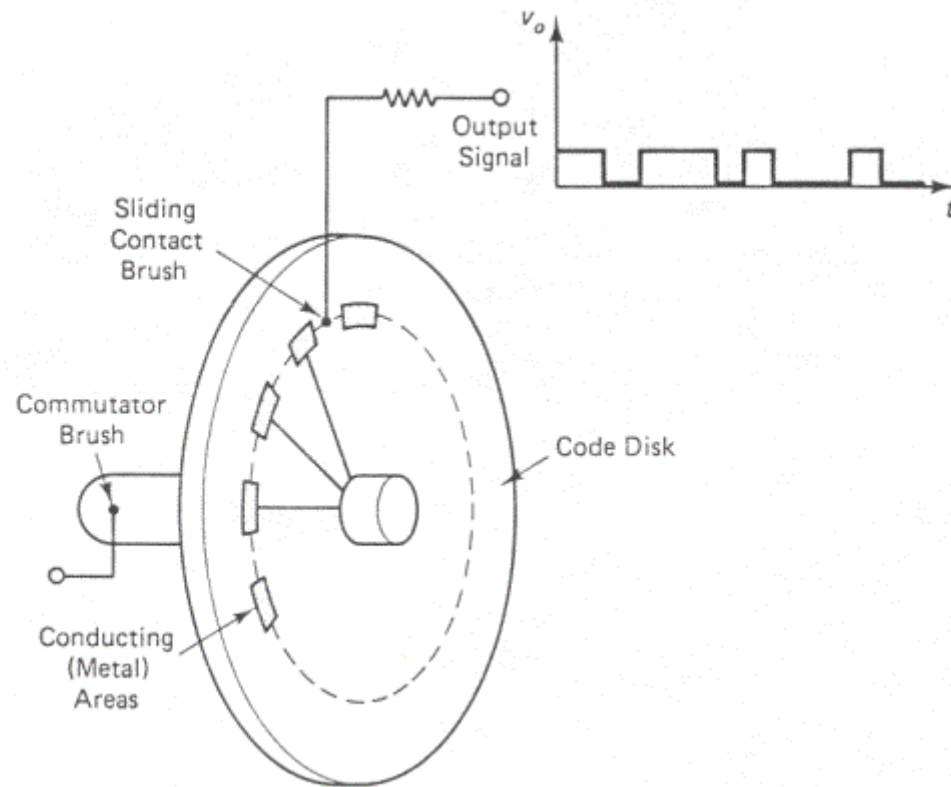


Schematic Representation of an Optical Encoder

One Track and One Pick-Off Sensor



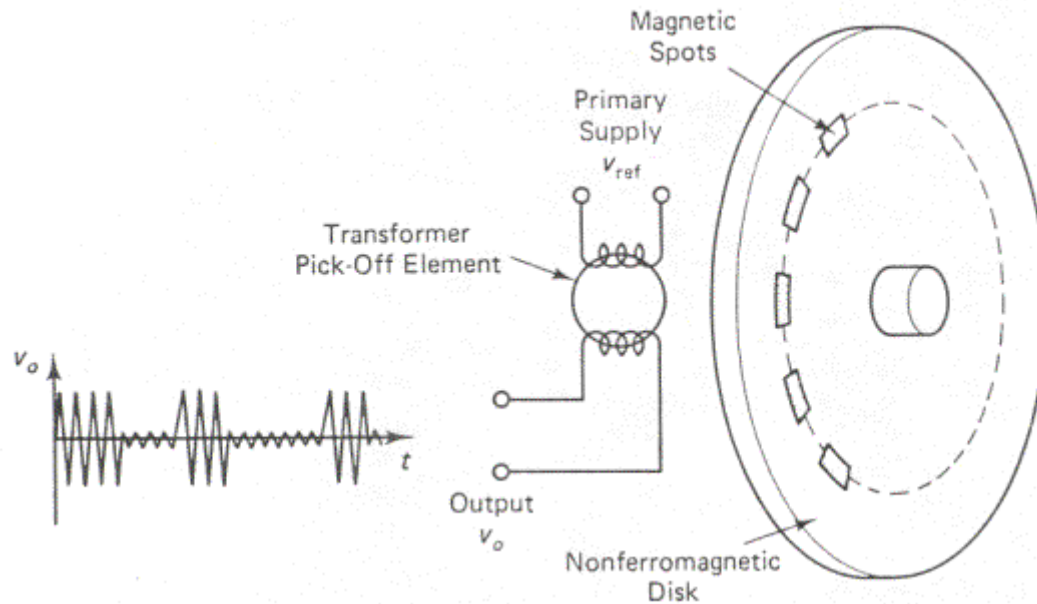
Schematic Representation of a Sliding Contact Encoder



Schematic Representation of a Magnetic Encoder

Pulse peak: nonmagnetic area

Pulse valley: magnetic area





Magnetic Encoder

(Magnetic Encoder Working)

- A magnetic pickup is essentially a coil wound around a permanently magnetized probe. When discrete ferromagnetic objects—such as gear teeth, turbine rotor blades, slotted discs, or shafts with keyways—are passed through the probe's magnetic field, the flux density is modulated. This induces AC voltages in the coil. One complete cycle of voltage is generated for each object passed.
- If the objects are evenly spaced on a rotating shaft, the total number of cycles will be a measure of the total rotation, and the frequency of the AC voltage will be directly proportional to the rotational speed of the shaft.
- (Output waveform is a function not only of rotational speed, but also of gear-tooth dimensions and spacing, pole-piece diameter, and the air gap between the pickup and the gear-tooth surface. The pole-piece diameter should be less than or equal to both the gear width and the dimension of the tooth's top (flat) surface; the space between adjacent teeth should be approximately three times this diameter. Ideally, the air gap should be as small as possible—typically 0.005 inch. A number of steel or cast-iron gears, precisely manufactured to AGMA standards, are available for use with the Model MP1A. The standard solid gear comes with various dimensions and with 48, 60, 72, 96, or 120 teeth

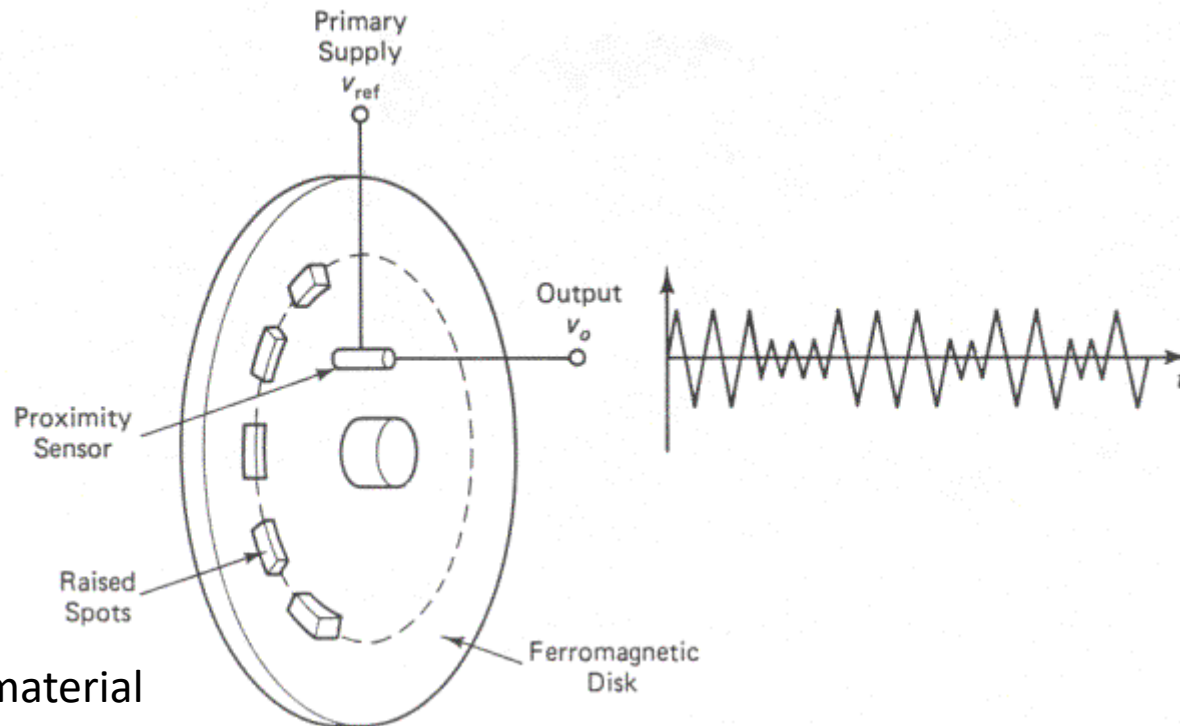


Magnetic Encoder

- A magnetic pickup may also be used as a timing or synchronization device—as, for example, in ignition timing of gasoline engines, angular positioning of rotating parts, or stroboscopic triggering of mechanical motion.

Schematic Representation of a Proximity Probe Encoder

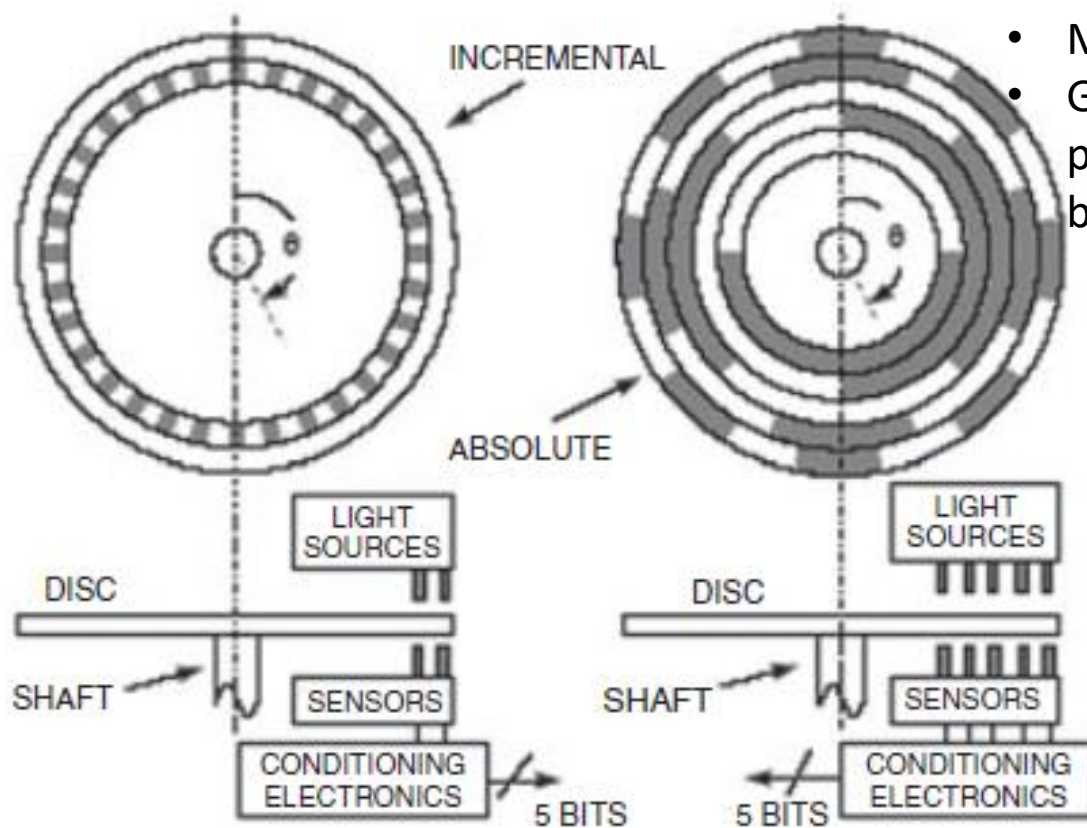
Proximity sensor: Magnetic induction



ferromagnetic material

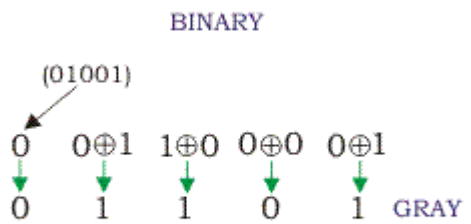
Incremental and absolute sensor

- N=Number of sectors-5
- Max/. Count= $2^N - 1$
- Gray code is preferred over binary code



Gray and Binary code

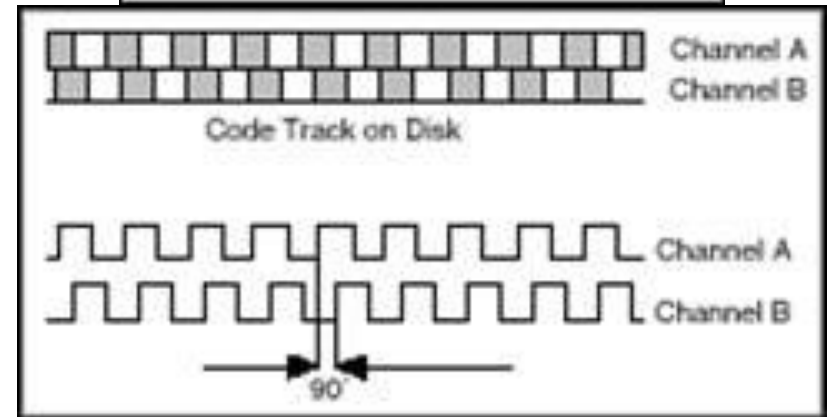
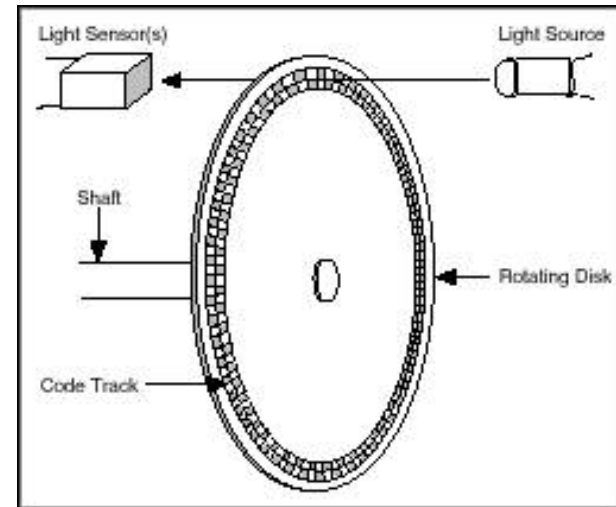
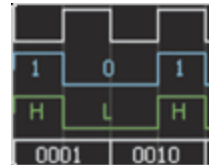
Decimal Number	4 bit Binary Number <u>ABCD</u>	4 bit Gray Code <u>G₁G₂G₃G₄</u>
0	0 0 0 0	0 0 0 0
1	0 0 0 1	0 0 0 1
2	0 0 1 0	0 0 1 1
3	0 0 1 1	0 0 1 0
4	0 1 0 0	0 1 1 0
5	0 1 0 1	0 1 1 1
6	0 1 1 0	0 1 0 1
7	0 1 1 1	0 1 0 0
8	1 0 0 0	1 1 0 0
9	1 0 0 1	1 1 0 1
10	1 0 1 0	1 1 1 1
11	1 0 1 1	1 1 1 0
12	1 1 0 0	1 0 1 0
13	1 1 0 1	1 0 1 1
14	1 1 1 0	1 0 0 1
15	1 1 1 1	1 0 0 0



Incremental encoder

A light-emitting diode (LED), a disk, and a light detector on the opposite side of the disk. The disk, which is mounted on the rotating shaft, has patterns of opaque and transparent sectors coded into the disk.

As the disk rotates, the opaque segments block the light and, where the glass is clear, light is allowed to pass. This generates square-wave pulses, which can then be interpreted into position or motion.



Quadrature Encoder Waveform

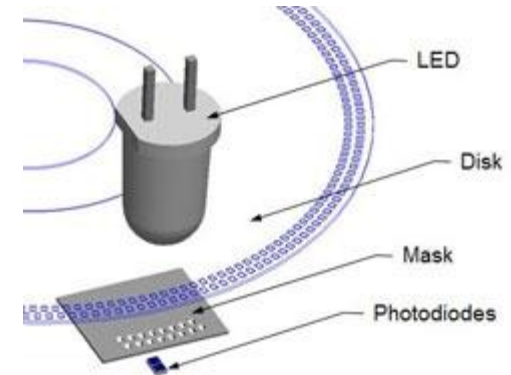
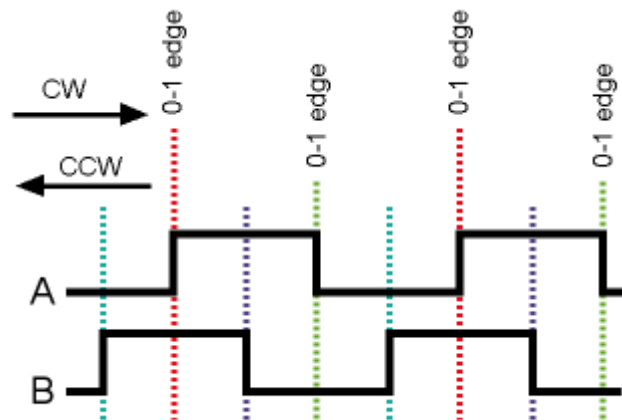


Figure 5: Adding a mask to a quadrature encoder helps prevent the signal from channel A from affecting channel B. (Courtesy of Dynapar Corp.)



Absolute encoder

- The absolute encoder uses multiple groups of segments that form concentric circles on the encoder wheel like a bull's-eye on a target or dartboard.
- The concentric circles start in the middle of the encoder wheel and, as the rings go out toward the outside of the ring, they each have double the number of segments than the previous inner ring



Resolution

- Encoders usually have from 100 to 6,000 segments per revolution. This means that these encoders can provide 3.6 deg of resolution for the encoder with 100 segments and 0.06 deg of resolution for the encoder with 6,000 segments.



Types based on signal

- Single ended encoder
- Differential encoder



Absolute encoder

- The first ring, which is the innermost ring, has one transparent and one opaque segment.
- The second ring out from the middle has two transparent and two opaque segments, and the third ring has four of each segment. If the encoder has 10 rings, its outermost ring has 512 segments, and if it has 16 rings, the outermost ring has 32,767 segments

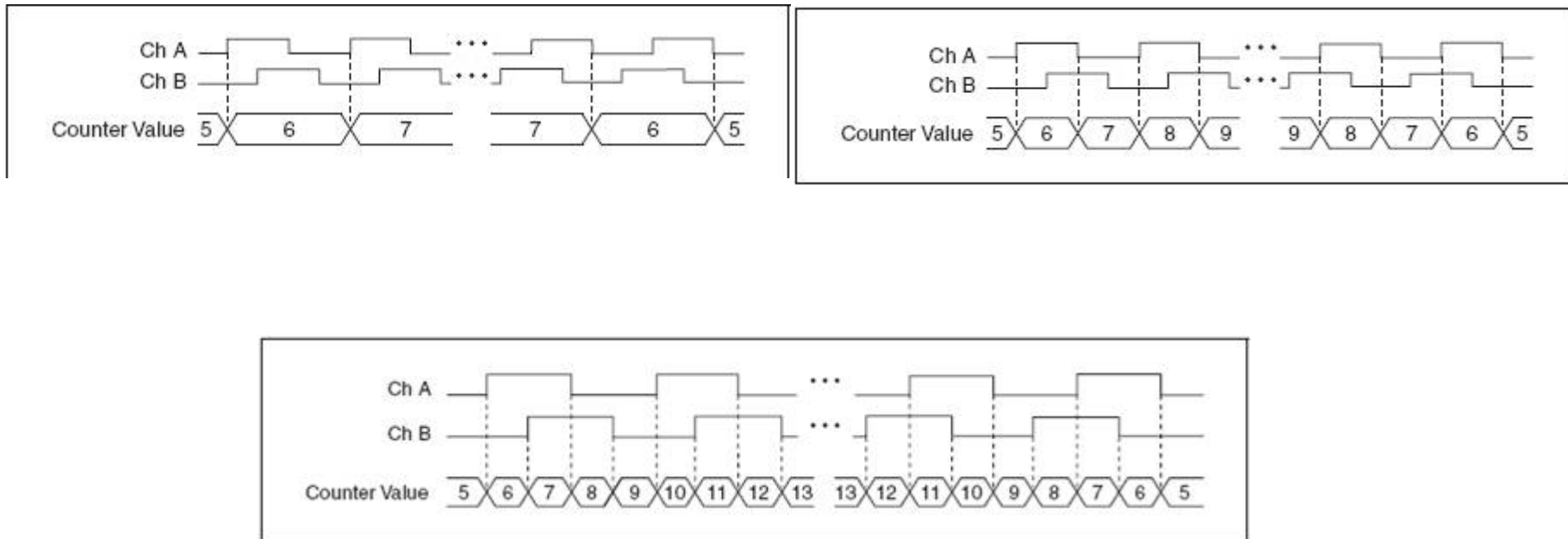


Advantage

- The advantage of the absolute encoder is that you can gear it down so that the encoder wheel makes one revolution during the full length of machine travel.
- If the length of machine travel is 10 in. and its encoder has 16-bit resolution, the resolution of the machine is $10/65,536$, which is 0.00015 in

Types of encoding

Once the edges are counted, the next concept you need to consider is how those values are converted to position. The process by which edge counts are converted to position depends on the type of encoding used. There are three basic types of encoding, X1, X2, and X4



Types of encoding

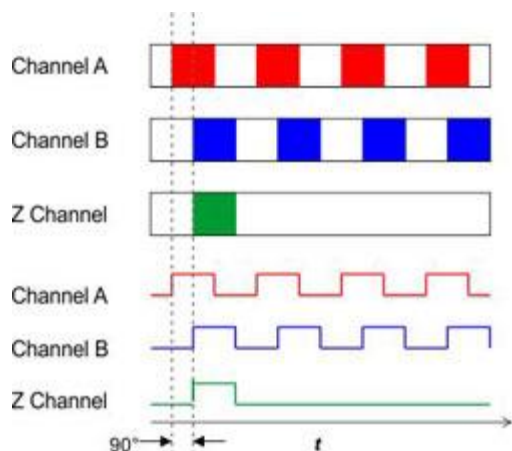


Figure 3: In a quadrature encoder, channel A leads channel B by 90°. Because channel A goes high first, the system can always determine the direction of rotation.

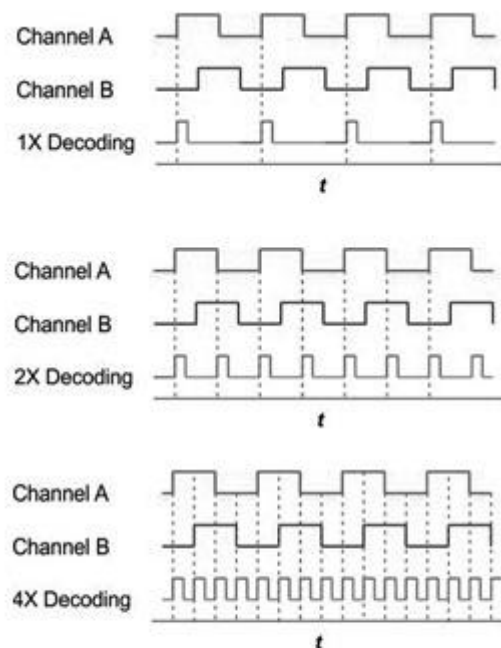


Figure 4: Triggering on the rising edge of channel A alone (top) gives a resolution equal to the PPR of the disk. Triggering on both the rising and falling edge of channel A (middle) doubles the resolution. Triggering on the rising and falling edges of both channels (bottom) increases resolution of the disk PPR by a factor of four.

Converting pulse to position

For Rotational Position

- Amount of Rotation is

$$(\text{°}) = \frac{\text{Edge_Count}}{xN} \cdot 360\text{°}$$

- where N = number of pulses generated by the encoder per shaft revolution

x = encoding type

For Linear Position

- Amount of displacement is

$$(\text{in}) = \frac{\text{Edge_Count}}{xN} \cdot \left(\frac{1}{PPI} \right)$$

- Where PPI = pulses per inch (a parameter specific to each encoder)

Magnetic encoder

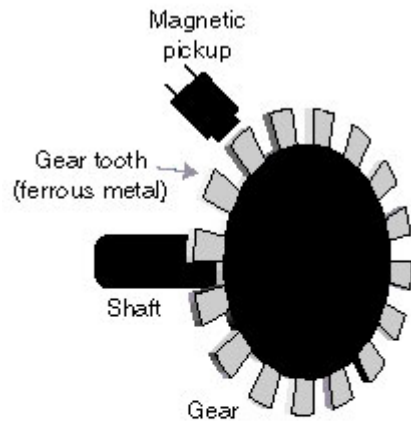


Figure 1: In a simple magnetic encoder, a toothed ferrous wheel perturbs the magnetic field at the sensor; the signal can be converted to position/speed. (Courtesy of National Instruments)

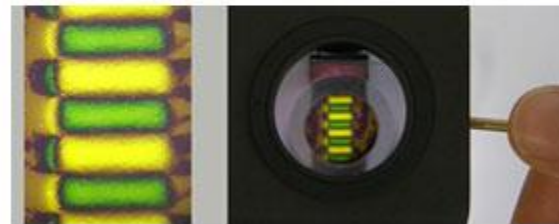
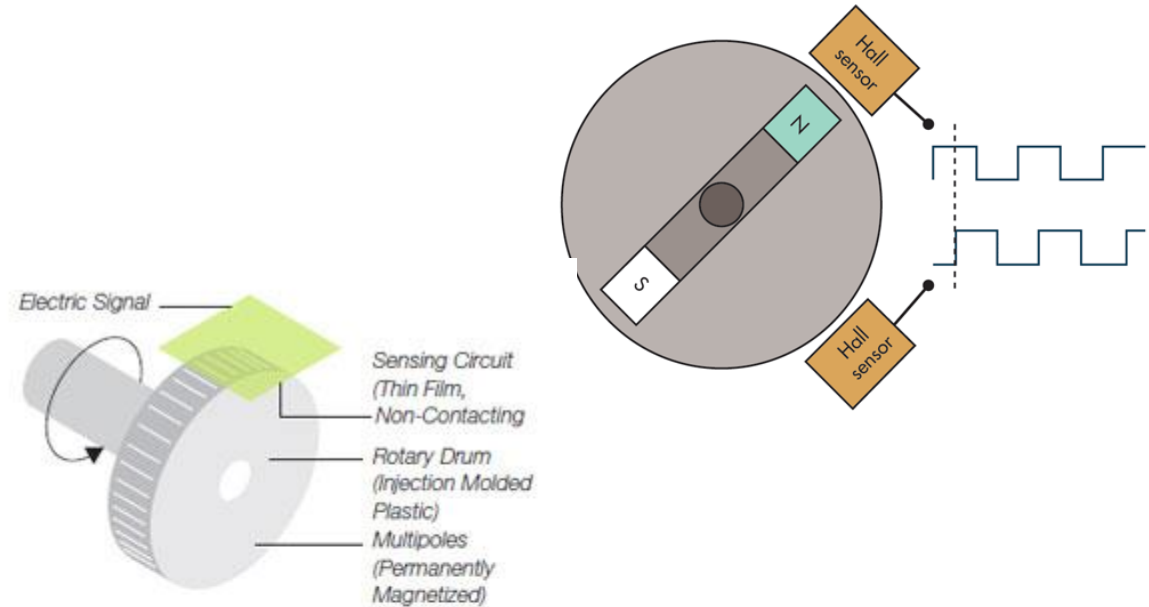
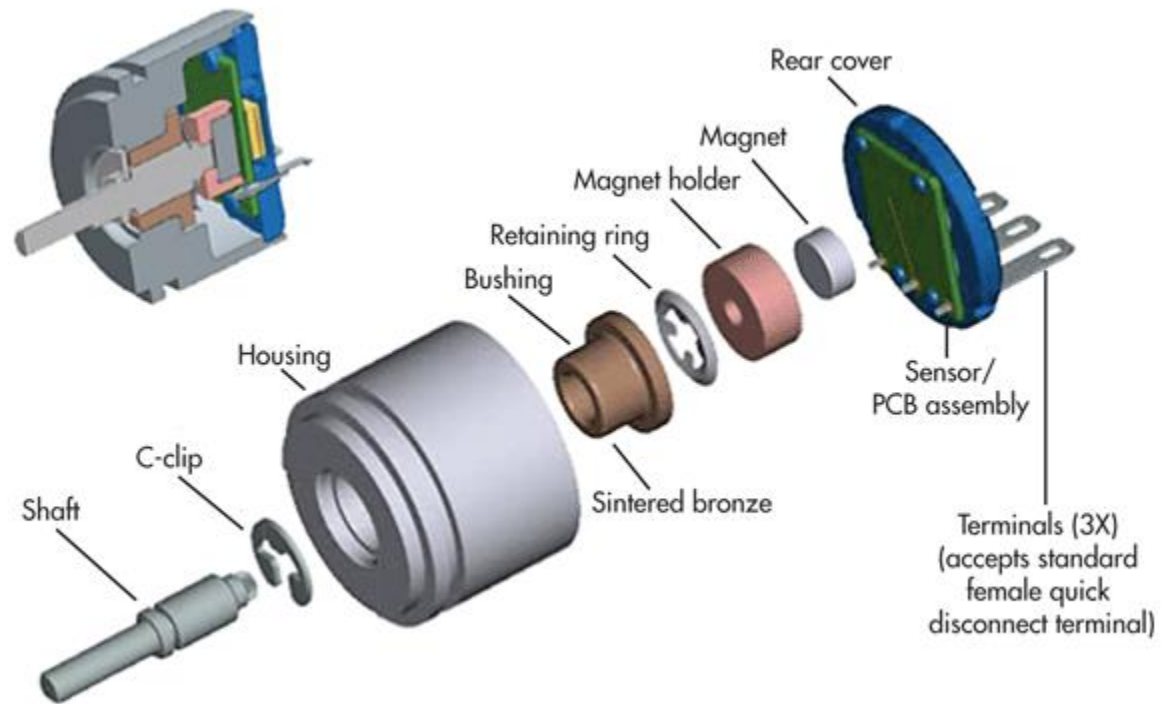


Figure 2: Magnetic encoders feature either a toothed ferromagnetic disk or a drum (top) or a strip (bottom) that features alternating magnetic fields about the circumference. (Courtesy of Dynapar)

Magnetic encoder



Bourns' AMS22S single-turn, magnetic rotary encoder resists side loads and axial forces acting on the shaft.

Eddy current Inductive encoder

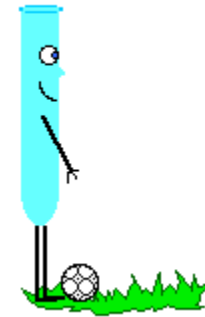
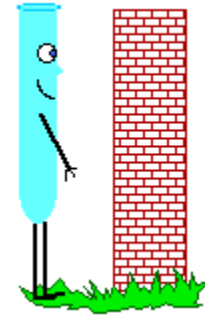


Figure 5: The eddy-current inductive encoder is small enough to fit in a flat motor.



Lecture-6

Accelerometer

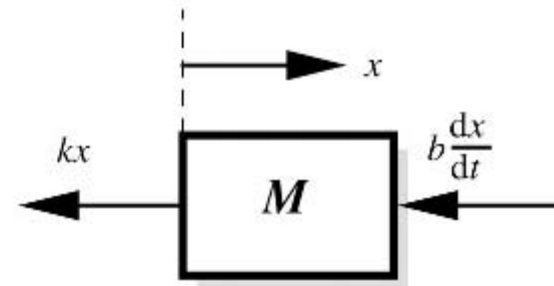
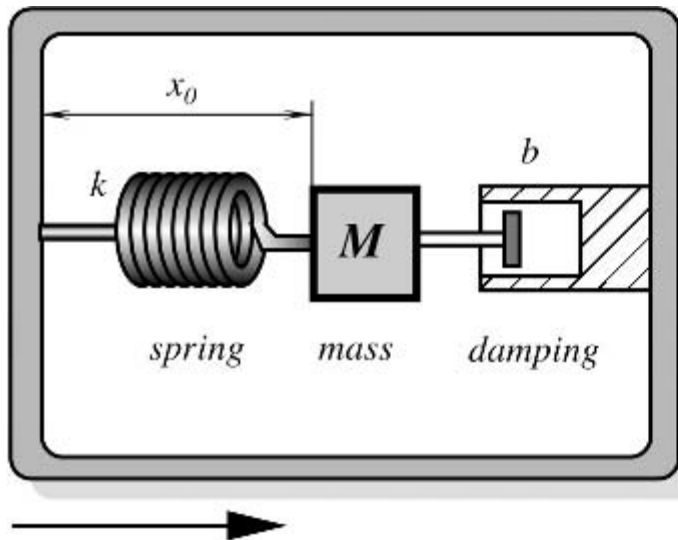


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What is accelerometer?

Accelerometers are inertial transducers that can sense mechanical motion and convert it into an electrical quantity that may be conveniently measured or recorded. The **accelerometer**, either alone or with other electrical components, produces an electrical output signal related to the applied motion.

$$F=ma \quad N(\text{FORCE} = \text{MASS times ACCELERATION})$$



Characteristics of accelerometer

According to newton's second law

$$Mf = -kx - b\frac{dx}{dt},$$

F is the acceleration of the mass relative to the earth

$$f = \frac{d^2x}{dt^2} - \frac{d^2y}{dt^2}.$$

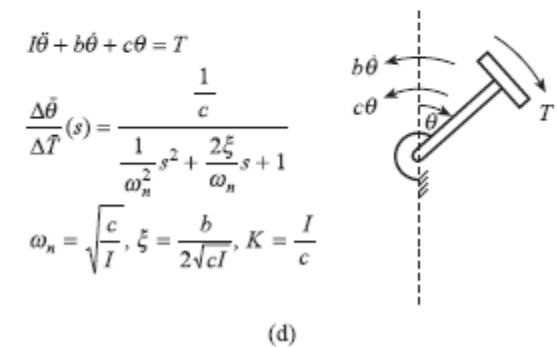
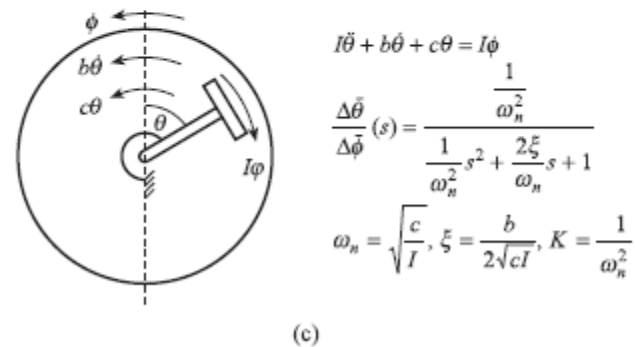
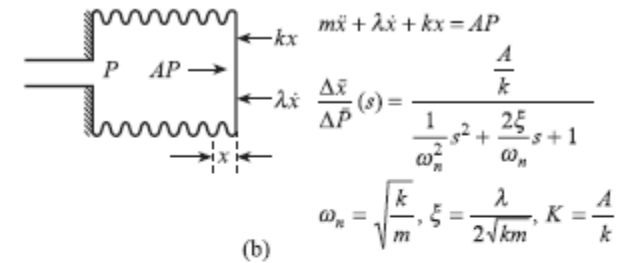
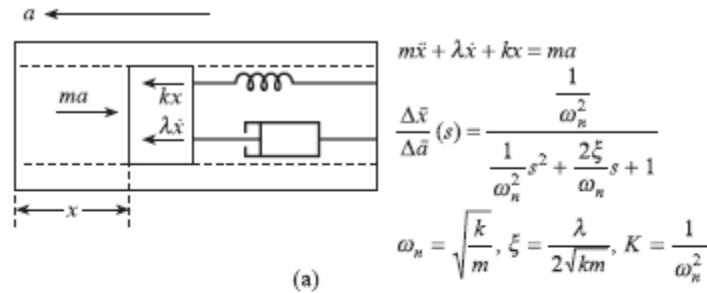
Substituting for f gives the required equation of motion as

$$M\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = M\frac{d^2y}{dt^2}.$$

The differential equation is of a second order, which means that the accelerometer output signal may have an oscillating shape. By selecting an appropriate damping coefficient b, the output signal may be brought to a critically damped state

Dynamic models of elastic elements:

- (a) Linear accelerometer
- (b) Pressure sensor
- (c) Angular accelerometer
- (d) Torque sensor.





Types

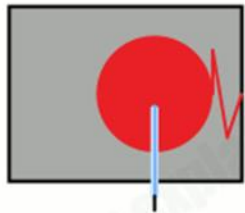
- Capacitive accelerometer
- Piezoresistive accelerometer
- Piezoelectric accelerometer
- Thermal accelerometer
 - Heated plate accelerometer
 - Heated gas accelerometer

For Understanding

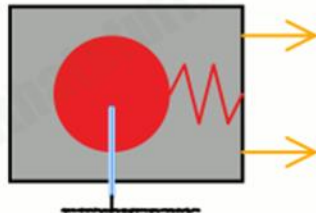
Mechanical accelerometer

www.explainthatstuff.com

2. Mass takes time to move



1. Mass suspended inside box



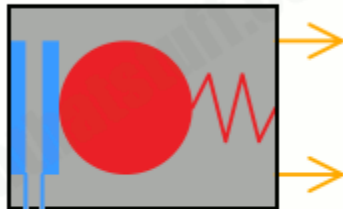
3. Pen leaves trace on paper

www.explainthatstuff.com

Capacitive accelerometer



1. Mass presses capacitor plate

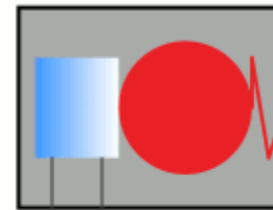


2. Mass closes plates, changing capacitance

Piezoelectric accelerometer

www.explainthatstuff.com

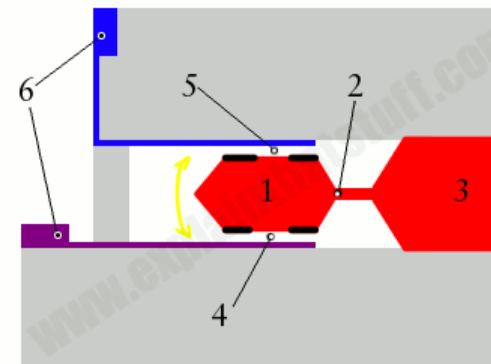
2. Mass squeezes crystal



1. Mass presses against crystal



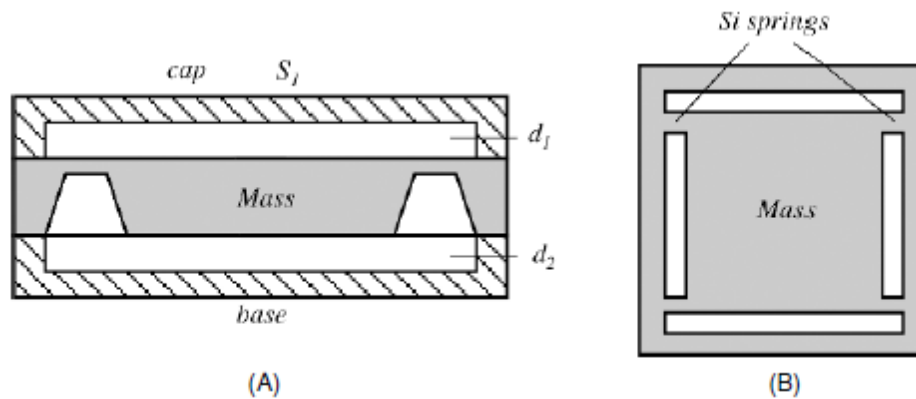
3. Squeezed crystal generates voltage



www.explainthatstuff.com

Capacitive accelerometer

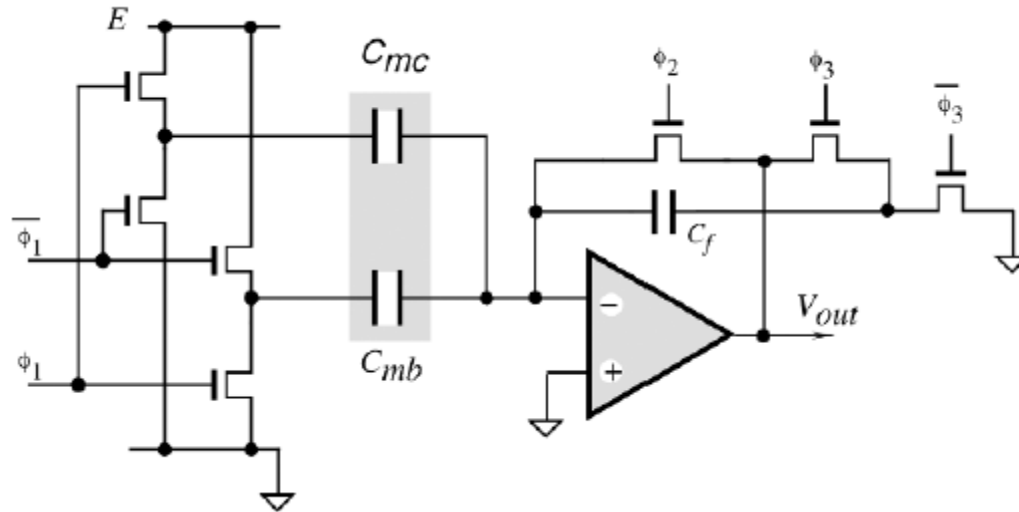
- Displacement sensor is employed to measure acceleration.



Where, value of Δ equal to

$$\Delta = \frac{F_m}{k}$$

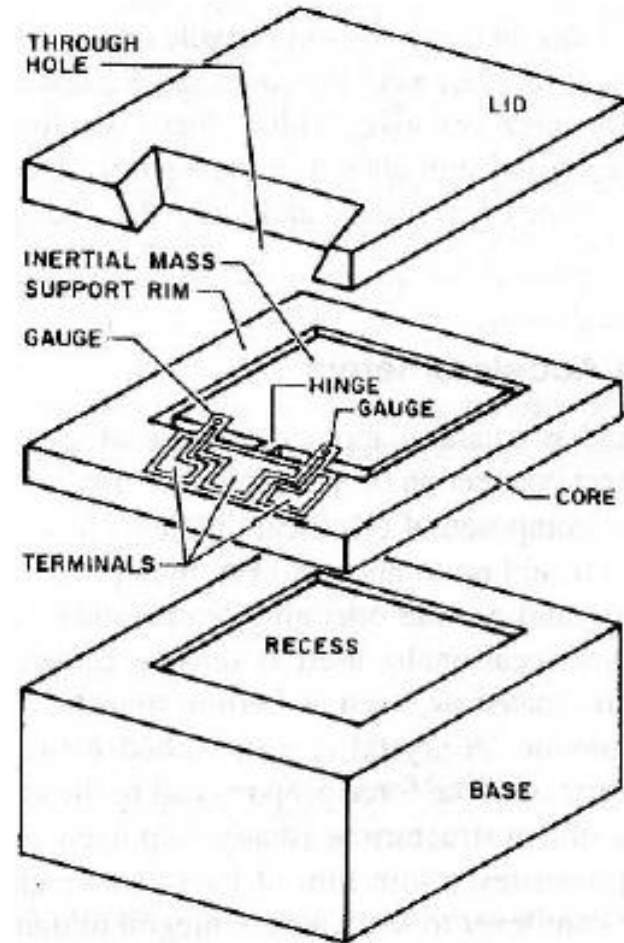
Signal conditioning circuit



$$V_{out} = 2E \frac{C_{mc} - C_{mb}}{C_f}$$

Peizoresistive accelerometer

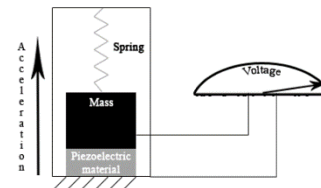
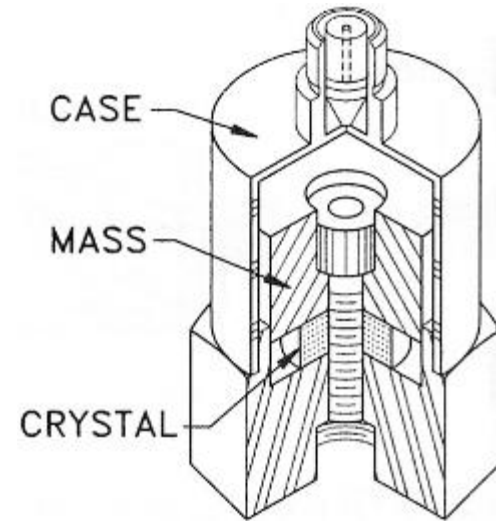
- Incorporated with strain gauge
- The strain can be directly correlated with the magnitude and rate of mass displacement and, subsequently, with an acceleration



Piezoelectric accelerometer

- Directly converting mechanical energy into electrical energy.
- Sensor operation is from 2Khz to 5Khz.
- Piezoelectric signal is amplified by a charge to voltage or current to voltage converter

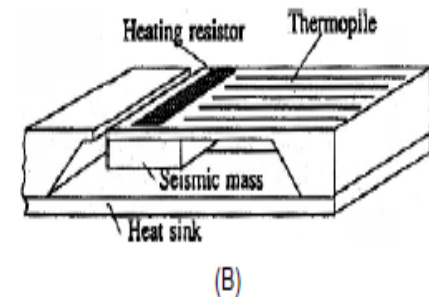
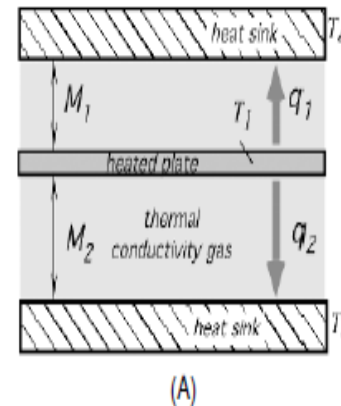
• **Material:** quartz crystals are occasionally used as sensing elements, the most popular are ceramic piezoelectric materials, such as barium titanate, lead zirconite titanate (PZT), and lead metaniobite



Thermal accelerometer

Heated plate accelerometer

- Seismic mass supported by cantilever structure is placed between the sink.
- Upper and lower Sink separated from mass with the distance of M_1 and M_2 respectively.
- Works on fundamental formula of heat transfer.
- Under no acceleration thermal equilibrium is maintained



$$\frac{d^2 T}{dx^2} - \lambda^2 T = 0,$$

$$\lambda = \sqrt{\frac{K_g(M_1 + M_2)}{L_{si} D M_1 M_2}},$$

$$T(x) = \frac{P \sinh(\lambda x)}{W D K_{si} \lambda \cosh(\lambda L)},$$

Heated gas accelerometer(HGA)

- Uses gas as seismic mass
- Heat transfer by forced convection
- Force is produced by acceleration

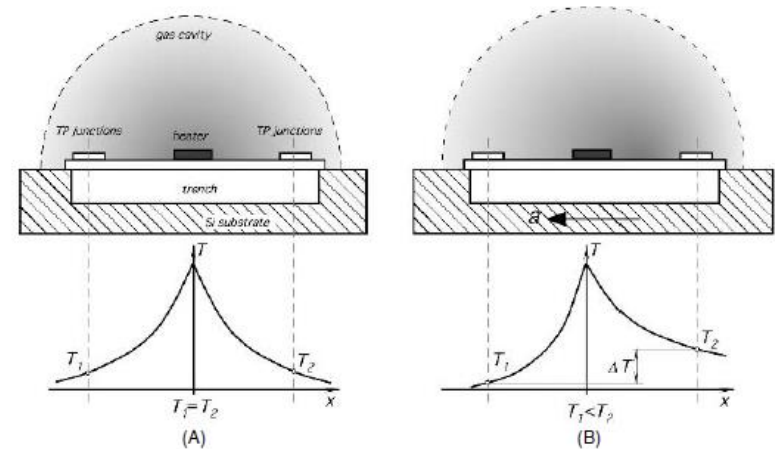


Fig. 8.8. (A) Cross-sectional view of the HGA sensor along the x axis. Heated gas is symmetrical around the heater. (B) Acceleration causes heated-gas shift to the right, resulting in a temperature gradient.

Thermal accelerometer sensitivity to ambient temperature

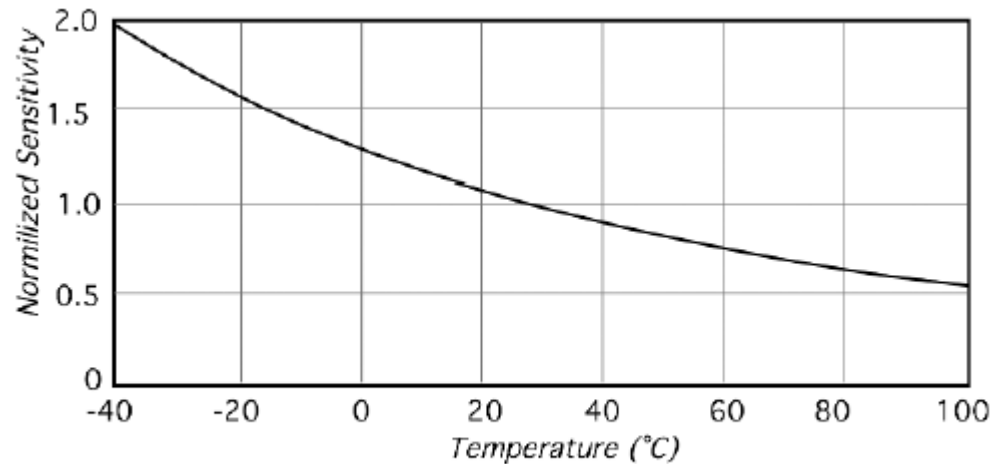
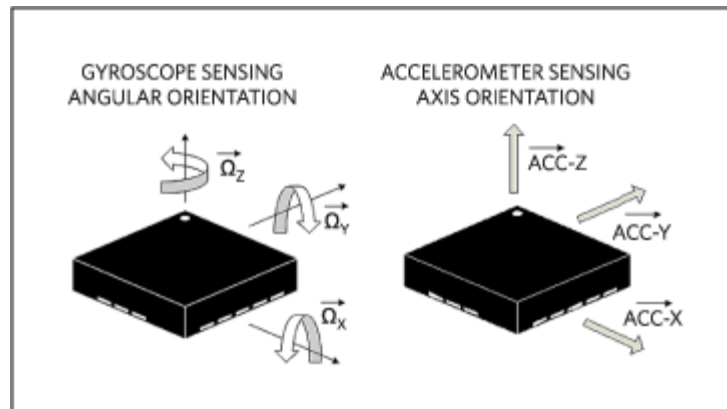


Fig. 8.9. Thermal accelerometer (HGA) sensitivity to ambient temperature.

Difference between accelerometer and gyro



<https://www.maximintegrated.com/en/app-notes/index.mvp/id/5830>



Communication Interface

- Accelerometers will communicate over an analog, digital, or pulse-width modulated connection interface.
- Accelerometers with an **analog interface** show accelerations through varying voltage levels. These values generally fluctuate between ground and the supply voltage level. An [ADC](#) on a microcontroller can then be used to read this value. These are generally less expensive than digital accelerometers.
- Accelerometers with a **digital interface** can either communicate over [SPI](#) or [I²C](#) communication protocols. These tend to have more functionality and be less susceptible to noise than analog accelerometers.
- Accelerometers that output data over **pulse-width modulation** ([PWM](#)) output square waves with a known period, but a duty cycle that varies with changes in acceleration.



How to Select an Accelerometer

- Power
- Communication Interfaces
- Most accelerometers will have a selectable range of forces they can measure. ($\pm 1g$ up to $\pm 250g$)
 - to measure small vibrations on a tabletop, using a small-range accelerometer will provide more detailed data than using a 250g range (which is more suited for rockets).



Range sensor

Range Sensors – RF beacons,
Ultrasonic Ranging, Reflective
beacons, Laser Range Sensor (LIDAR)



RF Beacons

- A beacon is an intentionally conspicuous device designed to attract attention to a specific location.

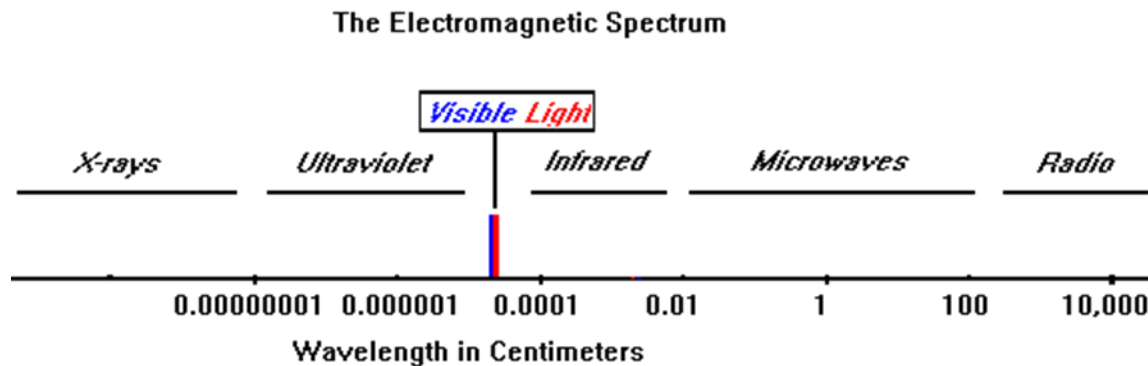


Radio waves

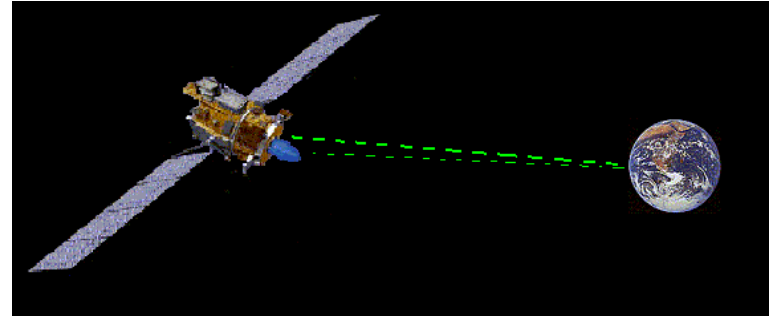
Radio waves are part of a larger group of waves classified all together as *electromagnetic radiation*. This large group of waves is broken down into smaller groups based upon their frequencies and wavelengths. Two examples of electromagnetic radiation (other than radio waves) are:

Light -- which is the group of electromagnetic radiation you can see with your eyes

X-rays -- which are a group from a higher frequency and they are what is used by doctors to see inside of you



How NASA communicating ?

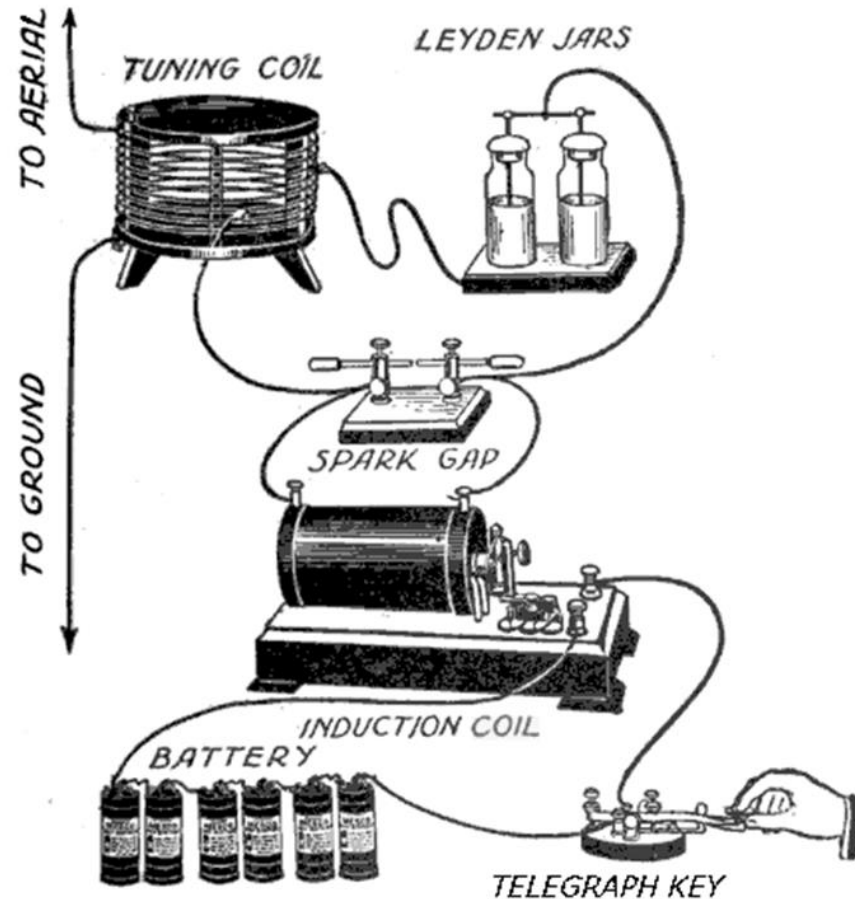


How radio waves produced?

When a direct electrical current is applied to a wire the current flow builds an electromagnetic field around the wire. This field sends a wave outward from the wire. When the current is removed, the field collapses which again sends a wave. If the current is applied and removed over and over for a period of time, a series of waves is propagated at a discrete frequency. If the current changes polarity, or direction repeatedly, that could make waves, too. This phenomenon is the basis of electromagnetivity and basically describes how radio waves are created within transmitters.

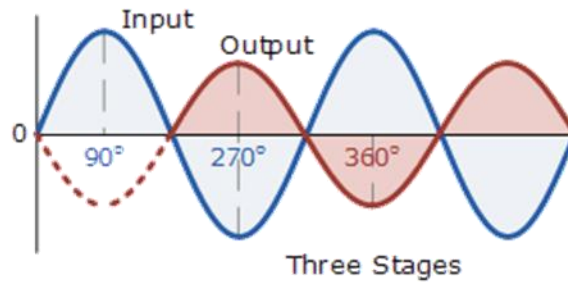
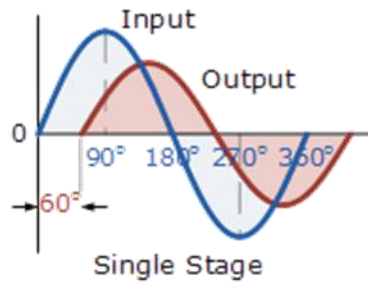
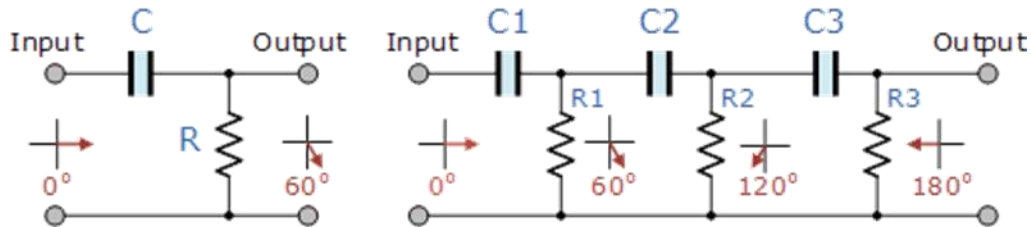
Other kinds of electromagnetic radiation, including radio waves, are made by natural processes such as the nuclear reactions in a star

How telegraph works

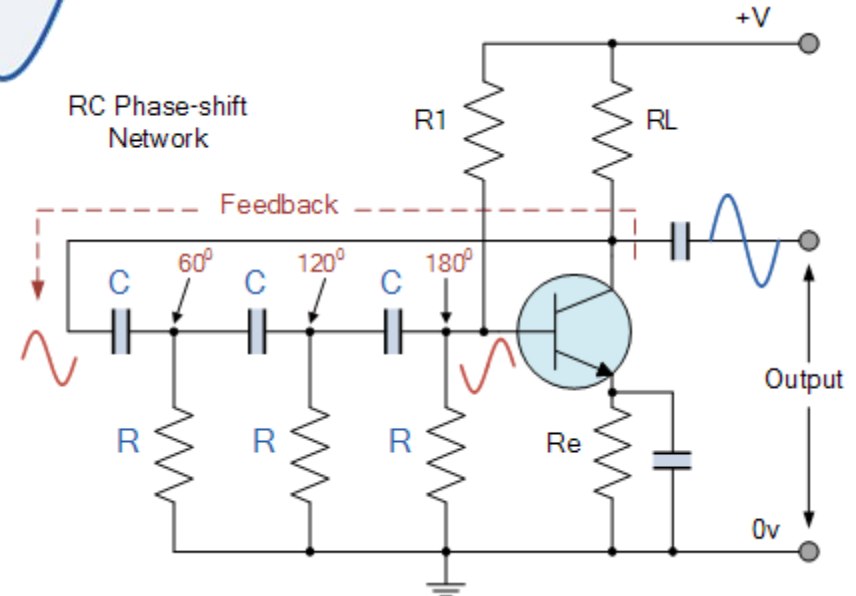


<https://www.quora.com/How-do-you-create-electromagnetic-waves-and-manipulate-its-frequencies>

Smart way of producing RF



Basic RC circuit



How to put data in radio waves

Low Amplitude
Radio Waves

High Amplitude
Radio Waves

High
frequency
radio waves

Low
frequency
radio waves

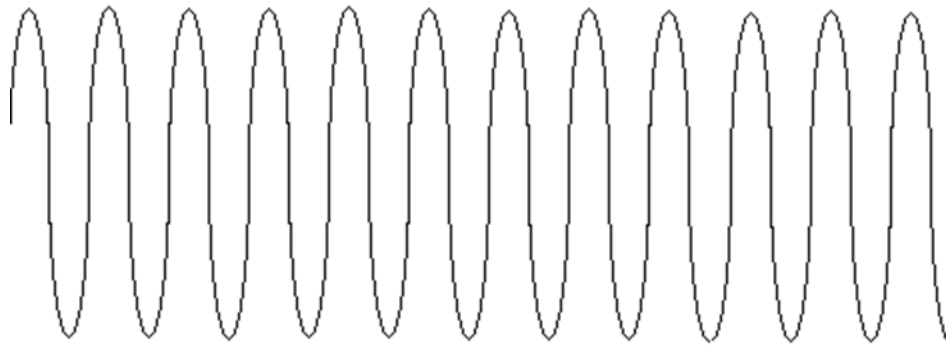
1 0 0 1 1

Information coded
using amplitude
modulation, or AM

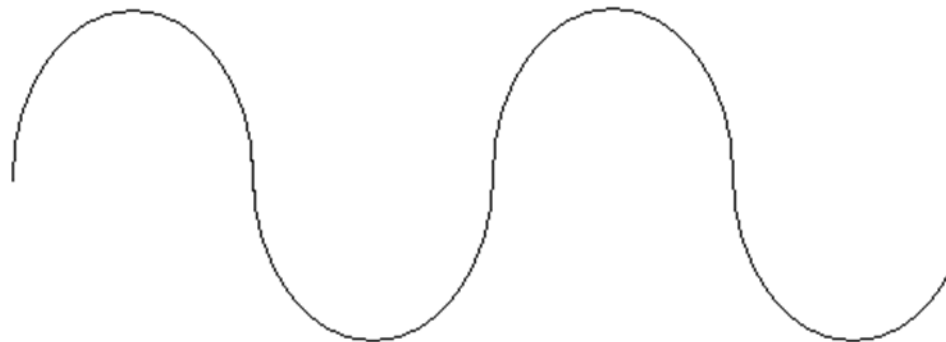
1 0 0 0 1

Information
encoded
using
frequency
modulation
(FM)

What is frequency?



High
frequency
radio waves



Low
frequency
radio waves

What is wavelength?

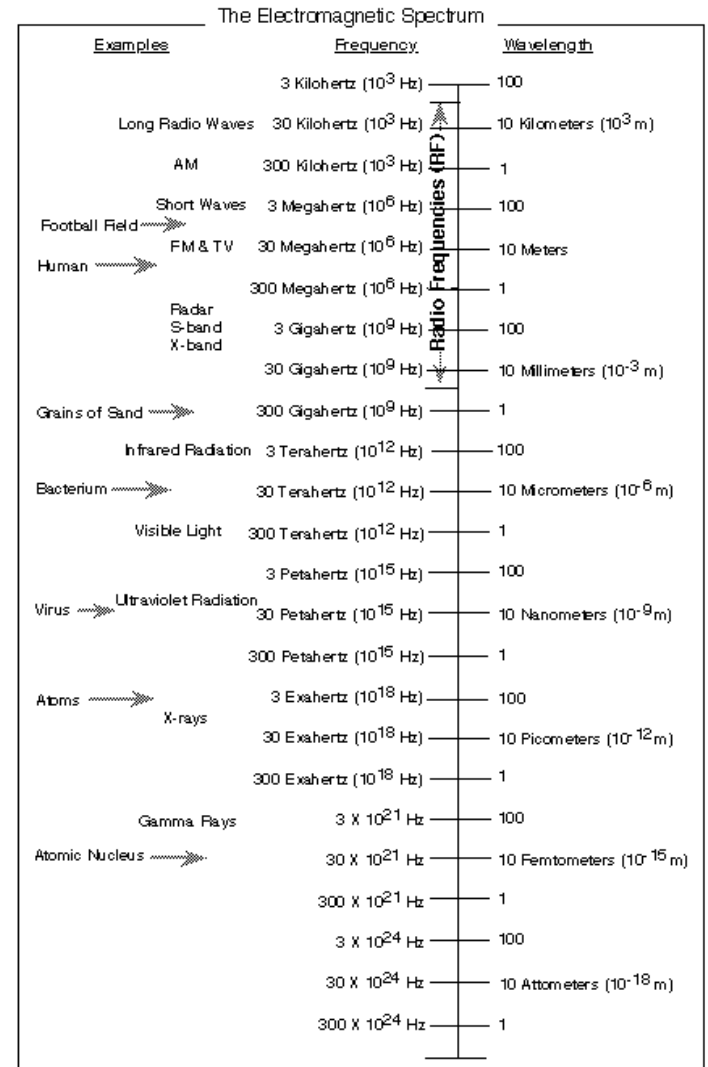
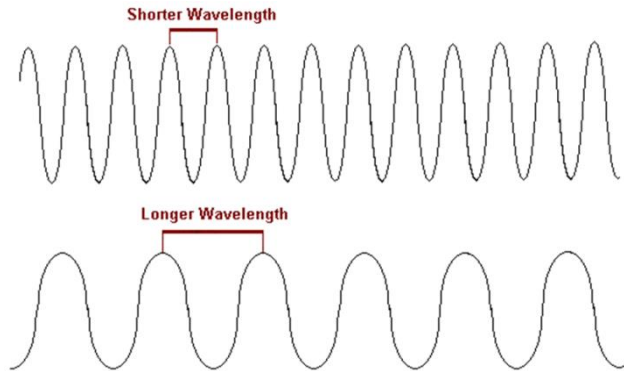


Figure from NASA's Jet Propulsion Laboratory's publication: *Basics of Space Flight Learner's Workbook*. <http://www-b.jpl.nasa.gov/basics/>



**RADAR(radio detection and rang
ing)**



Introduction

- Imagine trying to land a jumbo jet the size of a large building on a short strip of tarmac, in the middle of a city, in the depth of the night, in thick fog.
- If you can't see where you're going, how can you hope to land safely? Airplane pilots get around this difficulty using radar, a way of "seeing" that uses high-frequency radio waves.
- Radar was originally developed to detect enemy aircraft during World War II, but it is now widely used in everything from police speed-detector guns to weather forecasting



History

- **1865** The Scottish physicist **James Clerk Maxwell** developed his electro-magnetic light theory (Description of the electro-magnetic waves and her propagation)
- **1886** The German physicist **Heinrich Rudolf Hertz** discovers the electro-magnetic waves and proves the theory of Maxwell with that.
- **1904** The German high frequency engineer **Christian Hülsmeyer** invents the “Telemobiloskop” to the traffic supervision on the water. He measures the running time of electro-magnetic waves to a metal object (ship) and back. A calculation of the distance is thus possible. This is the first practical radar test. Hülsmeyer registers his invention to the patent in Germany and in the United Kingdom.
- **1917** The French engineer **Lucien Lévy** invents the super-heterodyne receiver. He uses as first the denomination “*Intermediate Frequency*”, and alludes the possibility of double heterodyning.
- **1921** The invention of the Magnetron as an efficient transmitting tube by the US-American physicist **Albert Wallace Hull**
- **1922** The American electrical engineers **Albert H. Taylor** and **Leo C. Young** of the Naval Research Laboratory (USA) locate a wooden ship for the first time.
- **1930** **Lawrence A. Hyland** (also of the Naval Research Laboratory), locates an aircraft for the first time.
- **1931** A ship is equipped with radar. As antennae are used parabolic dishes with horn radiators.
- **1936** The development of the Klystron by the technicians **George F. Metcalf** and **William C. Hahn**, both from General Electric. This will be an important component in radar units as an amplifier or an oscillator tube.
- **1940** Different radar equipments are developed in the USA, Russia, Germany, France and Japan.

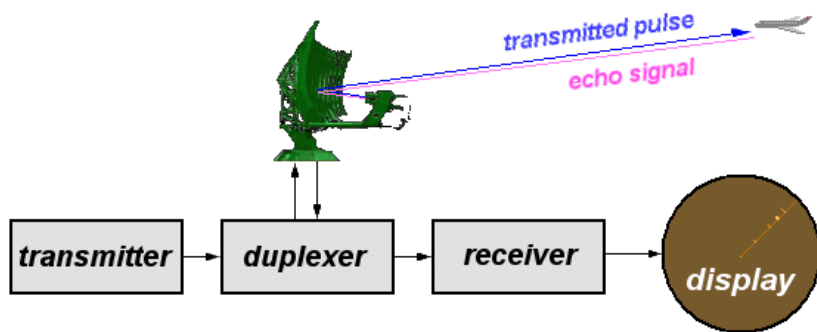
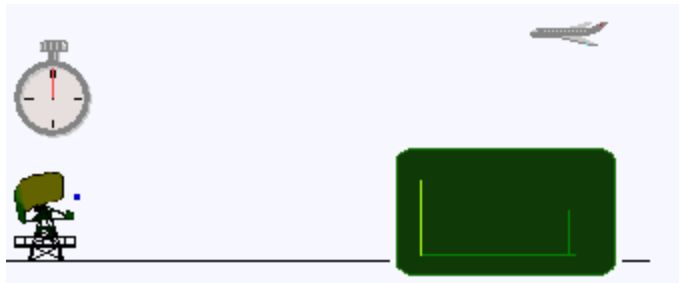


Principle

- The electronic principle on which radar operates is very similar to the principle of sound-wave reflection. If you shout in the direction of a sound-reflecting object (like a rocky canyon or cave), you will hear an echo. If you know the speed of sound in air, you can then estimate the distance and general direction of the object. The time required for an echo to return can be roughly converted to distance if the speed of sound is known.
- Radar uses electromagnetic energy pulses in much the same way, as shown in Figure 3. The radio-frequency (RF) energy is transmitted to and reflected from the reflecting object. A small portion of the reflected energy returns to the radar set. This returned energy is called an ECHO, just as it is in sound terminology. Radar sets use the echo to determine the direction and distance of the reflecting object.

RADAR WORKING

Pulse radar: The round-trip time for the radar pulse to get to the target and return is measured. The distance is proportional to this time.



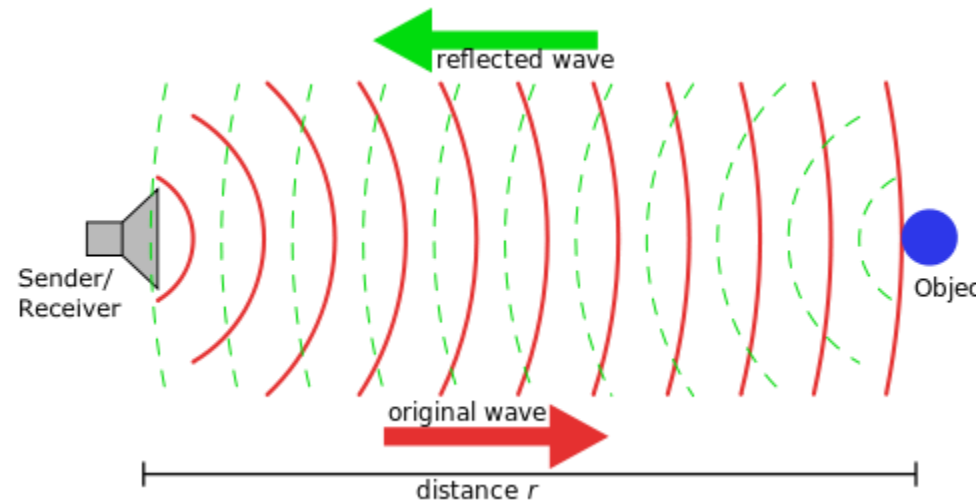
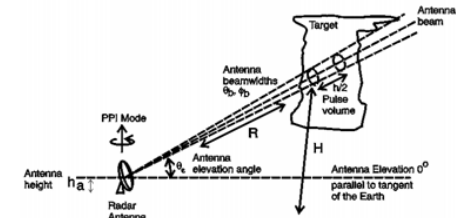
BEAM HEIGHT WITH DISTANCE (AGL)

$$H = \left(\sqrt{r^2 + (k_e a_e)^2} + 2r k_e a_e \sin(\theta_e) \right) - k_e a_e + h_a$$

r : distance k_e : 4/3 (Standard refraction coefficient)

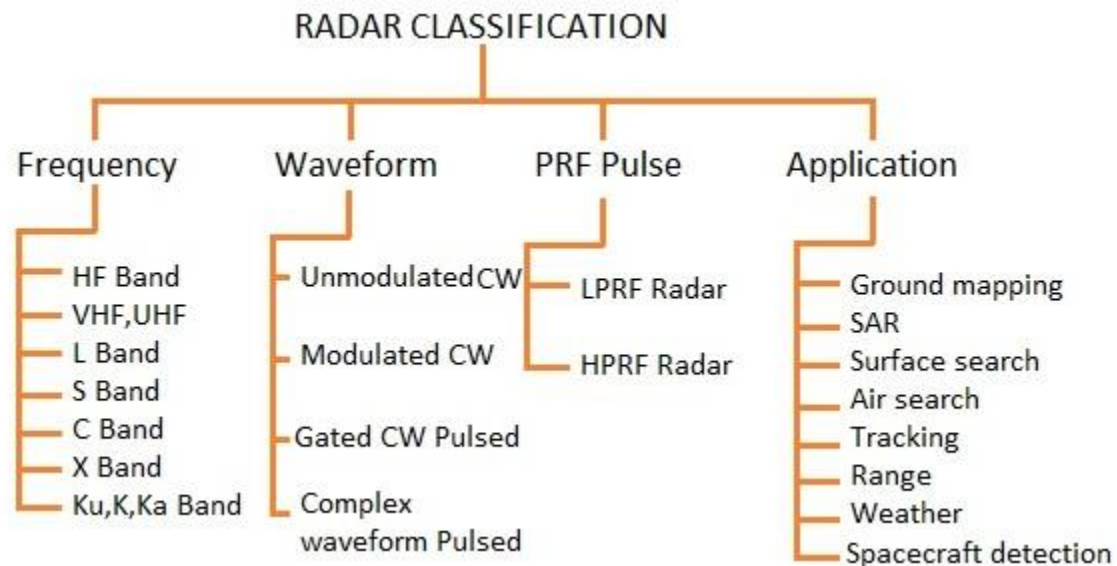
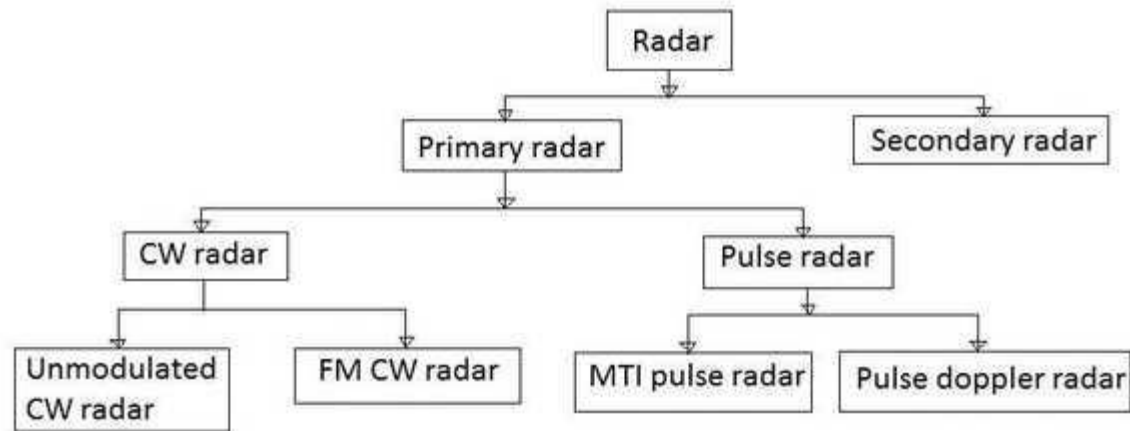
a_e : Earth radius θ_e : Elevation angle

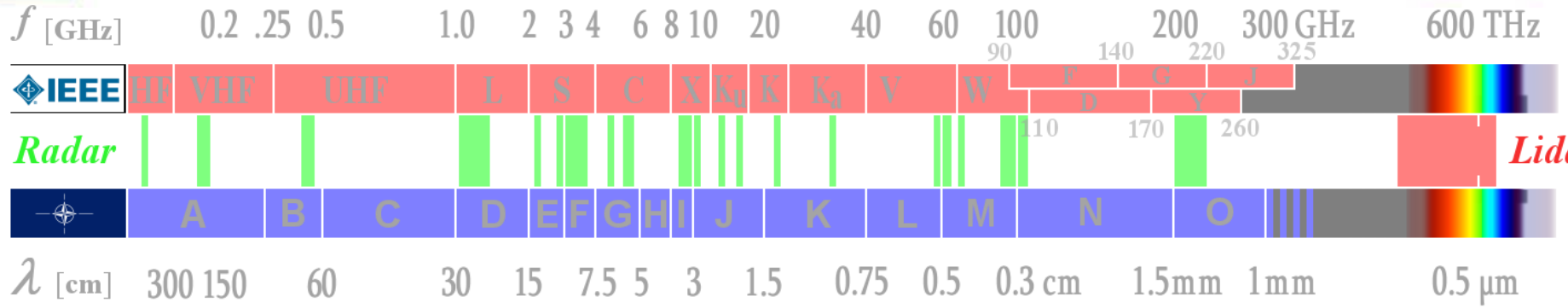
h_a : Height of radar above ground



Continuous wave (CW) radar

Classification





- **A- and B- Band (HF- und VHF- Radar)**
- These radar bands below 300 MHz have a long historical tradition because these frequencies represented the frontier of radio technology at the time during the World War II.
- Today these frequencies are used for early warning radars and so called Over The Horizon (OTH) Radars. Using these lower frequencies it is easier to obtain high-power transmitters. The attenuation of the electromagnetic waves is lower than using higher frequencies.
- On the other hand the accuracy is limited, because a lower frequency requires antennas with very large physical size which determines angle accuracy and angle resolution. These frequency-bands are used by other communications and broadcasting services too, therefore the bandwidth of the radar is limited (at the expense of accuracy and resolution again).
- These frequency bands are currently experiencing a comeback, while the actually used Stealth technologies don't have the desired effect at extremely low frequencies.

- ***C- Band (UHF- Radar)***
- There are some specialized Radar sets developed for this frequency band (300 MHz to 1 GHz). It is a good frequency for the operation of radars for the detection and tracking of satellites and ballistic missiles over a long range. These radars operate for early warning and target acquisition like the surveillance radar for the Medium Extended Air Defense System (MEADS). Some weather radar-applications e.g. wind profilers work with these frequencies because the electromagnetic waves are very low affected by clouds and rain.
- The new technology of Ultrawideband (UWB) Radars uses all frequencies from A- to C-Band. UWB- radars transmit very low pulses in all frequencies simultaneously. They are used for technically material examination and as Ground Penetrating Radar (GPR) for archaeological explorations.

- **D- Band (L-Band Radar)**
- This frequency band (1 to 2 GHz) is preferred for the operation of long-range air-surveillance radars out to 250 NM (≈ 400 km). They transmit pulses with high power, broad bandwidth and an intrapulse modulation often. Due to the curvature of the earth the achievable maximum range is limited for targets flying with low altitude. These objects disappear very fast behind the radar horizon.
- In Air Traffic Management (ATM) long-range surveillance radars like the Air Route Surveillance Radar (ARSR) works in this frequency band. Coupled with a Monopulse Secondary Surveillance Radar (MSSR) they use a relatively large, but slower rotating antenna. The designator L-Band is good as mnemonic rhyme as *large antenna* or *long range*.

- **E/F-Band (S-Band Radar)**
- The atmospheric attenuation is higher than in D-Band. Radar sets need a considerably higher transmitting power than in lower frequency ranges to achieve a good maximum range. As example given the Medium Power Radar (MPR) with a pulse power of up to 20 MW. In this frequency range the influence of weather conditions is higher than in D-band. Therefore a couple of weather radars work in E/F-Band, but more in subtropic and tropic climatic conditions, because here the radar can see beyond a severe storm.
- Special Airport Surveillance Radars (ASR) are used at airports to detect and display the position of aircraft in the terminal area with a medium range up to 50...60 NM (≈ 100 km). An ASR detects aircraft position and weather conditions in the vicinity of civilian and military airfields. The designator S-Band (contrary to L-Band) is good as mnemonic rhyme as smaller antenna or shorter range.



- **G- Band (C-Band Radar)**

- In G- Band there are many mobile military battlefield surveillance, missile-control and ground surveillance radar sets with short or medium range. The size of the antennas provides an excellent accuracy and resolution, but the relatively small-sized antennas don't bother a fast relocation. The influence of bad weather conditions is very high. Therefore air-surveillance radars use an antenna feed with circular polarization often. This frequency band is predetermined for most types of weather radar used to locate precipitation in temperate zone like Europe.

- **I/J- Band (X- and Ku- Band Radars)**

- In this frequency-band (8 to 12 GHz) the relationship between used wave length and size of the antenna is considerably better than in lower frequency-bands. The I/J- Band is a relatively popular radar band for military applications like airborne radars for performing the roles of interceptor, fighter, and attack of enemy fighters and of ground targets. A very small antenna size provides a good performance. Missile guidance systems at I/J- band are of a convenient size and are, therefore, of interest for applications where mobility and light weight are important and very long range is not a major requirement.
- This frequency band is wide used for maritime civil and military navigation radars. Very small and cheap antennas with a high rotation speed are adequate for a fair maximum range and a good accuracy. Slotted waveguide and small patch antennas are used as radar antenna, under a protective radome mostly.
- This frequency band is also popular for spaceborne or airborne imaging radars based on Synthetic Aperture Radar (SAR) both for military electronic intelligence and civil geographic mapping. A special Inverse Synthetic Aperture Radar (ISAR) is in use as a maritime airborne instrument of pollution control.



- **K- Band (K- and Ka- Band Radars)**
- The higher the frequency, the higher is the atmospheric absorption and attenuation of the waves. Otherwise the achievable accuracy and the range resolution rise too. Radar applications in this frequency band provide short range, very high resolution and high data renewing rate. In ATM these radar sets are called Surface Movement Radar (SMR) or (as p. o.) Airport Surface Detection Equipment (ASDE). Using of very short transmitting pulses of a few nanoseconds affords a range resolution, that outline of the aircraft can be seen on the radars display.



- ***V-Band***
- By the molecular dispersion (here this is the influence of the air humidity), this frequency band stay for a high attenuation. Radar applications are limited for a short range of a couple of meters here.

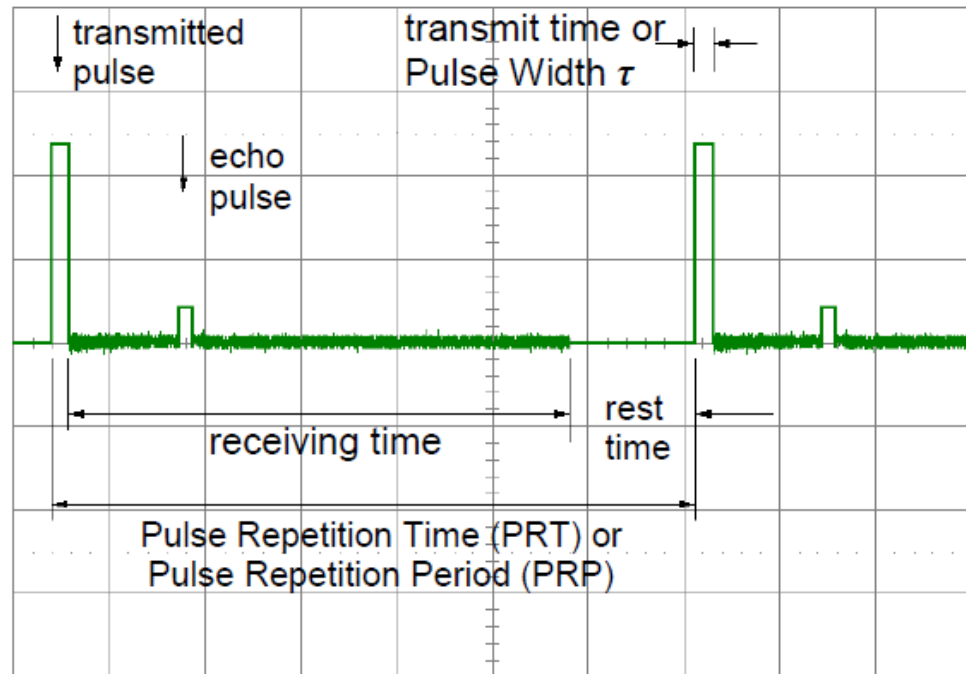


- **W-Band**

- Here are two phenomena visible: a maximum of attenuation at about 75 GHz and a relative minimum at about 96 GHz. Both frequency ranges are in use practically. In automotive engineering small built in radar sets operate at 75...76 GHz for parking assistants, blind spot and brake assists. The high attenuation (here the influence of the oxygen molecules O_2) enhances the immunity to interference of these radar sets.
- There are radar sets operating at 96 to 98 GHz as laboratory equipment's yet. These applications give a preview for a use of radar in extremely higher frequencies as 100 GHz.

Signal Timing

- $PRT = 1/PRF$
- Where, pulse-repetition time (PRT)
- The Pulse Repetition Frequency (PRF)



Ranging

$$R = \frac{t_{\text{delay}} \cdot c_0}{2}$$

R is the slant range

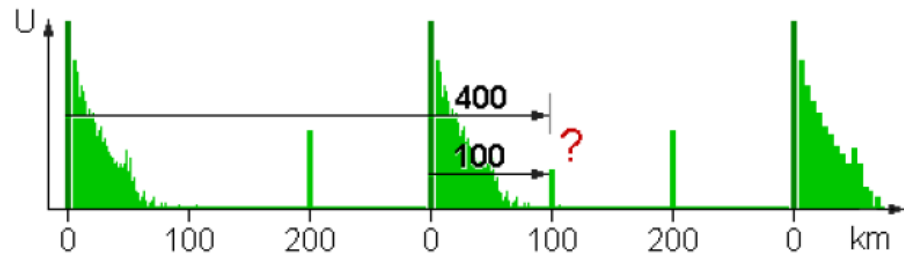
t_{delay} is the time taken for the signal to travel to the target
and return

c_0 is the speed of light (approximately $3 \cdot 10^8$ m/s)

Maximum Unambiguous Range

- The **unambiguous range** of a radar is the maximum **range** at which a target can be located so as to guarantee that the reflected signal/pulse from that target corresponds to the most recent transmitted pulse. The **radar range** is measured by the time delay between pulse transmission and reception
- The maximum unambiguous range for given radar system can be determined by using the formula:

$$R_{unamb} = (PRT - \tau) \cdot c_0 / 2$$



- In this case, the radar will determine the wrong time interval and therefore the wrong range. The measurement process assumes that the pulse is associated with the second transmitted pulse and declares a much reduced range for the target. This is called range ambiguity and occurs where there are strong targets at a range in excess of the pulse repetition time. The pulse repetition time defines a maximum unambiguous range. To increase the value of the unambiguous range, it is necessary to increase the PRT, this means: to reduce the PRF.
- Echo signals arriving after the reception time are placed either into the
 - transmit time where they remain unconsidered since the radar equipment isn't ready to receive during this time, or
 - into the following reception time where they lead to measuring failures (ambiguous returns).

- The pulse repetition time (PRT) of the radar is important when determining the maximum range because target return-times that exceed the PRT of the radar system appear at incorrect locations (ranges) on the radar screen.
- Returns that appear at these incorrect ranges are referred as ambiguous returns or second time around (second-sweep) echoes. The pulse width τ in this equation indicates that the complete echo impulse must be received.



Radar Waveforms Minimum Range

- The minimum detectable range (or blind distance) is also a consideration. When the leading edge of the echo pulse falls inside the transmitting pulse, it is impossible to determine the “round trip time”, which means that the distance cannot be measured. The minimum detectable range R_{min} depends on the transmitters pulse with τ , and the recovery time $t_{recovery}$ of the duplexer.

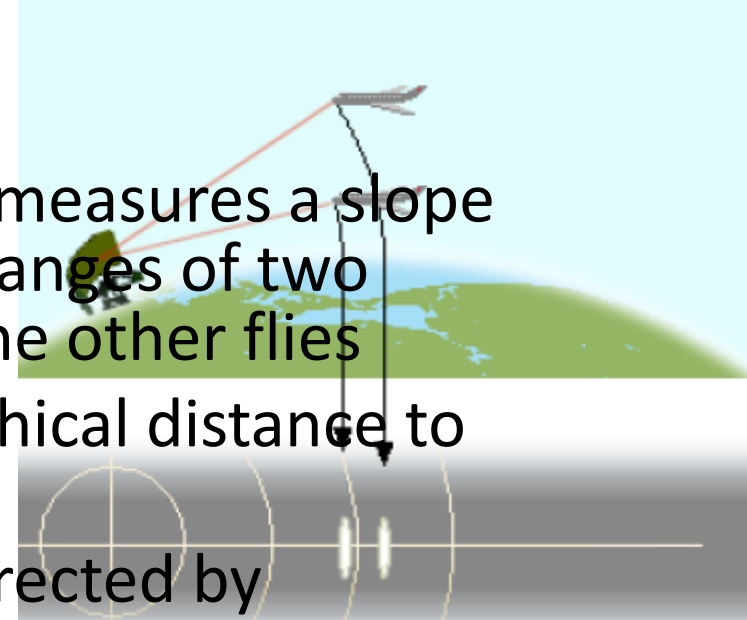
$$R_{min} = \frac{(\tau + t_{recovery}) \cdot c_0}{2}$$

The receiver does not listen during the transmitting pulse, because it needs to be disconnected from the transmitter during transmission to avoid damage. In that case, the echo pulse comes from a very close target. Targets at a range equivalent to the pulse width from the radar are not detected. A typical value of 1 μ s for the pulse width of short range radar corresponds to a minimum range of about 150 m, which is generally acceptable. However, radars with a longer pulse width suffer a relatively large minimum range, notably pulse compression radars, which can use pulse lengths of the order of tens or even hundreds of microseconds. Typical pulse width τ for

- ❑ Air-defense radar: up to 800 μ s ($R_{min} = 120$ km !)
- ❑ ATC air surveillance radar: 1.5 μ s ($R_{min} = 250$ m)
- ❑ surface movement radar: 100 ns ($R_{min} = 25$ m)

Slant Range

- Cause by the fact that the radar unit measures a slope range, the radar measures different ranges of two airplanes, which exactly one above the other flies
- (therefore having the same topographical distance to the radar unit exactly).
- This false measurement could be corrected by
- software, or module in modern radar sets with digital signal processing. These software modules then must also especially be adapted on the geographical coordinates of the radar site, however. The calculation is very complicated and also requires some weather data to the correction.

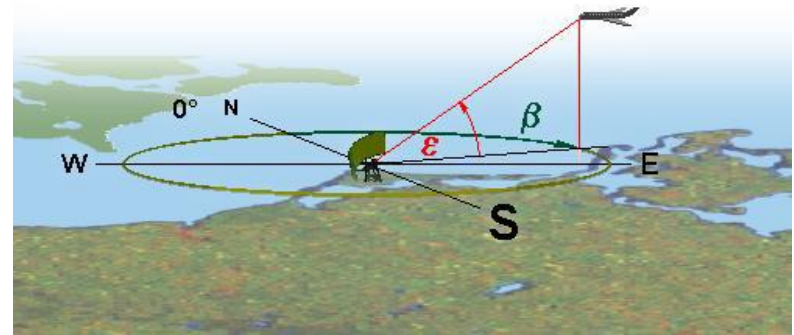


Direction determination: Bearing

- The direction to the target is determined by the directivity of the antenna. Directivity, sometimes known as the directive gain, is the ability of the antenna to concentrate the transmitted energy in a particular direction. An antenna with high directivity is also called a directive antenna.
- By measuring the direction in which the antenna is pointing when the echo is received, both the azimuth and elevation angles from the radar to the object or target can be determined. The accuracy of angular measurement is determined by the directivity, which is a function of the size of the antenna.

Elevation Angle

- The elevation angle is the angle between the horizontal plane and the line of sight, measured in the vertical plane. The Greek letter Epsilon (ϵ) describes the elevation angle. The elevation angle is positive above the horizon (0° elevation angle), but negative below the horizon.



Height

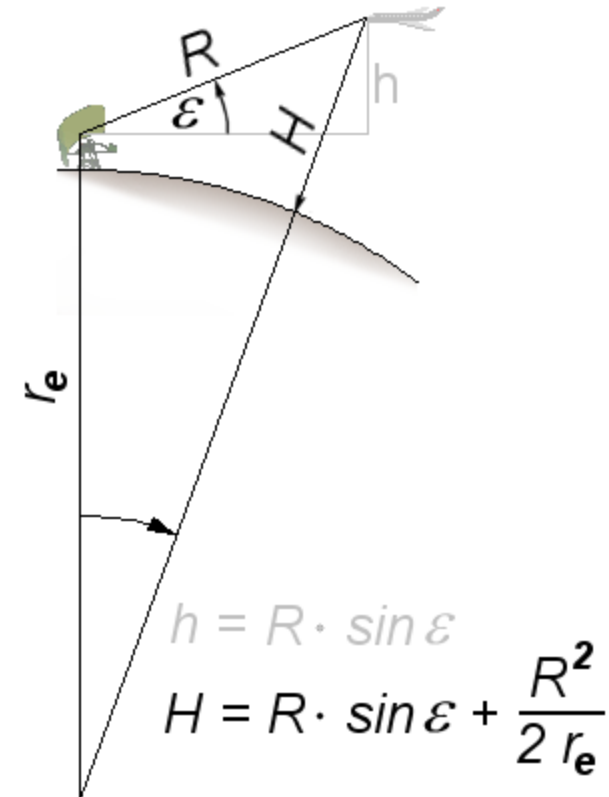
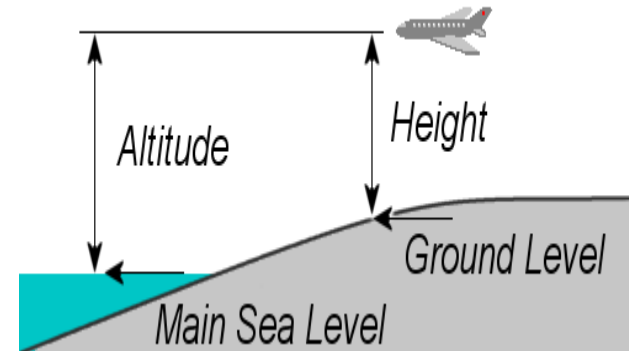
- The height of a target over the earth's surface is called height or altitude. This is denominated by the letter H (like: Height) in the following formulae and figures. True altitude is the actual airplane distance above mean sea level. The altitude can be calculated with the values of distance R and elevation angle ϵ , as shown in figure , where:

R = aims slant range

ϵ = measured elevation angle

r_e = earth's equivalent radius (about 6370 km)

- In practice, however, the propagation of electromagnetic waves is also subject to refraction, this means, the transmitted beam of the radar unit isn't a straight side of this triangle but this side is also bent and it depends on:
 - the transmitted wavelength,
 - the barometric pressure,
 - the air temperature and
 - the atmospheric humidity.
- Therefore all these equations are an approximation only.





Accuracy

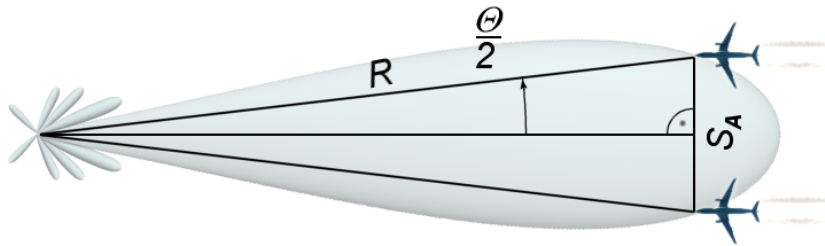
- Accuracy is the degree of conformance between the estimated or measured position and/or the velocity of a platform at a given time and its true position or velocity. Radio navigation performance accuracy is usually presented as a statistical measure of system error. Accuracy should not be confused with radar resolution.



Radar Resolution

- The target resolution of radar is its ability to distinguish between targets that are very close in either range or bearing. Weapons-control radar, which requires great precision, should be able to distinguish between targets that are only yards apart. Search radar is usually less precise and only distinguishes between targets that are hundreds of yards or even miles apart. Radar resolution is usually divided into two categories; range resolution and angular (bearing) resolution.

Angular Resolution and Range resolution



$$S_A \leq 2R \cdot \sin \frac{\Theta}{2} \quad [m]$$

Θ = antenna beam width (Theta)

S_A = angular resolution as a distance between the two targets

R = slant range aims - antenna

$$S_r = \frac{c_0 \cdot \tau}{2} \quad [m]$$

c_0 = speed of light

τ = transmitters pulse width

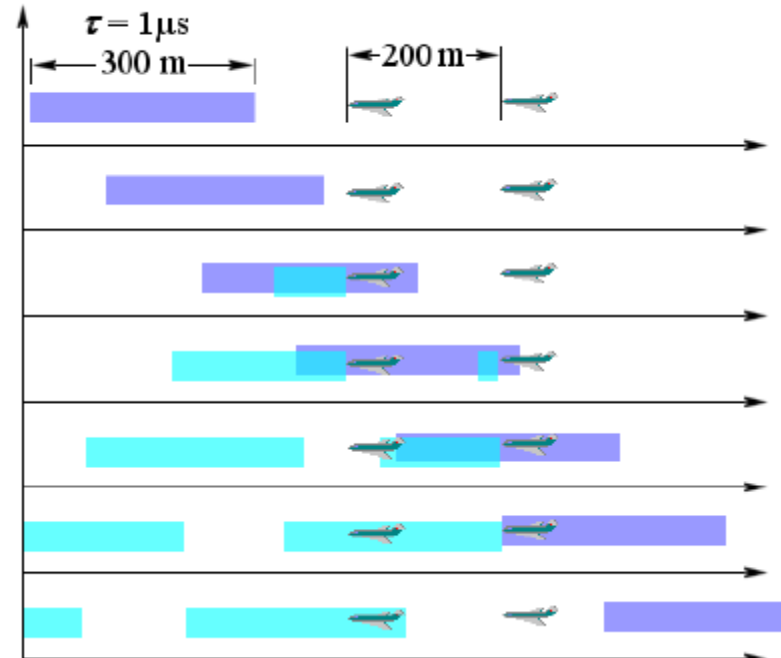
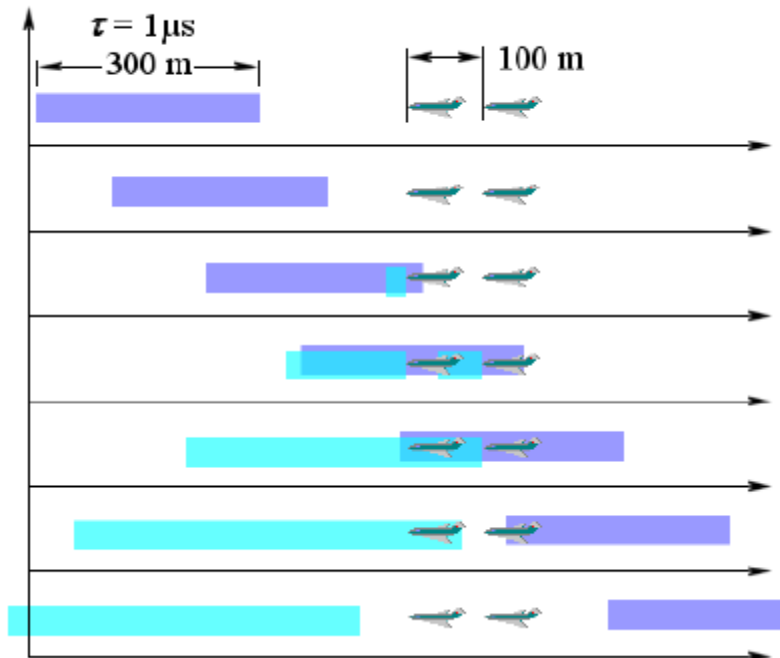
S_r = range resolution as a distance between the two targets



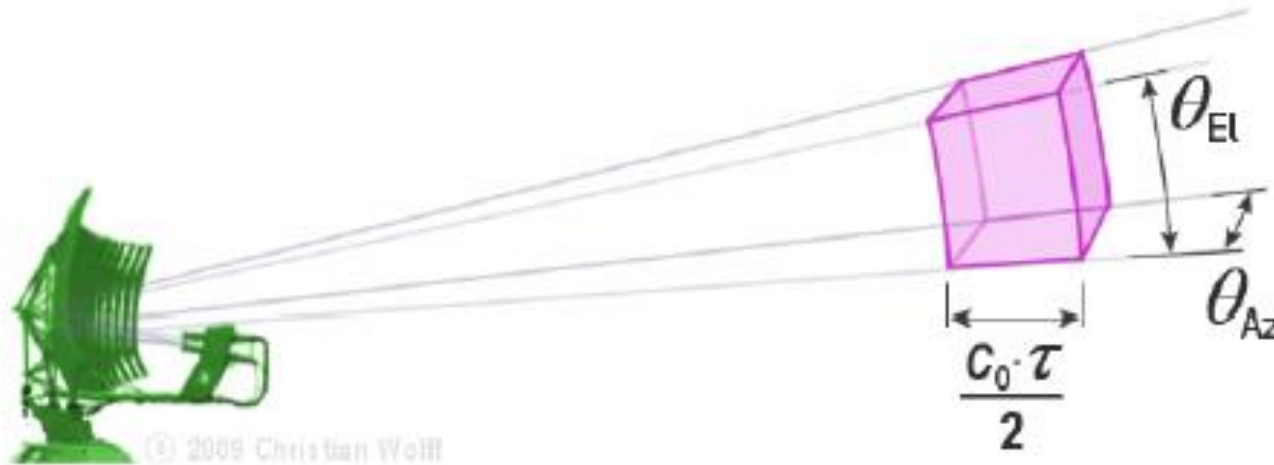
Range resolution

- Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges. The degree of range resolution depends on the width of the transmitted pulse, the types and sizes of targets, and the efficiency of the receiver and indicator.
- Pulse width is the primary factor in range resolution. A well-designed radar system, with all other factors at maximum efficiency, should be able to distinguish targets separated by one-half the pulse width time.

Range Resolution



Resolution cell



Radar scan types

Electronic

Agile Beam

Conical

TWS

Steady

Lobe Switching

Circular

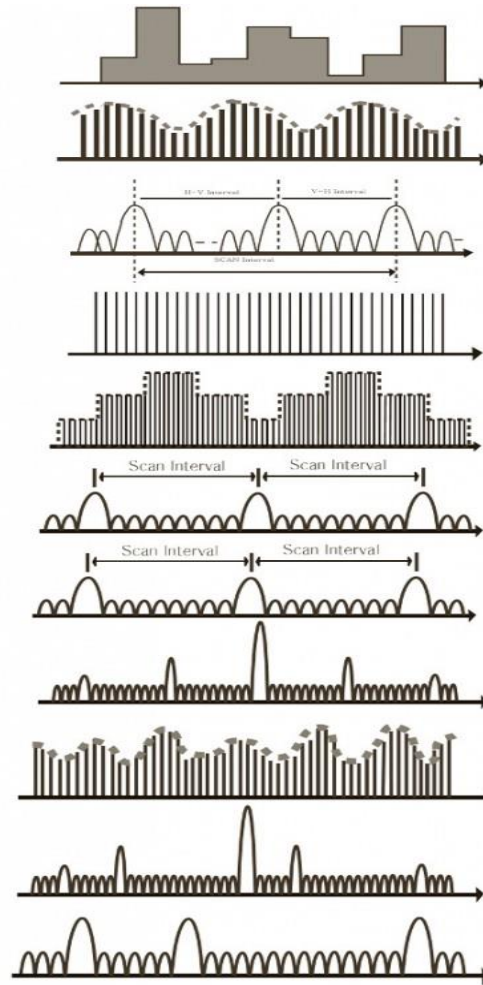
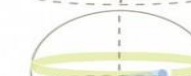
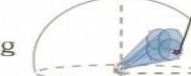
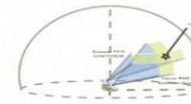
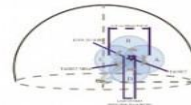
Sector

Helical

Spiral

Raster

Bi-Directional



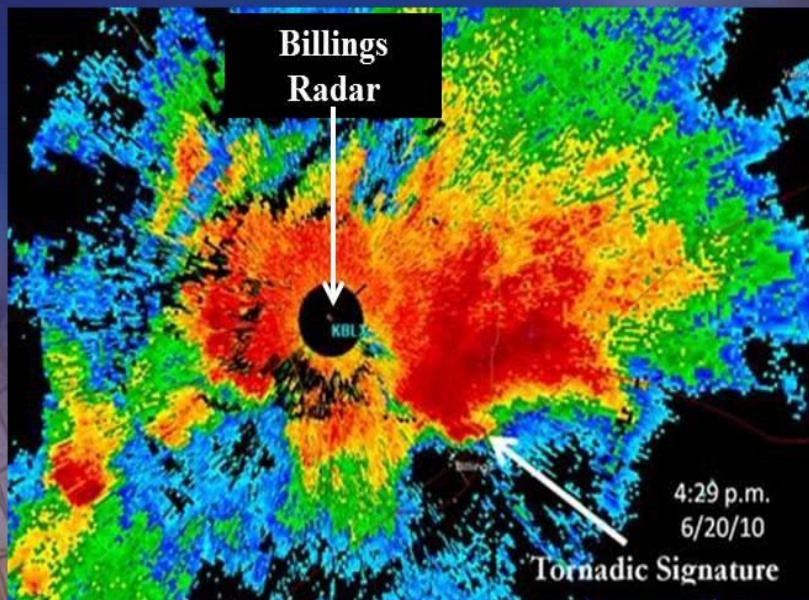
Application



Weather Radar: Reflectivity Explained

Areas of heavy precipitation (with big raindrops or snowflakes) return a lot of power to the radar and appear as brighter colors in reflectivity images

*In this reflectivity image, the heaviest precipitation is in **red**, while lighter precipitation is in **blue** and **green***

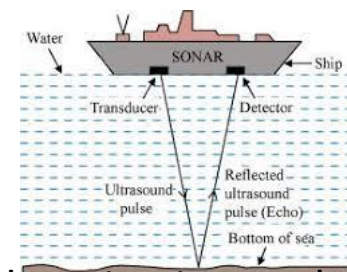
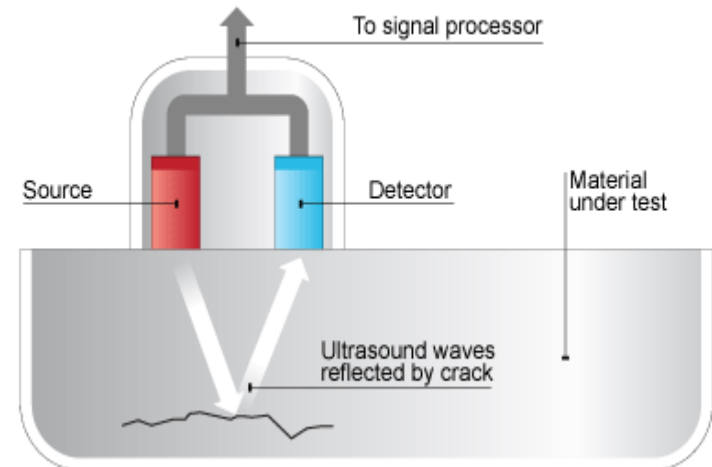
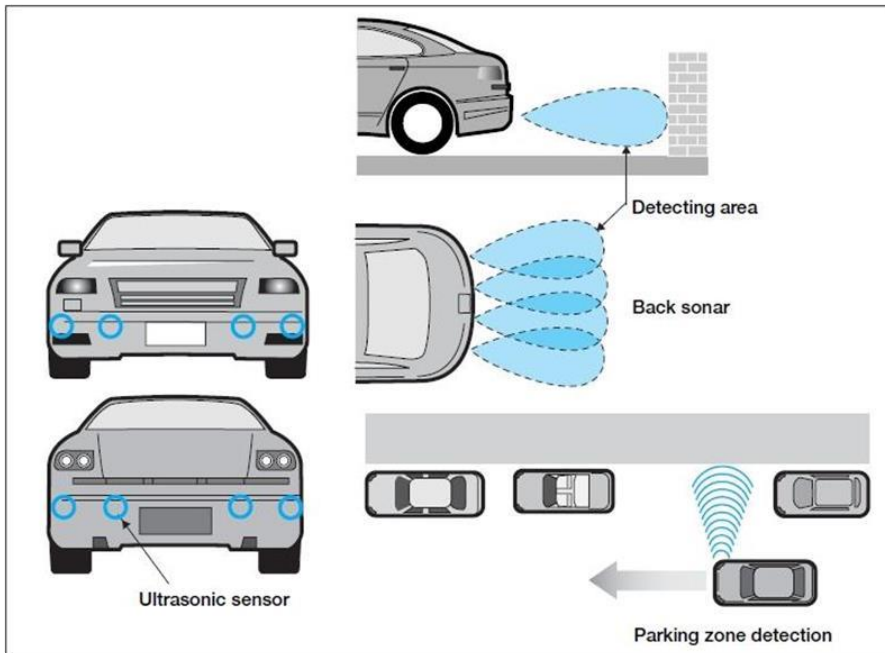
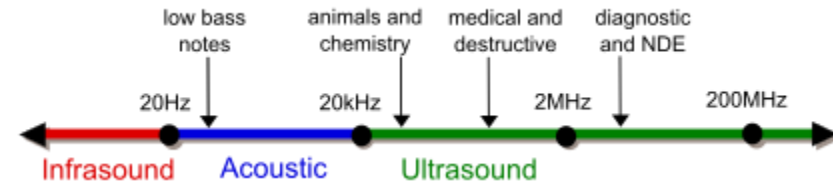
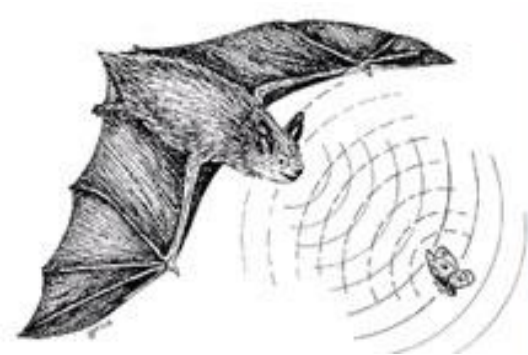




Different between radio waves and sound waves

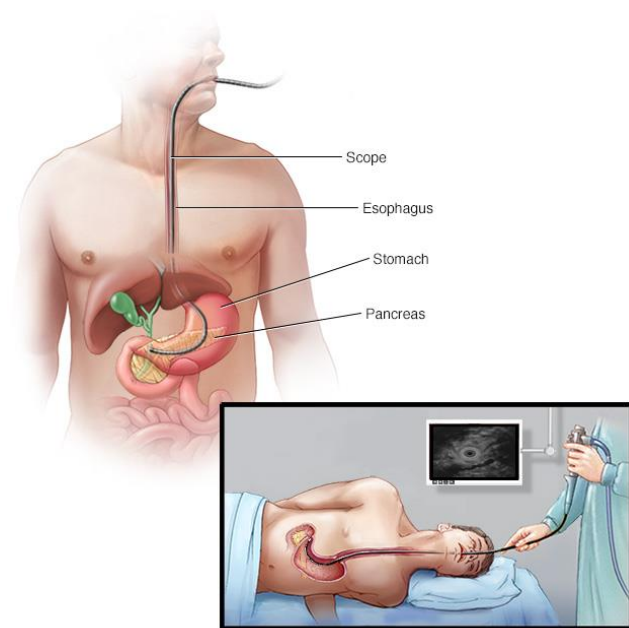
- The differences between radio waves and sound waves are as follows: Radio waves can be considered to be made of waves as well as particles. Sound is only a wave. It does not show particle nature.
 - Radio waves are electromagnetic waves while sound waves are mechanical waves.
 - Radio waves are transverse while sound waves are longitudinal.
 - Radio waves can travel in vacuum. Sound waves require a material medium to travel, and hence, cannot travel in vacuum.
 - The speed of radio waves in a medium is constant. The speed of sound waves can change.
 - In sound waves, the particles of the medium actually oscillate. In a radio wave, the electric and magnetic vectors oscillate.
 - Radio waves can be polarized, but sound waves cannot.
 - Radio waves travel much faster than sound waves. The speed of radio waves is a physical constant. Its value is exactly 299,792,458 metres per second in vacuum. The speed of sound is 343 metres per second in dry air at 20°C.
 - Radio waves are electromagnetic radiation and travel at the speed of light.
- Sound waves are mechanical vibrations in a medium.

Ultrasonic sensor



SOund Navigation And Ranging

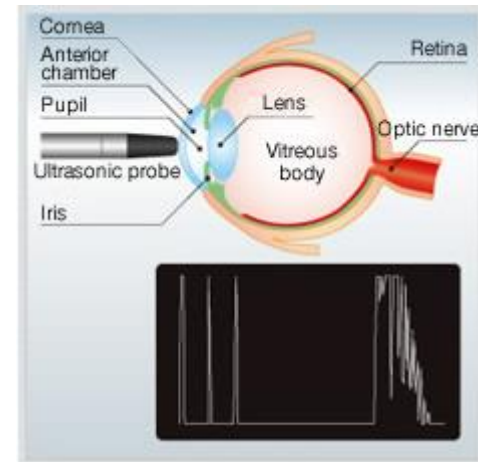
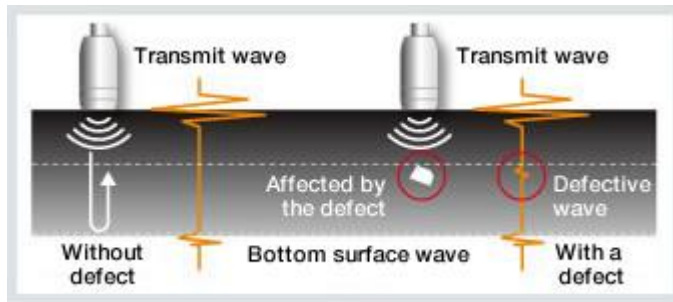
Medical application



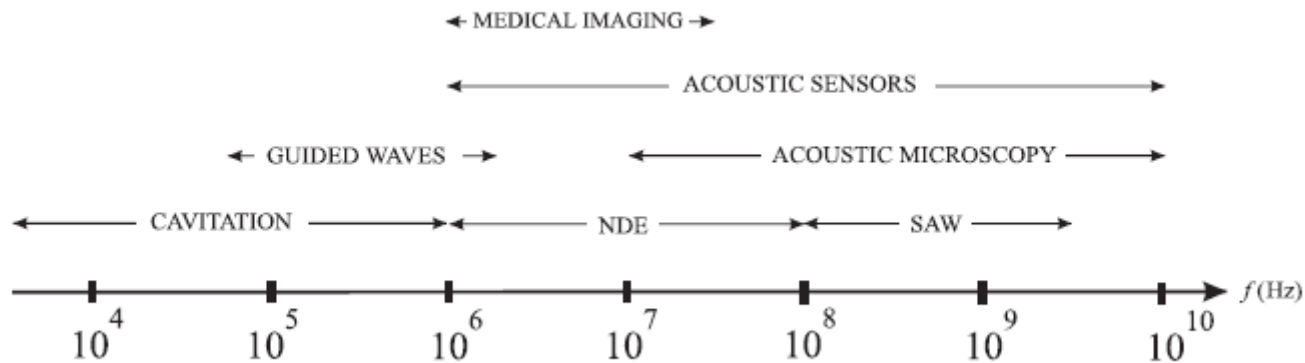
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During an endoscopic ultrasound of the pancreas, your doctor inserts a thin, flexible tube (endoscope) down your throat and into your abdomen. An ultrasound device at the end of the tube emits sound waves that generate images of your pancreas and nearby tissues.

Metal or concrete flaw measurement



Frequency range for different applications

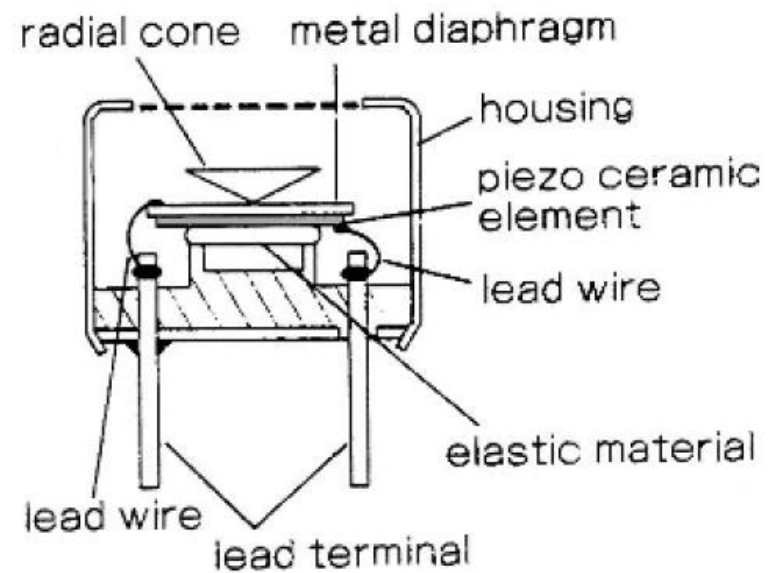
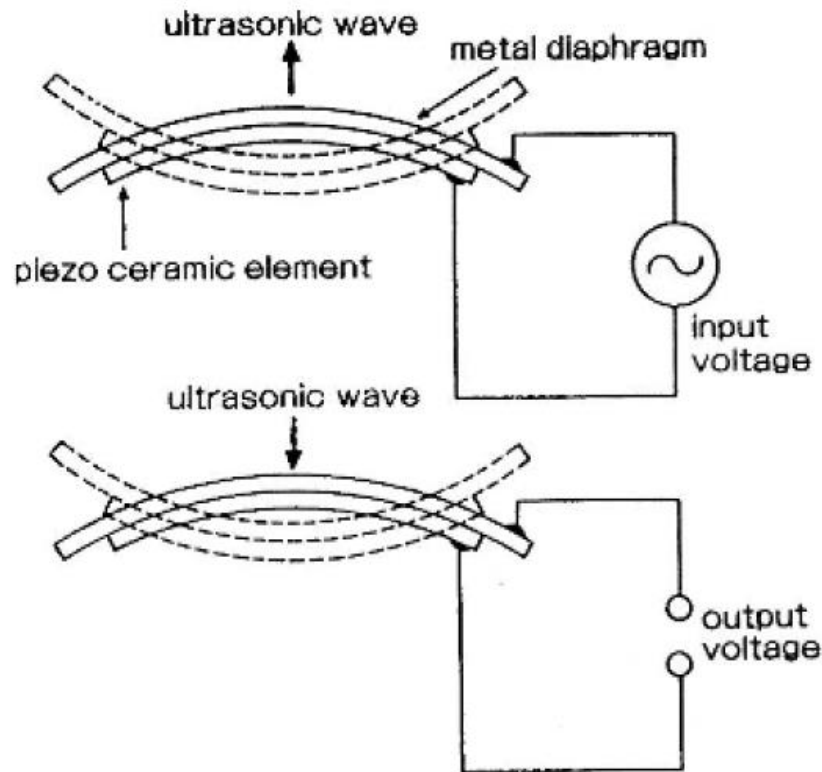




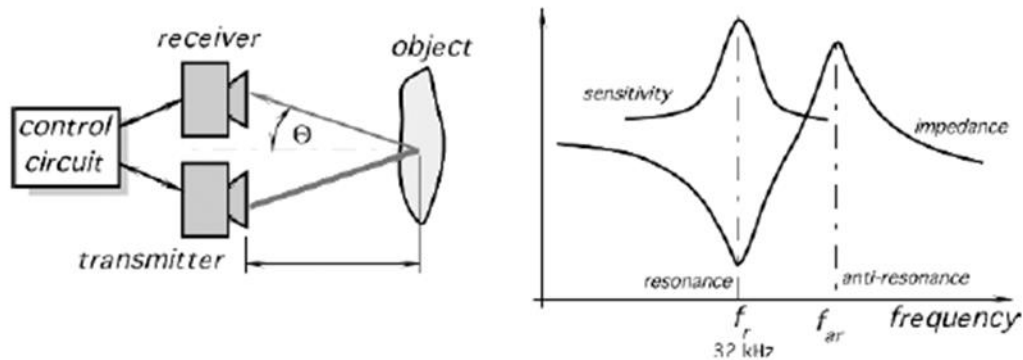
Working

- An ultrasonic transducer is a device that converts AC into ultrasound, as well as the reverse, sound into AC. In ultrasonics, the term typically refers to piezoelectric transducers or capacitive transducers.
- Piezoelectric crystals change size and shape when a voltage is applied; AC voltage makes them oscillate at the same frequency and produce ultrasonic sound.
- Capacitive transducers use electrostatic fields between a conductive diaphragm and a backing plate

Ultrasonic sensor



Distance calculation

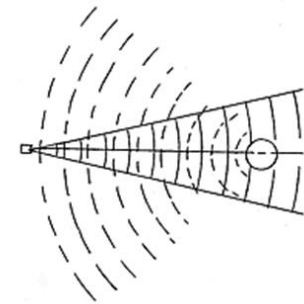


$$L_0 = \frac{vt \cos \Theta}{2},$$

Where,

V-speed

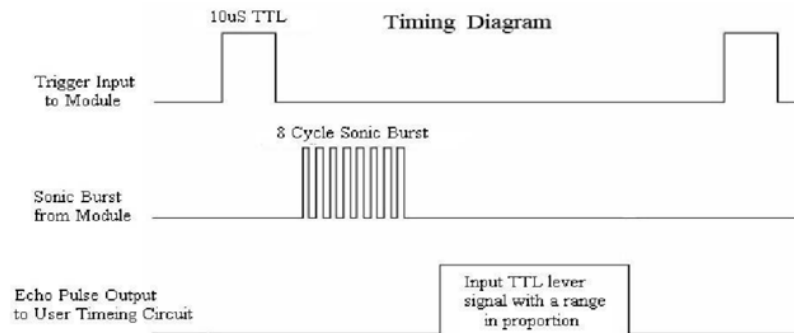
t-time taken by waves to travel between object and back to receiver



A small sphere used as a target partially reflects the beam and reradiates an echo.

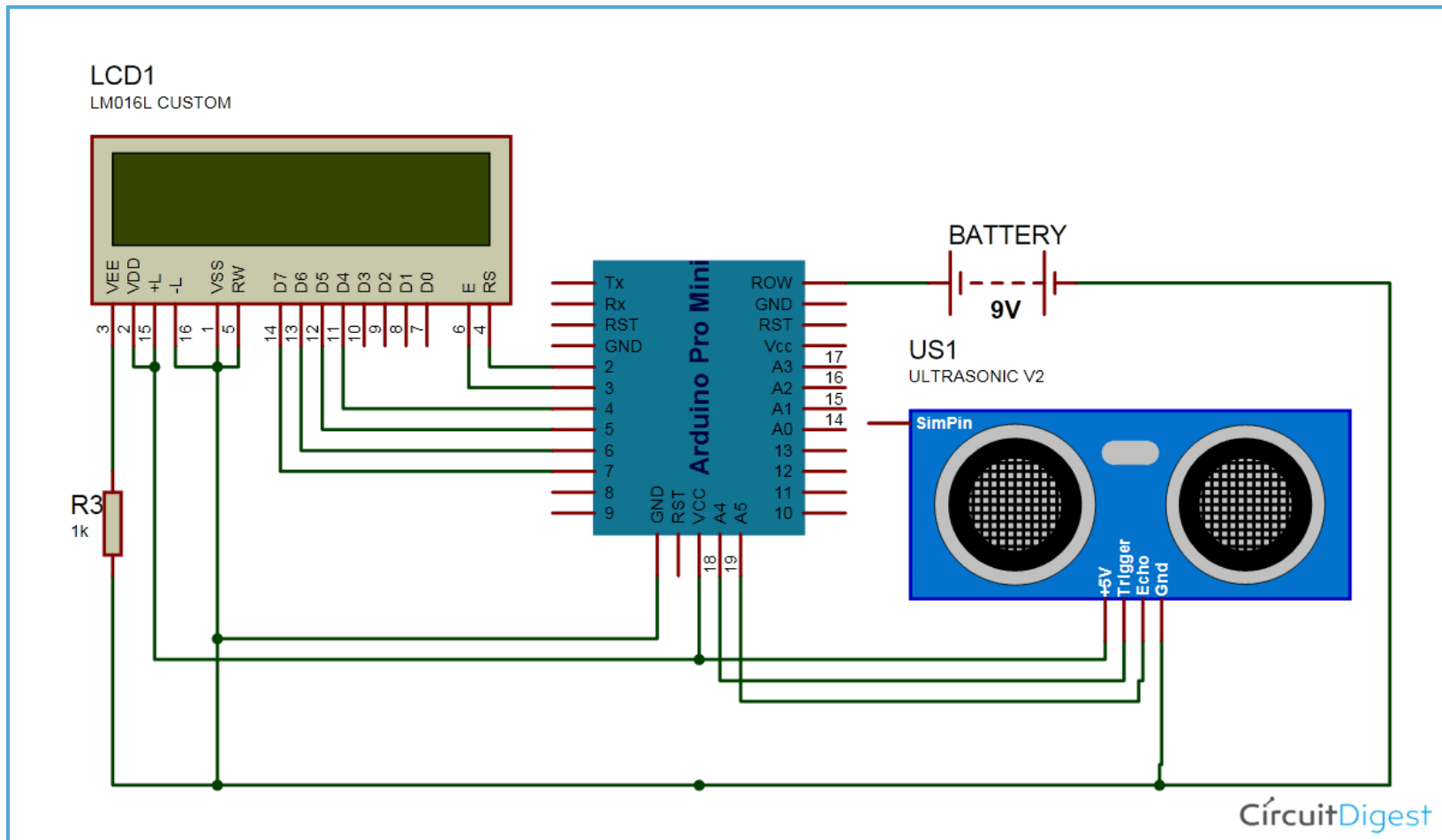
Distance calculation

- Distance= (time x speed)/2.
- **Distance= (Time x Speed of Sound in Air (340 m/s))/2**

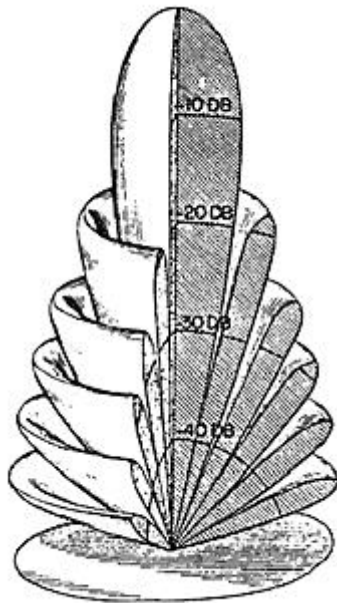


<http://circuitdigest.com/microcontroller-projects/arduino-ultrasonic-sensor-based-distance-measurement>

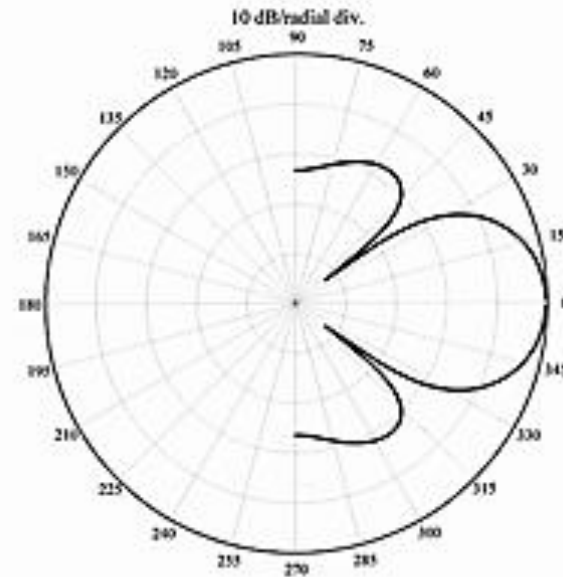
Connecting ultrasonic sensor with controller



3D & 2D representation of beam pattern



A transducer with a circular radiating surface whose diameter is large in comparison to a wavelength produces a narrow, conical beam pattern with multiple secondary lobes



This 2D polar plot represents the beam pattern of a transducer with a circular disc radiator mounted in an infinite baffle, where $D/\lambda = 2$.



Targets' Effect on Echoes

- For reradiating targets, the echo level as a function of target range is:
- $EL_f(R) = SPL(R_0) - 40 \log(R/R_0) - 2\alpha_f R + TS$

where:

$EL_f(R)$ = echo level at frequency f

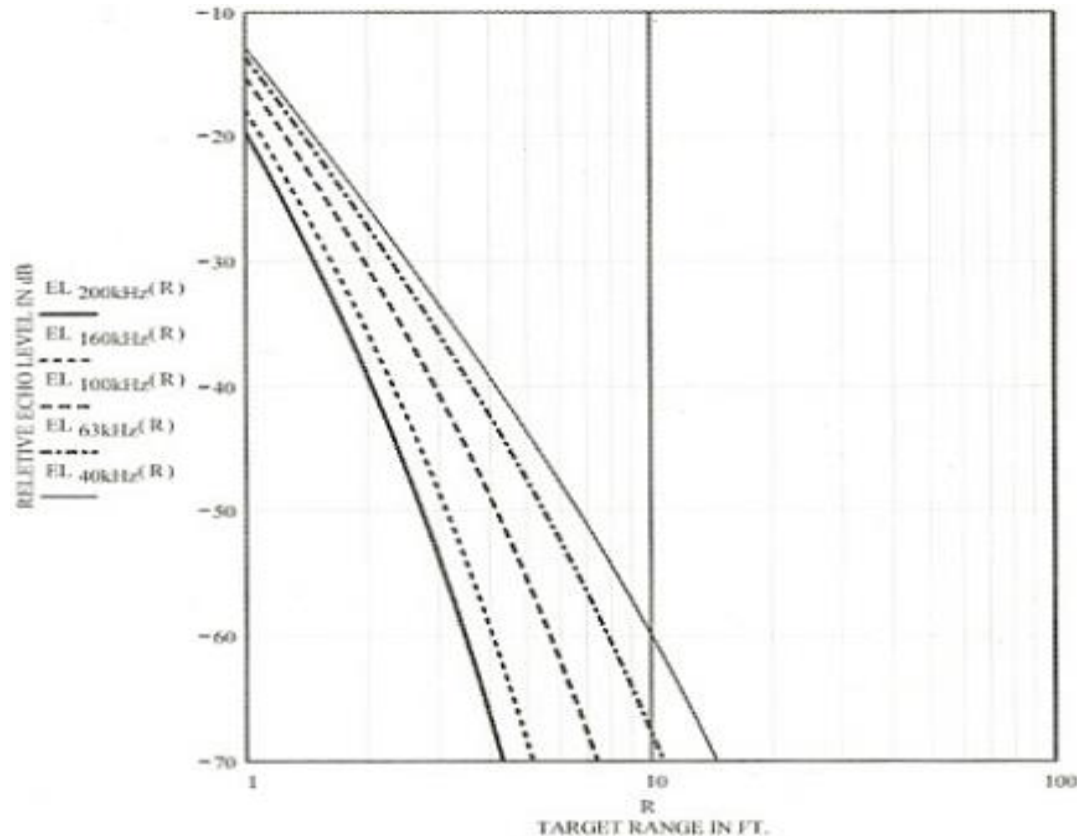
R = range distance to target

$SPL(R_0)$ = sound pressure level of transmitter at reference distance R_0

α_f = attenuation coefficient of sound at frequency f

TS = target strength

The relative echo levels from a 6-in.-radius sphere at varying distances are plotted against range for different frequencies.





For example

- It is assumed that the same sound pressure level is produced by the sensor at all frequencies, and that the same target is placed in line with the acoustic axis of the transducer.
- For illustration, the target is assumed to be a sphere with a radius equal to 6 in. (1/2 ft).
- From Table 2, this will result in a TS equal to -12 dB. Figure 12 shows plots of the relative ELf (R) from a reflecting sphere with a 6 in. radius at different distances from sensors operating at different frequencies.

TABLE 2

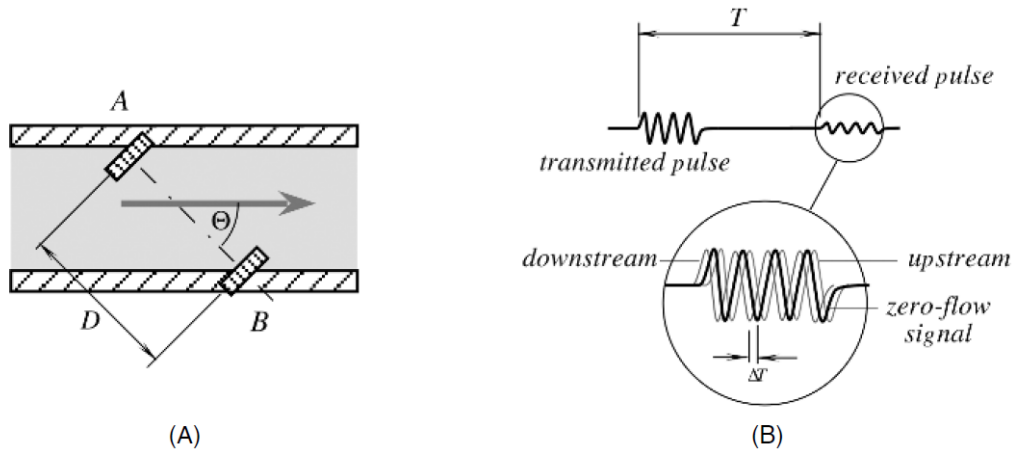
Theoretical Target Strengths for Simple Forms

R_0 =reference range; $k=2\pi/\lambda$; R =range to target
(all dimensions, including R and R_0 , must be in same units)

Form	t ($TS = 10 \log t$)	Definitions	Direction of Incidence	Conditions
Sphere	$a^2/4$	a = radius of sphere	any	$ka > 1$ $R > a$
Cylinder, Infinitely Long	$aR/2$	a = radius of cylinder	normal to axis of cylinder	$ka > 1$ $R > a$
Cylinder, Finite Length	$aL^2/2\lambda$	L = length a = radius	normal to axis of cylinder	$ka > 1$ $R > L^2/\lambda$
Smooth Convex Object	$S/16\pi$	S = total surface area of object	average over all directions	All dimensions $> \lambda$
Ellipsoid	$(bc/2a)^2$	a, b, c = semimajor axes of ellipsoid	normal to major axis	$ka, kb, kc > 1$ $R > a, b, c$

<https://www.fierceelectronics.com/components/choosing-ultrasonic-sensor-for-proximity-or-distance-measurement-part-1-optimizing>

Ultrasonic flow meter



- $T = D / (c + v_c \cos \theta)$

Where, c - velocity of sound in the fluid

- v_c = Flow velocity averaged along the path of the ultrasound



Ultrasonic flow meter

An ultrasonic sensor is installed in the upstream and in the downstream of a flow each to determine the difference in time of propagation caused by the flow, which can be used to calculate the flow rate.

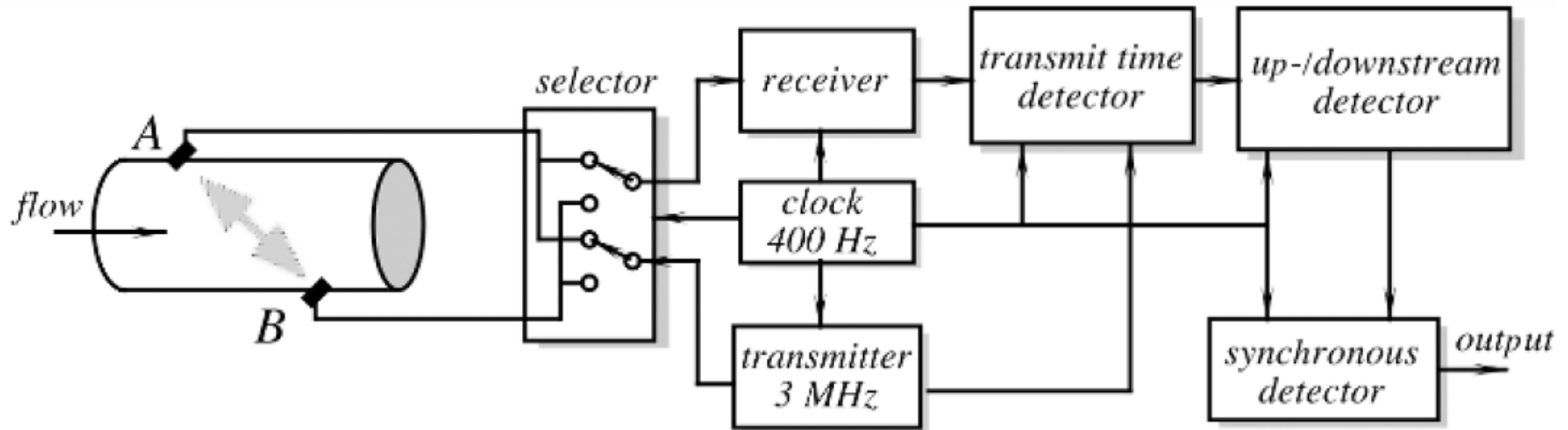
Besides the propagation time difference detection stated above, there are other methods to determine the flow rate. One of them is the Doppler method with which an ultrasonic wave is applied to air bubbles or foreign substances in the liquid and the frequency variation of the echo is determined to calculate the flow rate.



Ultrasonic flow meter

- Laminar flow $v_c = 4v_a/3$, and for turbulent flow, $v_c = 1.07v_a$, where v_a is the flow averaged over the cross-sectional area

Ultrasonic with transmitter and receiver

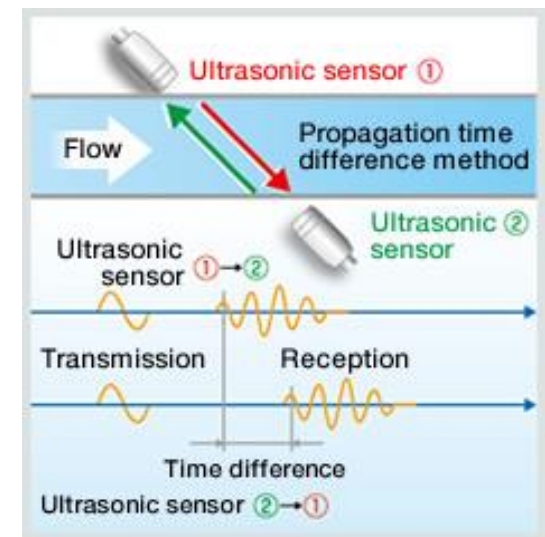


The time difference between downstream and upstream velocities

$$\Delta T = \frac{2Dv_c \cos \Theta}{c^2 + v_c \cos^2 \Theta} \approx \frac{2Dv_c \cos \Theta}{c^2},$$

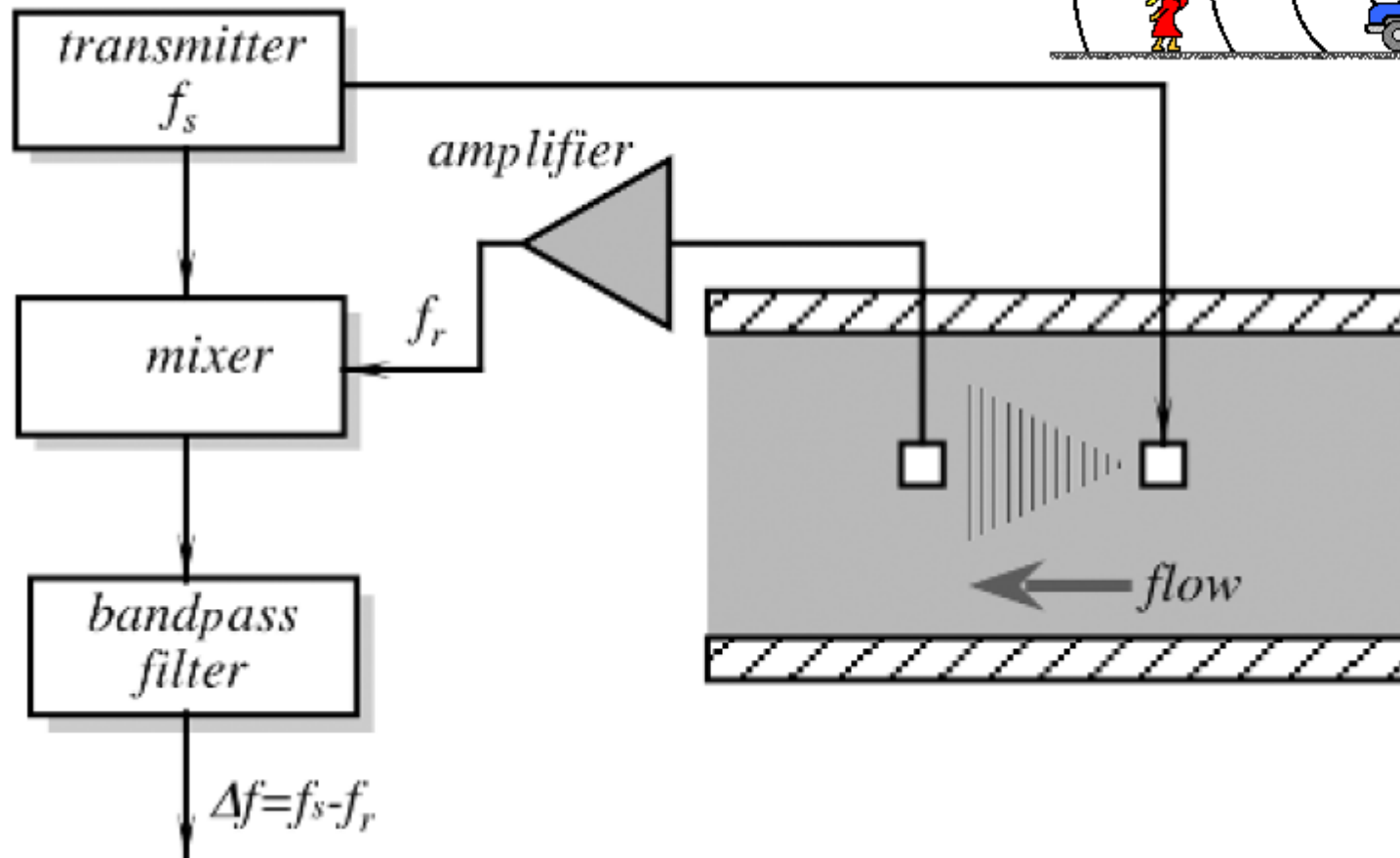
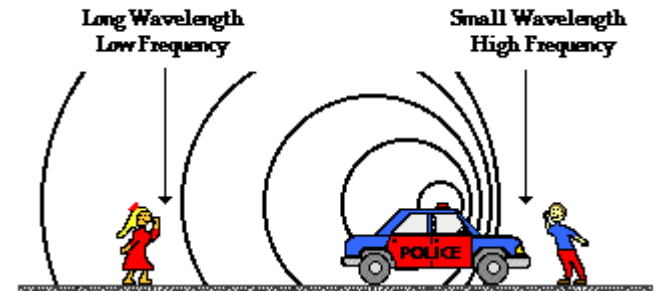
The phase difference can be derived from

$$\Delta f = \frac{4\pi f D v_c \cos \Theta}{c^2},$$



Ultrasonic Doppler flow meter

The Doppler Effect for a Moving Sound Source





Working

- The Doppler Effect Ultrasonic Flow meter use reflected ultrasonic sound to measure the fluid velocity. By measuring the frequency shift between the ultrasonic frequency source, the receiver, and the fluid carrier, the relative motion are measured.
- The resulting frequency shift is named the Doppler Effect.



Relation

- The fluid velocity can be expressed as

- $$v = c (f_r - f_t) / 2 f_t \cos\Phi$$

where

- f_r = *received frequency*
- f_t = *transmission frequency*
- v = *fluid flow velocity*
- Φ = *the relative angle between the transmitted ultrasonic beam and the fluid flow*
- c = *the velocity of sound in the fluid*



Other applications

- Ultrasonic waves are used to enable stable detection of transparent objects, such as transparent films, glass bottles, plastic bottles, and plate glass, using Through-beam or Reflective Sensors.



Advantage & limitation

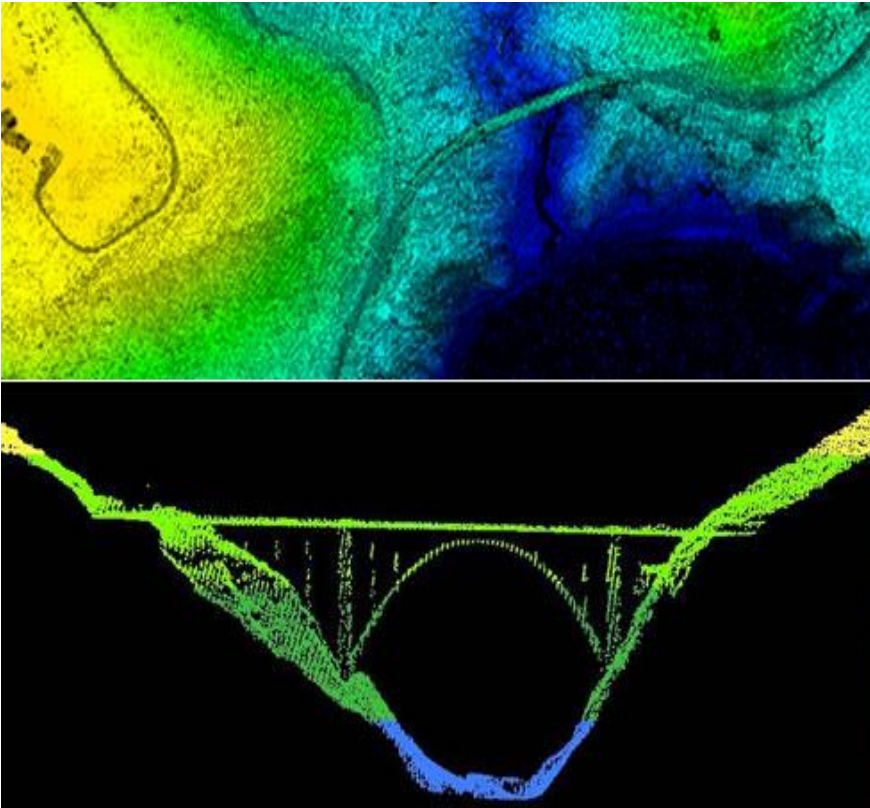
- **Advantages with the Doppler Effect Ultrasonic Flowmeter**
- Doppler meters may be used where other meters don't work. This might be liquid slurries, aerated liquids or liquids with some small or large amount on suspended solids. The advantages can be summarized to:
 - Obstruct less flow
 - Can be installed outside the pipes
 - The pressure drop is equal to the equivalent length of a straight pipe
 - Low flow cut off
 - Corrosion resistant
 - Relative low power consumption
- **Limitations with Doppler Effect Ultrasonic Flowmeters**
- The Doppler flowmeters performance are highly dependent on physical properties of the fluid, such as the sonic conductivity, particle density, and flow profile.
- Non uniformity of particle distribution in the pipe cross section may result in a incorrectly computed mean velocity. The flowmeter accuracy is sensitive to velocity profile variations and to the distribution of acoustic reflectors in the measurement section.
- Unlike other acoustic flowmeters, Doppler meters are affected by changes in the liquid's sonic velocity. As a result, the meter is also sensitive to changes in density and temperature. These problems make Doppler flowmeters unsuitable for highly accurate measurement applications.



Advantage & Disadvantage

- **Benefits with Ultrasonic Flowmeters**
- Obstruction less flow
- Pressure drop equal to an equivalent length of straight pipe
- Unaffected by changes in temperature, density or viscosity
- Bi-directional flow capability
- Low flow cutoff
- Corrosion-resistant
- Accuracy about 1% of flow rate
- Relative low power consumption
- **Limitations with Ultrasonic Flowmeters**
- The operating principle for the ultrasonic flowmeter requires reliability high frequency sound transmitted across the pipe. Liquid slurries with excess solids or with entrained gases may block the ultrasonic pulses.
- Ultrasonic flowmeters are not recommended for primary sludge, mixed liquor, aerobically digested sludge, dissolved air flotation thickened sludge and its liquid phase, septic sludge and activated carbon sludge.
- Liquids with entrained gases cannot be measured reliably.
- ***Ref:http://www.engineeringtoolbox.com/ultrasonic-doppler-flow-meter-d_495.html***

LIDAR(Light Detection and Ranging)





LIDAR

- LIDAR data is often collected by air, such as with this NOAA survey aircraft (right) over Bixby Bridge in Big Sur, Calif. Here, LIDAR data reveals a top-down (top left) and profile view of Bixby Bridge. NOAA scientists use LIDAR-generated products to examine both natural and manmade environments. LIDAR data supports activities such as inundation and storm surge modeling, hydrodynamic modeling, shoreline mapping, emergency response, hydrographic surveying, and coastal vulnerability analysis.



LIDAR

- LIDAR, which stands for Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses—combined with other data recorded by the airborne system— generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.
- A LIDAR instrument principally consists of a laser, a scanner, and a specialized GPS receiver. Airplanes and helicopters are the most commonly used platforms for acquiring LIDAR data over broad areas. Two types of LIDAR are topographic and bathymetric. Topographic LIDAR typically uses a near-infrared laser to map the land, while bathymetric lidar uses water-penetrating green light to also measure seafloor and riverbed elevations.
- LIDAR systems allow scientists and mapping professionals to examine both natural and manmade environments with accuracy, precision, and flexibility. NOAA scientists are using LIDAR to produce more accurate shoreline maps, make digital elevation models for use in geographic information systems, to assist in emergency response operations, and in many other applications.



LIDAR in robotic application

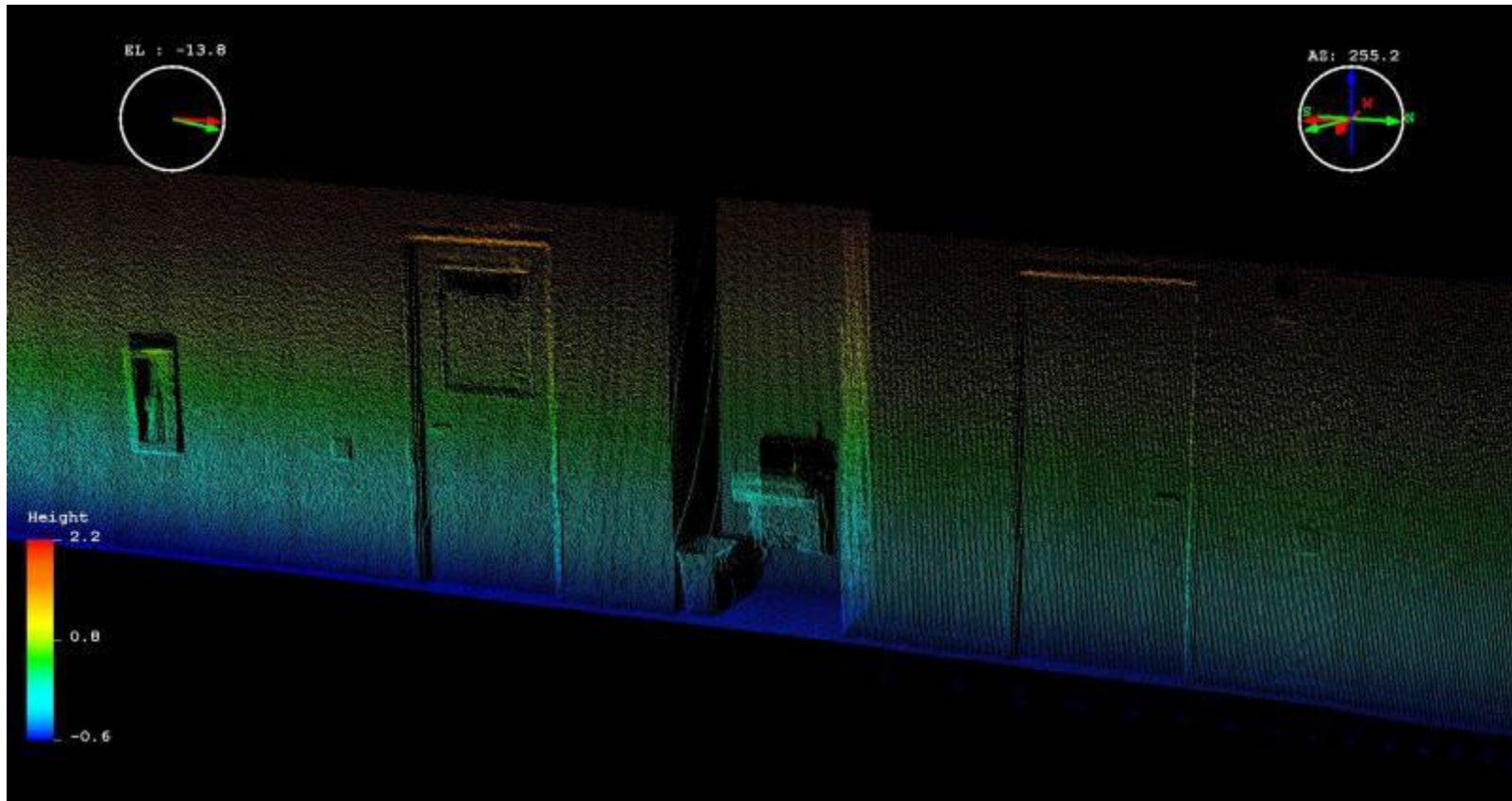
- This article was republished with permission from Comet Labs, a VC fund dedicated to accelerating intelligent machine (robotics and artificial intelligence) innovation.
- Imagine standing in a dark room, and the only way you can sense the environment around you is by reaching out to objects with a stick. First, you reach straight in front of you, and the stick goes 12 feet before hitting a solid object.
- Then you extend the stick to your right, 8 feet until it stops. Next you try to your left, and you get 12 feet. Behind you, the stick goes 18 feet. Now, even though you can't see anything, and you haven't moved, you have some information about the room.



LIDAR in robotic application

- If you repeated this hundreds, or thousands of times in different directions (and had a really good memory), you would be able to produce a rough representation of the room based on how far away objects are from you.
- If you angled the stick above and below horizontal, you would even be able to “see” objects around you like chairs and doors, based on their outlines. From this information, you could produce something called a “point cloud”, which is a set of points in a 3D coordinate system. With enough points, you could make a really detailed point cloud of the room, like this:

LIDAR in robotic application





LIDAR in robotic application

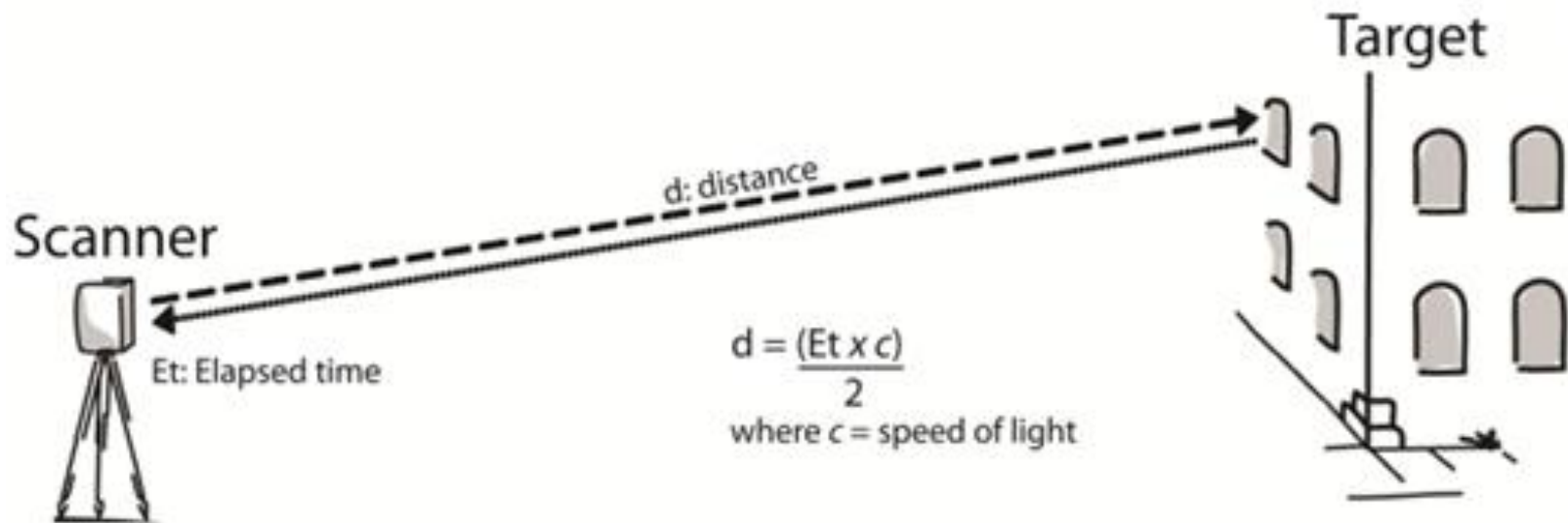
- Lidar (a portmanteau of “light” and “radar” which also stands for Light Detection and Ranging) is a sensor designed to quickly build these point clouds. By using light to measure distance, Lidar is able to sample points extremely quickly - up to 1.5 million data points per second. This sampling rate has enabled the technology to be deployed on applications such as autonomous vehicles.



How Lidar Works

- Lidar measures the time of flight of a pulse of light to be able to tell the distance between the sensor and an object. Imagine starting a stopwatch when the pulse of light is emitted, and then stopping the timer when the pulse of light returns (from being reflected off the first object it encounters). By measuring the “time of flight” of the laser, and knowing the speed that the pulse travels, the distance can be solved. Light travels at 300 million meters per second (186,000 miles per second), so very high precision equipment is needed to be able to generate data about distance.

How Lidar Works





- To produce complete point clouds, the sensor must be able to sample the entire environment very quickly. One way that Lidar does this is by using a very high sampling rate on the individual emitters/receivers. Each one emits tens, or hundreds of thousands of laser pulses every second. That means, within 1 second, as many as 100,000 laser pulses complete a round trip from the emitter on the Lidar unit, out to the object being measured, and back to the receiver on the Lidar unit, near the emitter. Large systems have as many as 64 of these emitter/receiver pairs, or “channels”. Multiple channels enable the system to generate more than a million data points per second.



- However, 64 stationary channels aren't enough to be able to map an entire environment - it would just give very clear resolution in very focused areas. Making more of these channels is expensive due to the precision required in the optics, so increasing the number of channels above 64 just increases cost faster. Instead, many Lidar systems use rotating assemblies, or rotating mirrors to enable the channels to sweep around the environment 360 degrees. Common strategies include angling each of the emitters and receivers above or below horizontal to blanket more of the environment in the field of view of the lasers. The Velodyne 64 channel Lidar system, for example has a 26.8 vertical field of view (the rotation gives it a 360 horizontal field of view). From 50 meters away, this Lidar could see the top of an object which is 12 meters tall

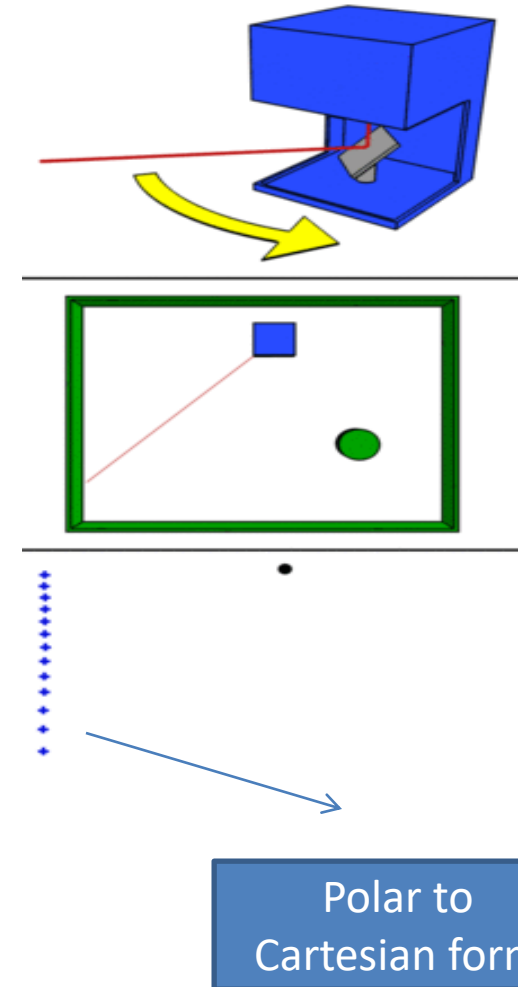


- The point cloud can be used to reproduce 3D models of landscapes or environments. A few applications include:
- Geological mapping/imaging to monitor erosion or other changes
- Monitoring growth of plants and trees
- Doing surveying work for construction projects
- Making accurate volumetric estimates of landfills





- **Lidar** (also written **LIDAR**, **LiDAR** or **LADAR**) is a remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light.
- lidar detection schemes: "incoherent" or direct energy detection (which is principally an amplitude measurement) and coherent detection (which is best for Doppler, or phase sensitive measurements)





components

- Optical remote sensing technology
- Scanner and optics
- Photo detector and receiver electronics
- Position and navigation system



source

- Ultraviolet
- Infrared
- Visible light



Laser

- 600-1000nm lasers are used for non scientific applications
- Better target pulses can be achieved with laser pulses provided detector and electronics having the bandwidth



Scanners and optics

- How fast images can be developed is also affected by speed at which it scans.
- Optic choices affect the angular resolution a hole mirror or beam splitter are options to collect the return signal.



Photo detector and receiver electronics

- Two main photo detector techniques are used in LIDARS: photodiodes and photo detector
- Sensitivity of the receiver is another parameter that has to be balanced in a LIDAR design.



Position and navigation systems

- LIDAR sensor are mounted on mobile platforms such as airplanes or satellite require instrumentation to determine the absolute position and orientation of the sensor.
- Such device includes a global positioning system receiver and an inertial measurement unit.



LIDAR types

- Other types
 - Coherent LIDAR (phase modulation)
 - Incoherent LIDAR(amplitude modulation)
- Based on backscattering
 - Reyleigh LIDAR
 - Mie LIDAR
 - Raman LIDAR



How it works

- Measuring the time delay between the transmission of the pulse and detection of the reflected signal.
- Measuring light reflected identifies surface types
- Laser return gives detailed results than radar



application

- Archeology
- Metrology
- Geology
- Physics and astronomy
- Biology and conservation
- Military and law enforcement
- Vehicles
- Imaging
- 3D mapping



Adv and Dis adv

- Higher accuracy
 - Fast acquisition and processing
 - Minimum human dependence
 - Weather/ light independence
 - Canopy penetration
 - Higher data density
 - cost
- High operating cost
 - Ineffective during heavy rain/cloud/mist
 - Degraded at high sun angles and reflections
 - Latency data not processed locally
 - Unreliable for water dept
 - Lack of vegetation penetration
 - Precise alignment must be maintained.



- Shoei RF-1200 Beacon Full Face Helmet Matte Red & Black product tutorial by PartsFish.com
- <http://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html>



GPS(Global Positioning System)

Lecture-8

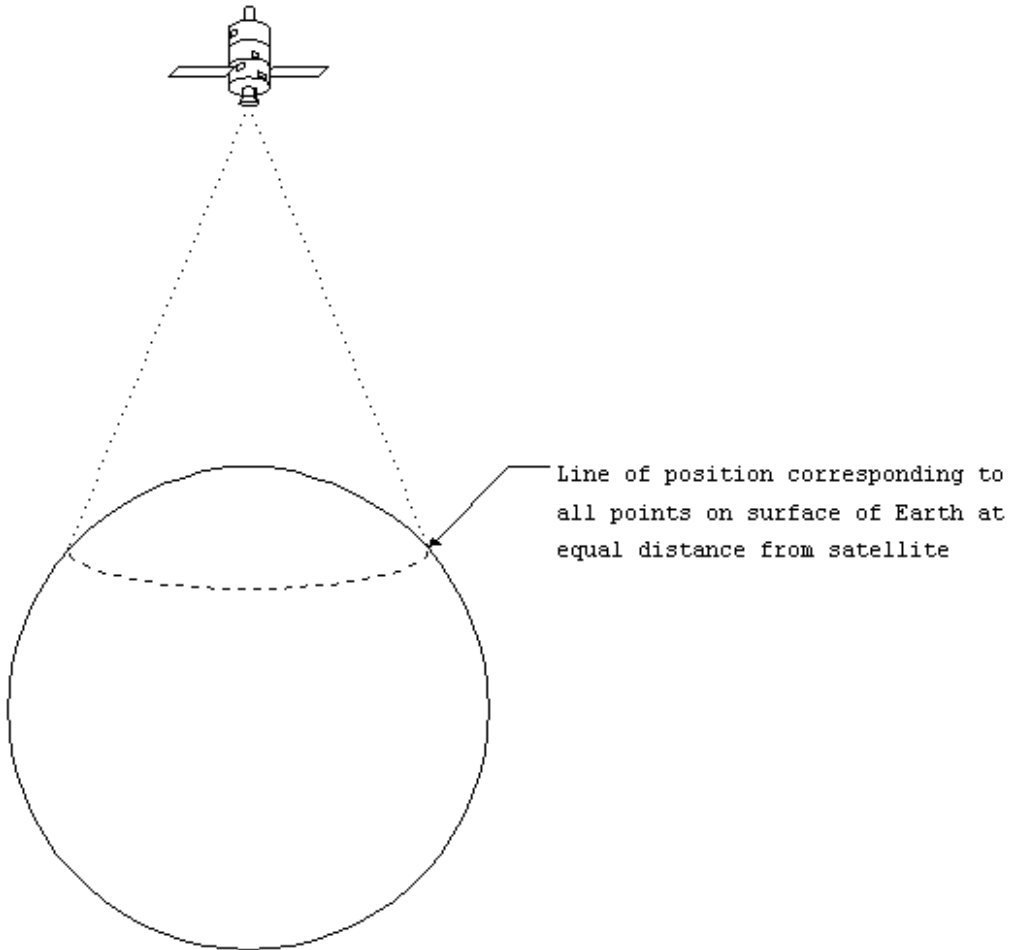
R.MATHIAZHAGAN

TEACHING FELLOW

DEPARTMENT OF PRODUCTION

TECHNOLOGY, MIT

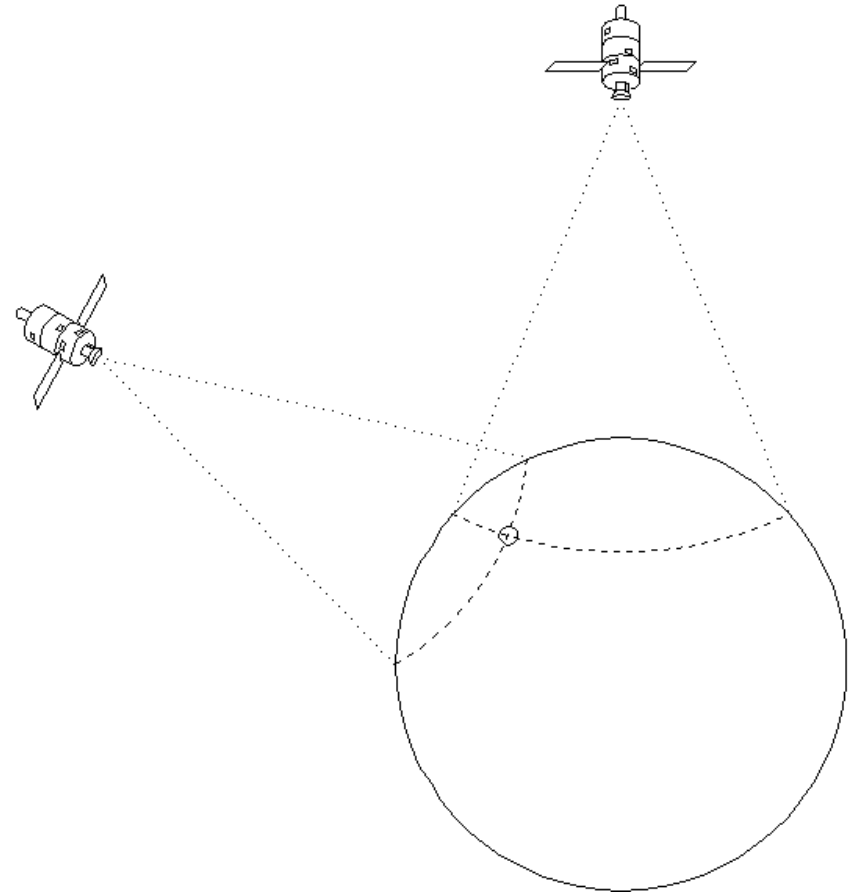
Line of position



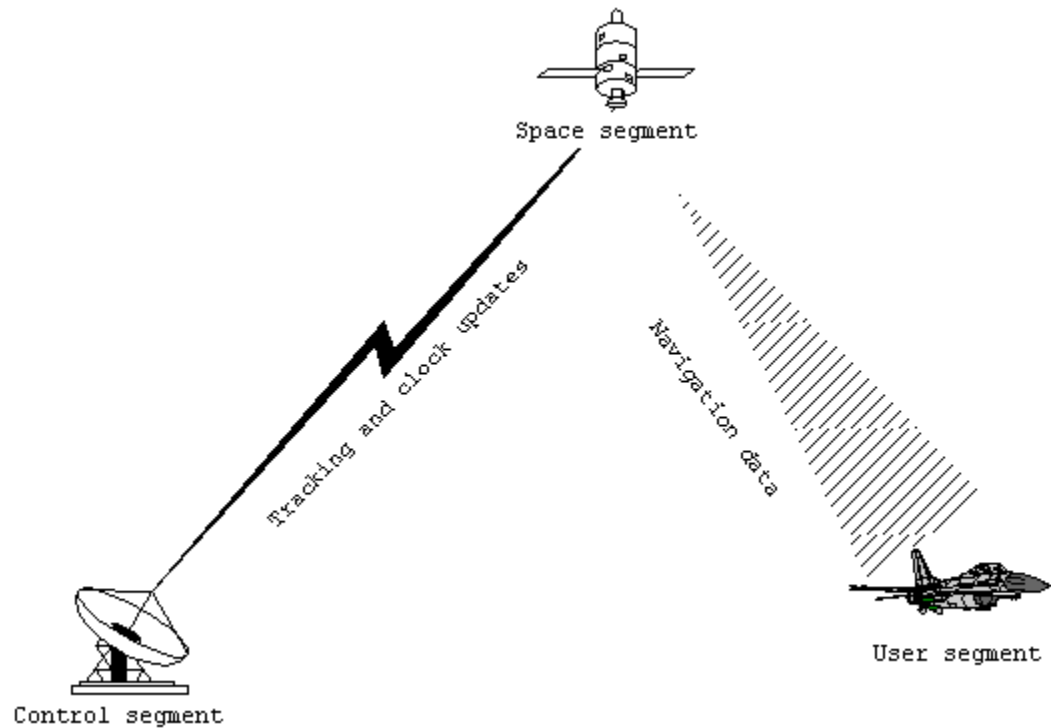
GPS is a satellite based navigation system. It uses a digital signal at about 1.5 GHz from each satellite to send data to the receiver. The receiver can then deduce its exact range from the satellite, as well as the geographic position (GP) of the satellite. The GP is the location on the Earth directly below the satellite. This establishes a line of position (LOP) on the Earth

Fix from two lines

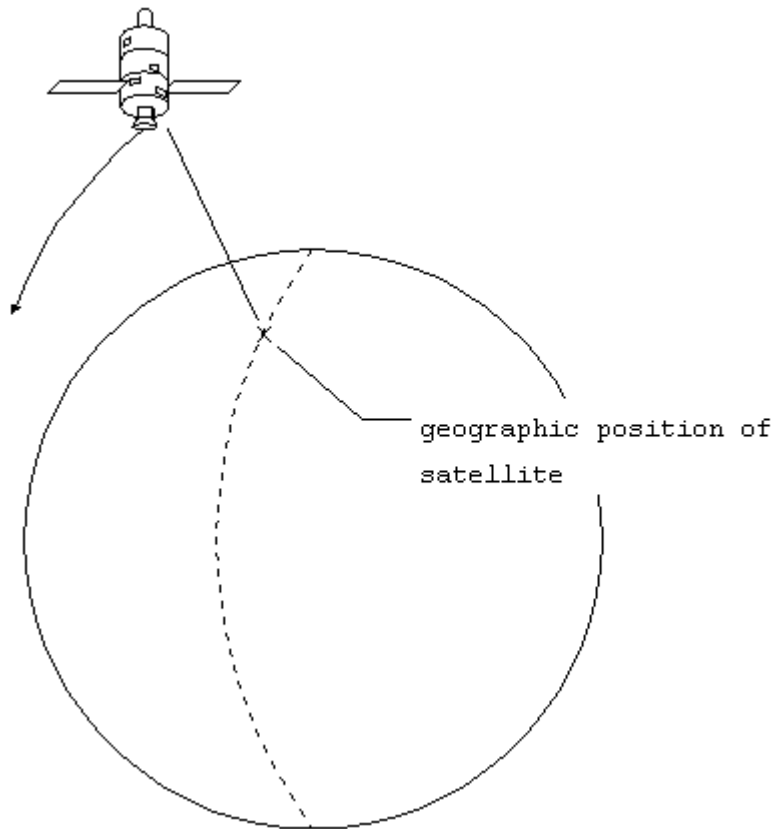
- A second LOP will provide for two possible locations, as shown in fig. and a third LOP will resolve that to a single position on the Earth



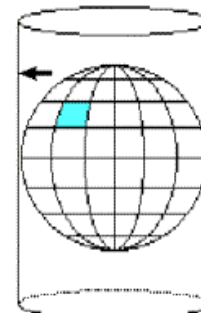
Segments of GPS.



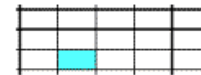
Spaced-based segment



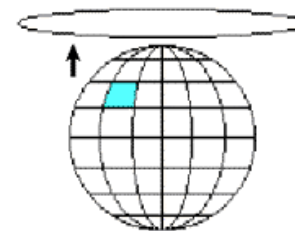
CYLINDRICAL



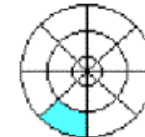
Graticule:



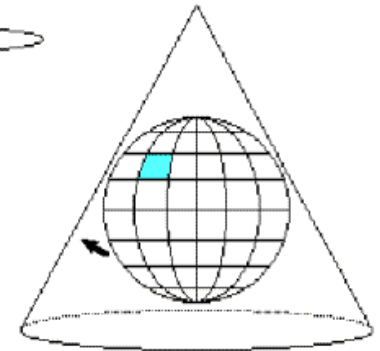
AZIMUTHAL



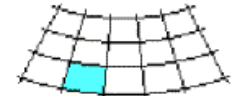
Graticule:



CONIC



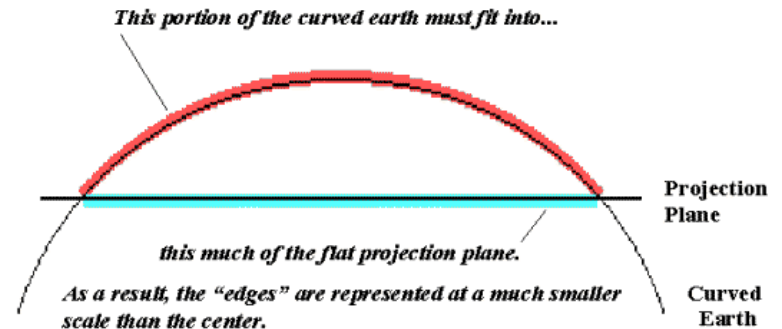
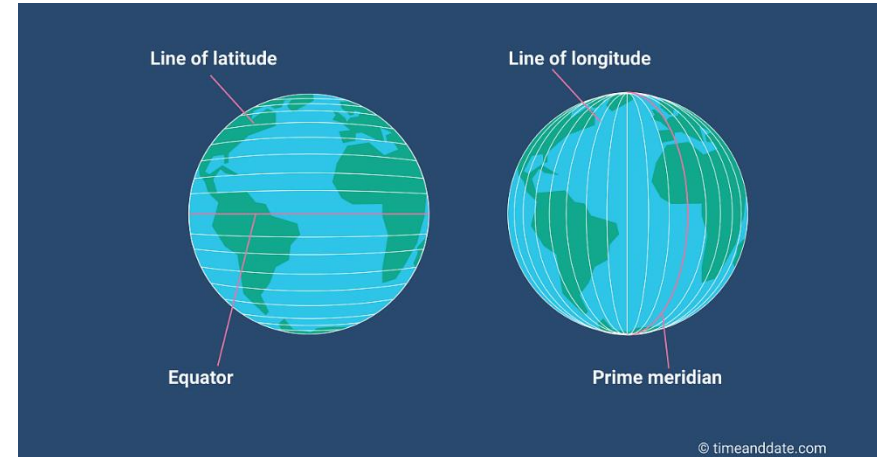
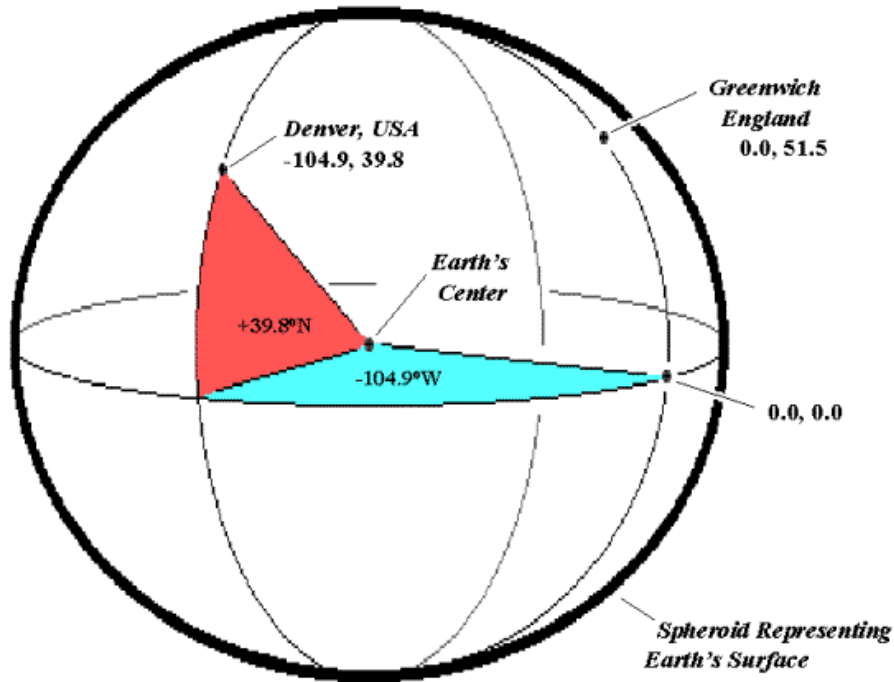
Graticule:



Polar orbit

The orbits of the various satellites are spaced at 55° intervals

Conceptual design of longitude/latitude coordinate system





intro

- The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations.
- GPS uses these "man-made stars" as reference points to calculate positions accurate to a matter of meters. In fact, with advanced forms of GPS you can make measurements to better than a centimeter!



Working

- The basis of GPS is "triangulation" from satellites.
- We're using the word "triangulation" very loosely here because it's a word most people can understand, but purists would not call what GPS does "triangulation" because no angles are involved. It's really "trilateration."
- Trilateration is a method of determining the relative positions of objects using the geometry of triangles.
- To "triangulate," a GPS receiver measures distance using the travel time of radio signals.
- To measure travel time, GPS needs very accurate timing which it achieves with some tricks.
- Along with distance, you need to know exactly where the satellites are in space. High orbits and careful monitoring are the secret.
- Finally you must correct for any delays the signal experiences as it travels through the atmosphere.

Calculation

(http://www.trimble.com/gps_tutorial/whygps.aspx)

- **Velocity (60 mph) x Time (2 hours) = Distance (120 miles)**

Step 2: Measuring distance from a satellite

Synchronizing our watches

- Timing is tricky
- We need precise clocks to measure travel time
- The travel time for a satellite right overhead is about 0.06 seconds.
- The difference in sync of the receiver time minus the satellite time is equal to the travel time

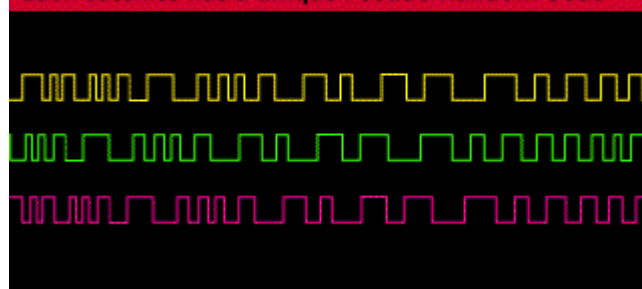
Step 2: Measuring distance from a satellite

velocity x time = distance



Step 2: Measuring distance from a satellite

Each satellite has a unique Pseudo Random Code





Atomic clock

- If measuring the travel time of a radio signal is the key to GPS, then our stop watches had better be darn good, because if their timing is off by just a thousandth of a second, at the speed of light, that translates into almost 200 miles of error!
- On the satellite side, timing is almost perfect because they have incredibly precise atomic clocks on board.

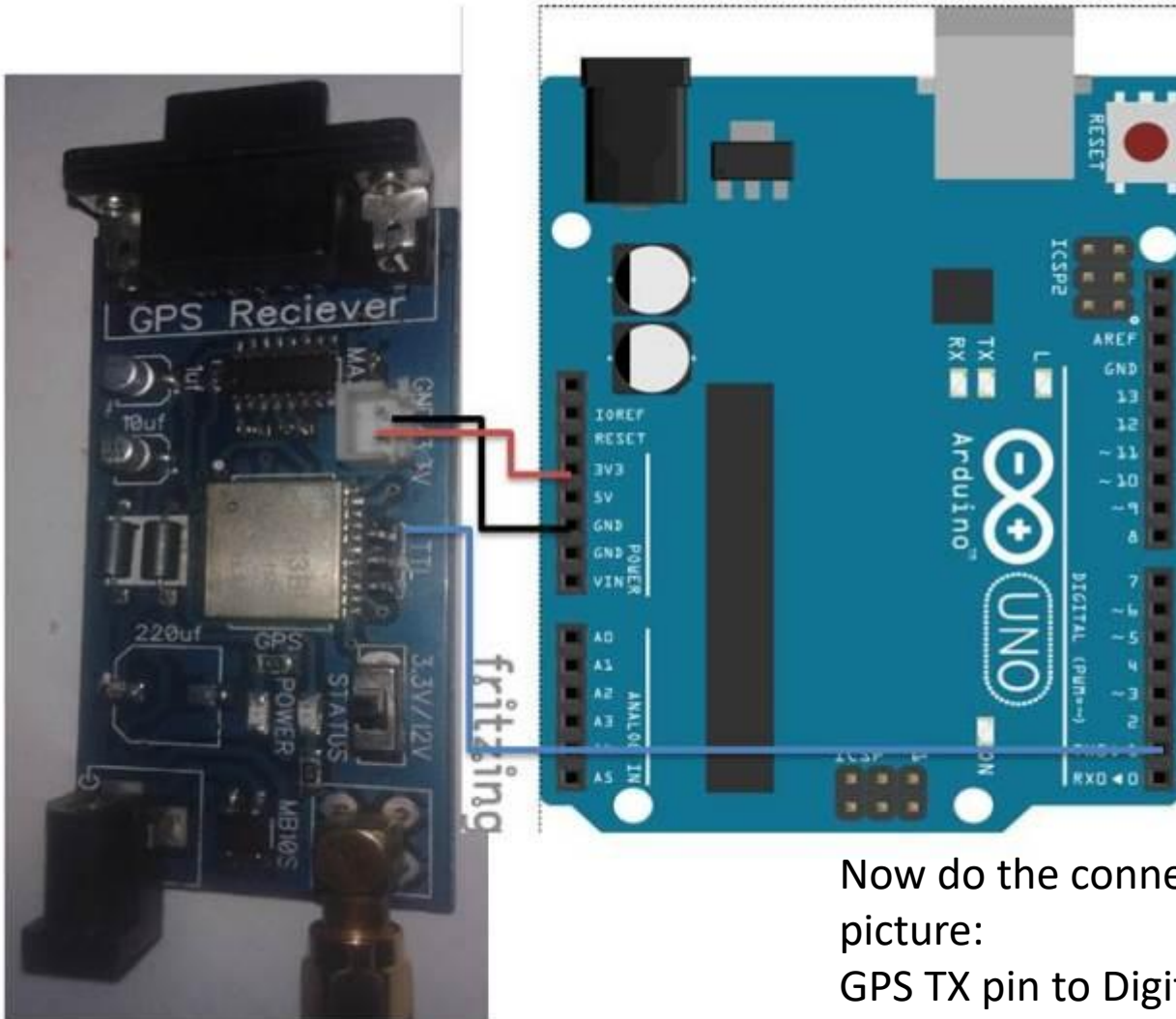
Atomic Clocks

- Atomic clocks don't run on atomic energy. They get the name because they use the oscillations of a particular atom as their "metronome." This form of timing is the most stable and accurate reference man has ever developed.



GPS interfacing with arduino

- GPS is a very useful device which is used in many electronics projects and applications like vehicle tracking system, GPS Clock, Accident Detection Alert System, traffic navigation and surveillance system etc.,
- GPS stands for Global Positioning System and used to detect the Latitude and Longitude of any location on the Earth, with exact UTC time (Universal Time Coordinated). This device receives the coordinates from the satellite for each and every second, with time and date. GPS offers great accuracy and also provides other data besides position coordinates



Now do the connection like given in below picture:

- GPS TX pin to Digital PIN 1 of Arduino (TXD)
- GPS Ground Pin to GND PIN of Arduino
- GPS Power (3.3v) Pin to 3.3v PIN of Arduino



Identifier	Description
\$GPGGA	Global Positioning system fix data
HHMMSS.SSS	Time in hour minute seconds and milliseconds format.
Latitude	Latitude (Coordinate)
N	Direction N=North, S=South
Longitude	Longitude(Coordinate)
E	Direction E= East, W=West
FQ	Fix Quality Data
NOS	No. of Satellites being Used
HDP	Horizontal Dilution of Precision
Altitude	Altitude (meters above from sea level)
M	Meter
Height	Height
Checksum	Checksum Data



- \$GPGGA: Global Positioning System Fix Data
- \$GPGSV: GPS satellites in view
- \$GPGSA: GPS DOP and active satellites
- \$GPRMC: Recommended minimum specific GPS/Transit data



```
COM13
$GPRMC,181926.000,A,2826.1628,N,07718.6434,E,0.09,0.00,260216,,,A*6C
$GPGGA,181927.000,2826.1629,N,07718.6434,E,1,4,1.19,49.0,M,-36.3,M,,*4D
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☐ Autoscroll Both NL & CR 9600 baud



Strain gage sensor

Lecture-10

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Introduction

- Lord kelvin 1856 first reported the relation between the strain and the resistance of wire conductors.
- Simmons at california institute of technology and ruge at MIT independently discovered in 1938 that the small conductor wire could be adhesively bonded to a structure to measure surface strain(SR-4 strain gauge).
- Metal foil gauges in 1954-Snaders and Roe in England.



Introduction

- 1960- semiconductor gauges were developed in bell laboratory.
- Present development is for better instrumentation and data reduction.
- Stress cannot be measured directly.
- Measured strains are converted to equivalent value of stress.



Characteristics desired in a Strain Gauge

- Small size (high stress gradient) and weight (inertia effects in the gage will be negligible under dynamic conditions)
- Ability to measure strains precisely under static and dynamic conditions.
- The possibility of remote observation and recording
- Independence of the influence of temperature
- Easy installation
- Stability of calibration
- Linear response to strain
- Low cost
- Dependability
- The possibility of operation as an individual strain gage, or in multiple arrangements



Basic Principle

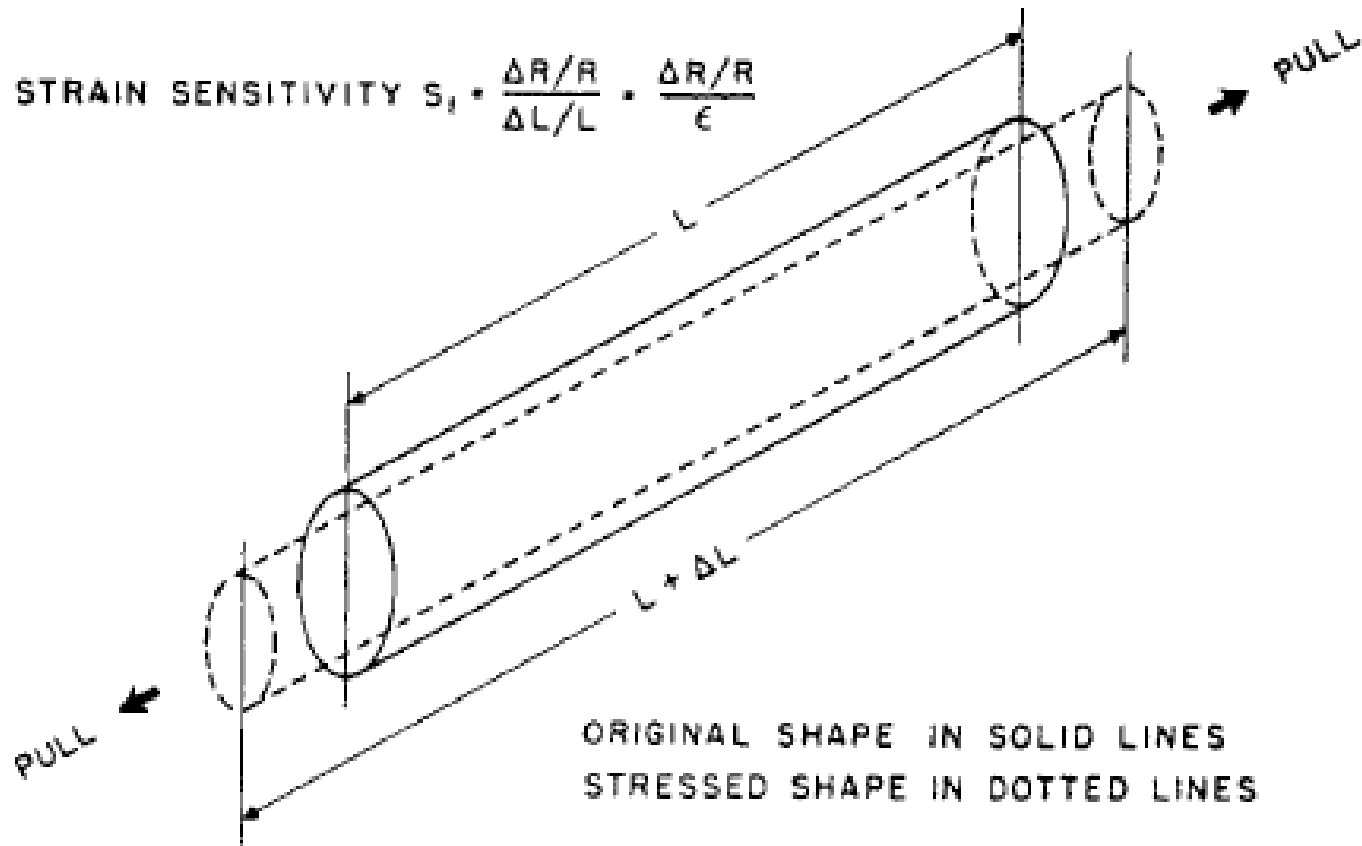
- The change of electrical resistance resulting from mechanical strain represents the basic principle upon which electrical resistance strain gages operate.
- For semiconductor gages, the detail of the means by which strain changes the resistance seems to be well understood, but for metallic conductors (wire or foil), we are still a long way from a complete understanding of what takes place within the material



Basic Principle

- When a conductor is strained in the axial direction,
 - The change in length,
 - The change in cross-sectional area, and
 - The change in specific resistivity,combine to produce a change in the overall electrical resistance of the conductor.

Schematic diagram of strained conductor





Strain Sensitivity

Where,

$$S_t = \frac{\frac{\Delta R}{R}}{\Delta L/L} = \frac{\frac{\Delta R}{R}}{\varepsilon}$$

S = strain sensitivity (factor) of the conductor and is dimensionless; this is a physical property of the material.

R = resistance in ohms

L = length in inches

ΔR , ΔL = corresponding changes in resistance and length, respectively, in ohms and inches

$\varepsilon = \Delta L/L$ = strain along the conductor (dimensionless)



Strain Sensitivity

- For the special case in which the resistance is directly proportional to the length, $R = KL$, where K is a constant. Thus, $\Delta R = K(\Delta L)$, and hence

$$S_t = \frac{\frac{\Delta R}{R}}{\Delta L/L} = \frac{\frac{K\Delta L}{KL}}{\Delta L/L} = 1$$

Since $R = \rho L/A$, therefore $K = \rho/A$, which means that to fulfill this condition, the specific resistivity, ρ will have to be proportional to the area of the cross section.



Strain Sensitivity

- Elastic strains in metals
- Plastic strains in metals
- Semiconductor materials

Semiconductor Material

$$\frac{\Delta R}{R_{0(T_0)}} = \left(\frac{T_0}{T}\right)(GF')\varepsilon + \left(\frac{T_0}{T}\right)^2 (C'_2)\varepsilon^2$$

Where,

ΔR = change in resistance from $R_{0(T_0)}$ (ohms)

$R_0(T_0)$ = resistance (ohms) of the unstressed material (prior to being mounted as a strain gage) at temperature T_0 , in Kelvin

T_0 = temperature at which $R_0(T_0)$ was determined (Kelvin)

T = temperature (Kelvin)

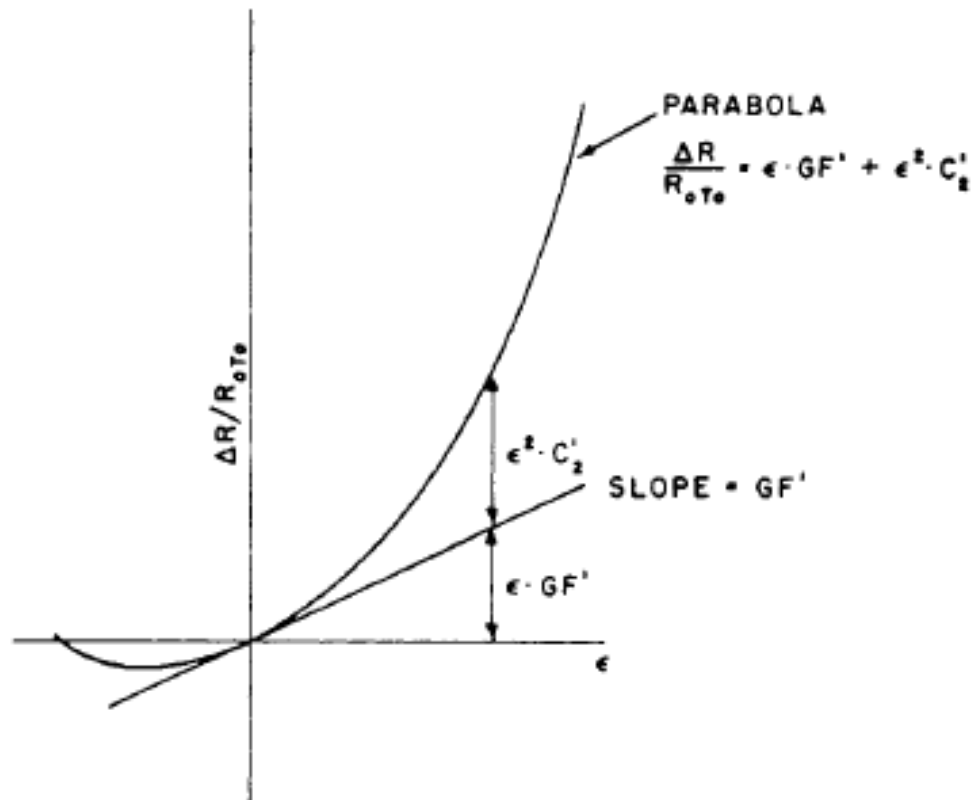
ε = strain (dimensionless)

GF' , C'_2 = constants for the particular piece of material (dimensionless)

$$\frac{\Delta R}{R_{0(T_0)}} = (GF')\varepsilon + (C'_2)\varepsilon^2$$

Schematic diagram for $\Delta R/R_{0(T0)}$ Vs ϵ

at constant Temperature Resistance = $\Delta R/R_0(T_0)$ when $R = \epsilon = 0$)

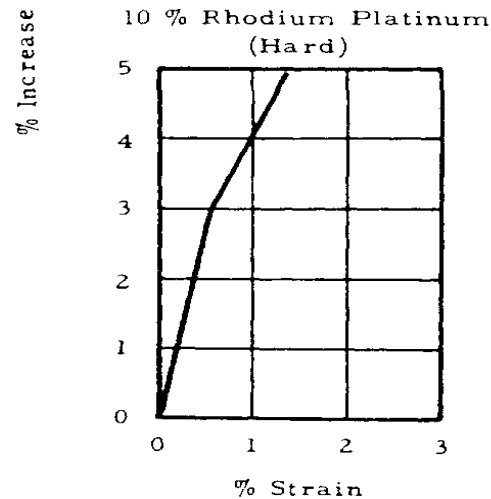
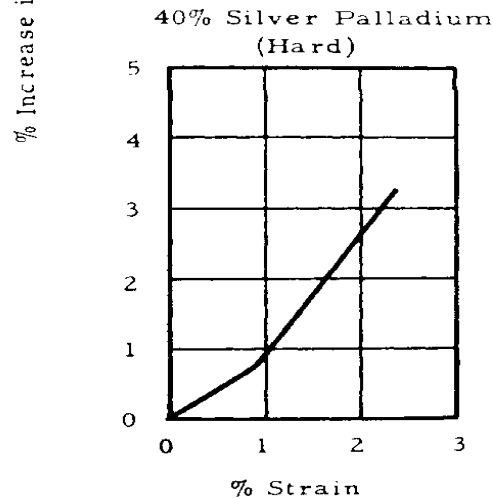
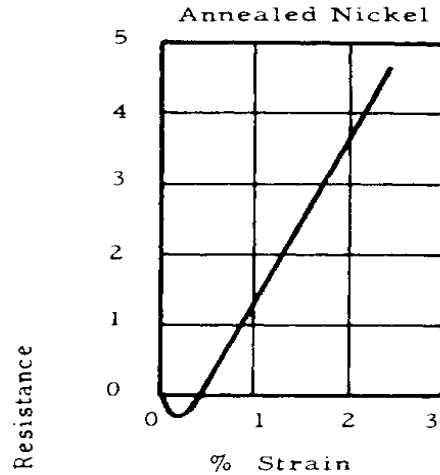
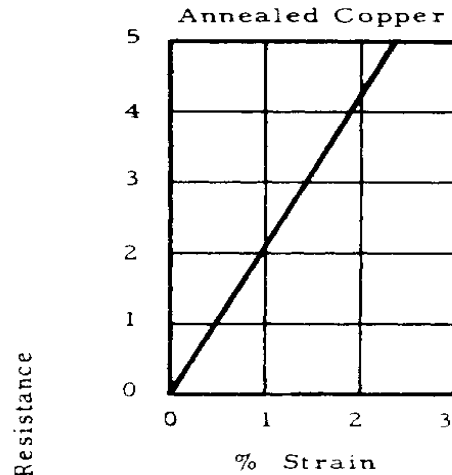




Desired properties of strain-sensitive materials

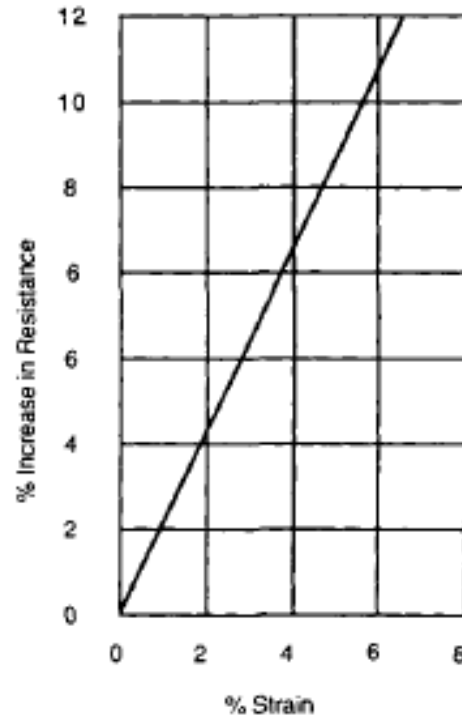
- Linear relation between unit change in resistance and change in strain(i.e., constant sensitivity).
- Negligible effect from temperature.
- High strain sensitivity factor.
- Moderately high resistance.
- Ability to be connected to lead wires easily.
- Low cost.
- Availability.
- Absence of creep and hysteresis.

Typical examples of resistance change vs. strain





Resistance change vs. strain for annealed Ferry wire (60/40 cupronickel).



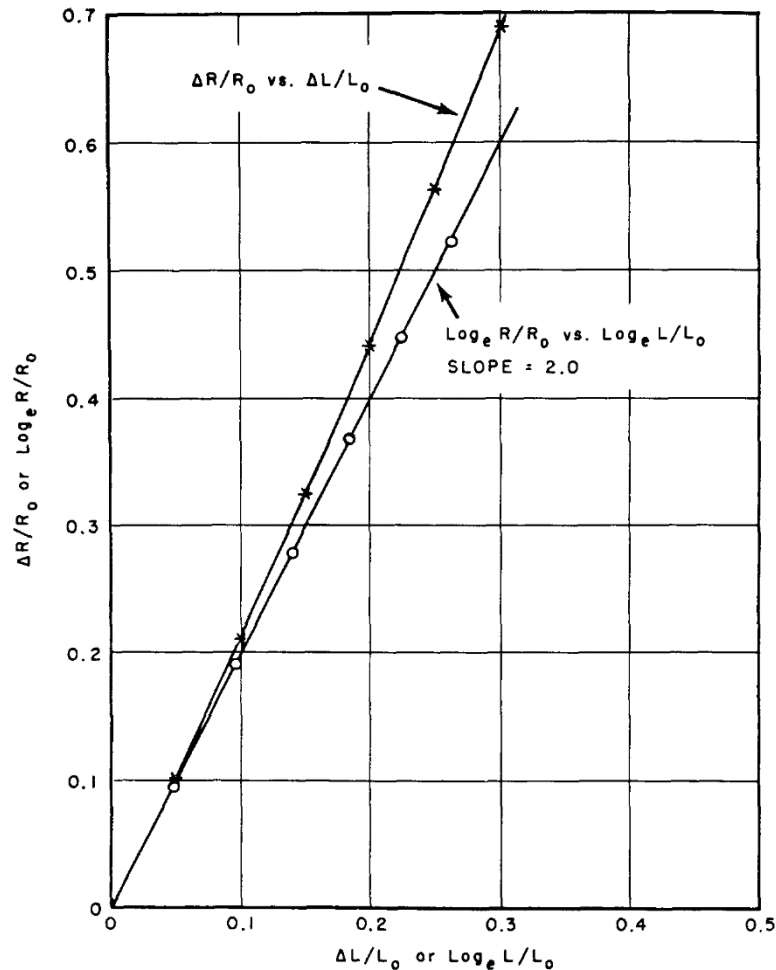
Typical strain sensitivity factors

Material	Strain sensitivity factor (for small strains)	Stress in lb/in ² equivalent to influence of temperature change of 1°C for installation on steel material ^a
Manganin	0.47	– 400
Nickel	– 12.1 (nonlinear)	– 13 500
Nichrome	2.1	2 100
Phosphor bronze	1.9	7 800
5% Iridium–Platinum	5.1	11 600
Advance	2.1 (selected material)	± 30
Copel	2.4	– 200
Monel	1.9	8 000
Isoelastic	3.6	5 000

Composition of alloys

Material	Composition
Advance and Copel	45% Ni; 55% Cu
5% Iridium-platinum	5% Ir; 95% Pt
Isoelastic	36% Ni; 8% Cr; 52% Fe; 0.5% Mo; + (Mn, Si, Cu, V) = 3.5%
Manganin	4% Ni; 12% Mn; 84% Cu
Nichrome V	80% Ni; 20% Cr

Weibull's experimental results from 0.45-mm diameter Copel wire



The expression for the resistance

The expression for the resistance in X-Direction is

$$R = \rho \frac{L}{A}$$

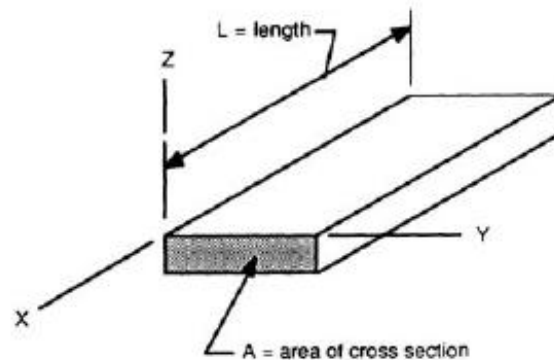
Where,

R = resistance in length L (ohms)

ρ = specific resistivity of the material (ohms-in)

L = length (in)

A = area of the cross section (in²)



Metal conductor referred to X, Y, and Z axes.

- By multiplying the numerator and denominator of the right-hand term by the length L

$$R = \rho \frac{L^2}{V}$$

where $V = LA = \text{volume (in}^3\text{)}$. By taking the logarithm of both sides.

$$\ln R = \ln \rho + 2 \ln L - \ln V$$

- Differentiation of Eq. results in

$$\frac{dR}{R} = \frac{d\rho}{\rho} + 2\frac{dL}{L} - \frac{dV}{V}$$

- Equation expresses the unit change in resistance in terms of the unit changes in resistivity, length, and volume.
- We now postulate that the unit change in resistivity can be related to the unit change in volume as follows

$$\frac{d\rho}{\rho} = m \frac{dV}{V}$$

Where,

m = a function of the material properties and the two ratios of the transverse to the longitudinal strain

By substituting the value of $d\rho/\rho$

$$\frac{dR}{R} = m \frac{dV}{V} + 2 \frac{dL}{L} - \frac{dV}{V} \quad \text{Or} \quad \frac{dR}{R} = 2 \frac{dL}{L} + (m - 1) \frac{dV}{V}$$

- Dividing all terms of above equ. by dL/L , we obtain

$$\frac{dR/R}{dL/L} = 2 + (m - 1) \frac{dV/V}{dL/L}$$

- Equation indicates that, for plastic deformation (which takes place at constant volume, so that $dV = 0$), the value of the instantaneous strain sensitivity can be expected to be 2 for any strain condition

- Since $dL/L = \epsilon_x$, and because $dV/V = (\epsilon_x + \epsilon_y + \epsilon_z)$, Then the equation can be expressed in terms of the strains as follows:

$$S_t = \frac{dR/R}{dL/L} = \frac{dR/R}{\epsilon_x} = 2 + (m - 1) \left[1 + \frac{\epsilon_y}{\epsilon_x} + \frac{\epsilon_z}{\epsilon_x} \right]$$

Special case of a uniform straight wire

- For the special case of a straight wire of any uniform cross section, which is free to contract or expand laterally due to the Poisson effect, the ratios of lateral to axial strain are given by the expression

$$\frac{\epsilon_y}{\epsilon_x} = \frac{\epsilon_z}{\epsilon_x} = -\nu$$

- Where ν = Poisson's ratio of the material
- When the values of the strain ratios, given for this special case by are substituted into Eq. S_t for strain sensitivity, we arrive at

$$S_t = \frac{dR/R}{dL/L} = \frac{dR/R}{\epsilon_x} = 2 + (m-1)(1-2\nu)$$



$$S_t = \frac{\Delta R/R_0}{\Delta L/L_0} = 2 + (m - 1)(1 - 2\nu)$$

Equations (1.15) and (1.16) can now be converted into a more familiar form customarily found in the literature. Expansion of the second term on the right-hand side of these equations results in the expression

$$S_t = \frac{dR/R}{dL/L} = 2 - 1 + 2\nu + m(1 - 2\nu)$$

In order to write Eq. (1.17) in a different form, the change in the volume of the wire as it is strained axially can be considered. The unstrained wire volume is

$$V = AL$$

Taking the logarithm of both sides and then differentiating yields

$$\frac{dV}{V} = \frac{dA}{A} + \frac{dL}{L}$$

As the wire is strained, its length increases by dL , but due to the Poisson effect its diameter decreases by $(- \nu dL/L)D$, where D is the wire diameter.

The final wire diameter is $D_f = D \left(1 - \nu \frac{dL}{L} \right)$

The change in area can now be written as

$$\begin{aligned} dA &= \frac{\pi}{4} (D_f^2 - D^2) = \frac{\pi D^2}{4} \left[\left(1 - \nu \frac{dL}{L} \right)^2 - 1 \right] \\ &= A \left[-2\nu \frac{dL}{L} + \left(\nu \frac{dL}{L} \right)^2 \right] \end{aligned}$$

If the higher-order term in Eq. (d) is neglected, then we can write

$$\frac{dA}{A} = -2\nu \frac{dL}{L}$$

Substituting the value of dA/A given by Eq. (e) into Eq. (b) gives

$$\frac{dV}{V} = -2\nu \frac{dL}{L} + \frac{dL}{L} = (1 - 2\nu) \frac{dL}{L}$$

Thus, Eq. (f) can be expressed as

$$(1 - 2\nu) = \frac{dV/V}{dL/L}$$



From Eq. (1.10) we can write $m = \frac{d\rho/\rho}{dV/V}$

If the values of $(1 - 2\nu)$ and m from Eqs. (g) and (h), respectively, are substituted in Eq. (1.17), then

$$S_t = \frac{dR/R}{dL/L} = 2 - 1 + 2\nu + \left(\frac{d\rho/\rho}{dV/V}\right)\left(\frac{dV/V}{dL/L}\right)$$

or

$$S_t = \frac{dR/R}{dL/L} = (1 + 2\nu) + \frac{d\rho/\rho}{dL/L}$$

For small changes, as encountered with elastic strains, we can write

$$S_t = \frac{\Delta R/R_0}{\Delta L/L_0} = (1 + 2\nu) + \frac{\Delta\rho/\rho_0}{\Delta L/L_0}$$

$$G = 1 + 2\nu + \frac{1}{e} \frac{\Delta\rho}{\rho}$$



1. Wire Strain gauge

- The unbonded wire strain gage
- The bonded wire strain gage
- Weldable wire gages



1.1 Unbonded wire strain gauge

- One of the early wire gages was the unbonded type.
- The strain-sensitive wire is mounted, under tension, on mechanical supports (pins) in such a manner that a slight relative motion of the supports will cause a change in strain.
- This, in turn, produces a change in electrical resistance.
- This resistance change is then a measure of the relative displacement of the supports and, in turn, may represent a strain or some other quantity.



1.1 Unbounded wire strain gauge

Disadvantage:

- The fact that the strain-sensitive wires must be carried on some sort of mechanical mount gives rise to certain difficulties in connection with attachment.
- Discrepancies, due to inertia, may be introduced when dynamic observations are made.
- The procedure of making observations at an appreciable distance from the surface on which strain is to be determined may sometimes be open to question.



1.2 The Bonded Wire Strain Gage

- Very fine strain-sensitive wire directly to the surface on which strain is to be measured.
- The filament has to be electrically insulated and the bonding perfect for the strain-sensitive element to follow the strain on the surface.
- The force necessary to strain the sensing element must be transmitted through its surface by shear in the cement, or bonding agent.
- The surface area (per unit length) of small-diameter wires is enormously greater than the cross-sectional area (for 0.001-in diameter wire, the ratio is 4000 to 1).
- The bonding agent is able to force the filament to take up the necessary strain without excessive stress in itself.



1.2 The Bonded Wire Strain Gage

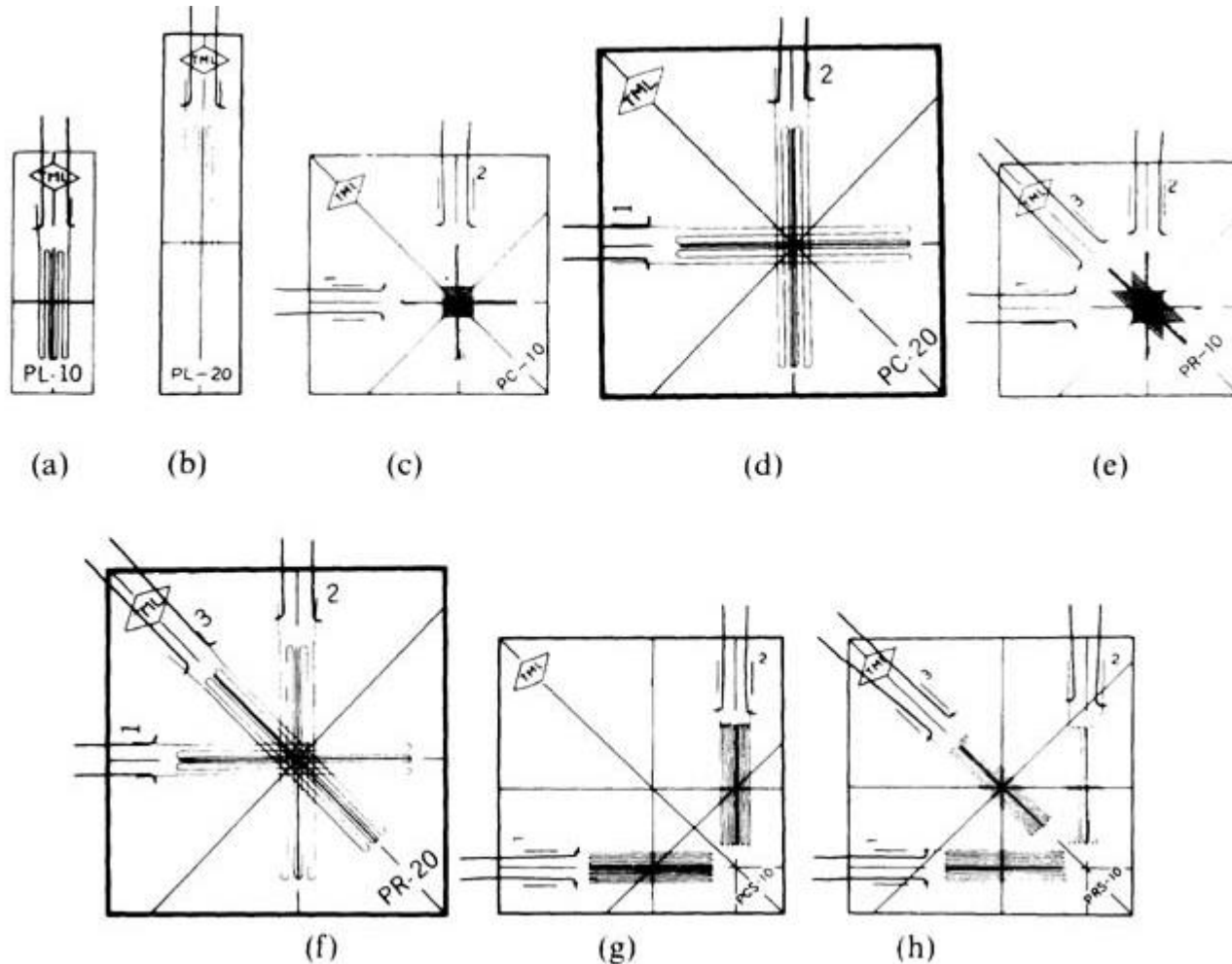
- The second major development, and that which has actually been responsible for making the bonded strain gage commercially attractive.
- The concept of premounting the strain-sensing element on some suitable carrier that can be attached to a surface.
- The strain gage wire was cemented directly to the surface on which strain was to be measured, and the glue or cement acted as insulation.
- As far as operation was concerned, this procedure was satisfactory, but from the point of view of gage installation, it was inconvenient.



1.2 The Bonded Wire Strain Gage

- The introduction of a paper, plastic, metal, or other type of carrier upon which the strain-sensing wire could be premounted, under controlled factory conditions.
- Most bonded wire strain gages are made from wire of approximately 0.001 in diameter, or less, and in resistances varying from about 50 ohms to several thousand ohms.
- When the gage is on a flat surface, the centre line of the entire sensing element lies in one plane that is parallel to the surface of attachment.

Types of strain gauge



Typical wire strain gauges, (a, b) Single element gauges, (c, d) Two-element stacked rectangular rosettes, (e, f) Three-element stacked rectangular rosettes, (g) Two-element rectangular rosette, (h) Three-element rectangular rosette.



Types of strain gauge

- (a, b) - Single element gages.
- (c, d) - Two-element stacked rectangular rosettes.
- (e, f) Three-element stacked rectangular rosettes.
- (g) Two-element rectangular rosette.
- (h) Three-element rectangular rosette.

1.2 The Bonded Wire Strain Gage

- Due to the geometrical differences between a straight wire and a strain gage grid, the value of the manufacturer's gage factor, GF , is generally slightly lower than the strain sensitivity factor, S .
- Gages containing a single continuous filament which is wound back and forth will respond slightly to the effect of lateral strain which is sensed by the end loops.



2. Foil strain gages

- The foil gage operates in essentially the same manner as a wire gage.
- However, the sensing element consists of very thin metal foil (about 0.0002 in thick) instead of wire.
- The most important advantages of the foil gage is that the ratio of contact surface area to the volume of the resistance element is relatively high, whereas in the wire gage, due to the circular cross section, this ratio is a minimum.



2. Foil strain gages

- The early foil gages, introduced in England in 1952, were made from foil cemented to a lacquer sheet.
- The desired grid design for the strain gage was printed on the foil with an acid-resisting ink and the sheet was then subjected to an acid bath which removed all metal except where the printed design protected it.



2. Foil strain gages

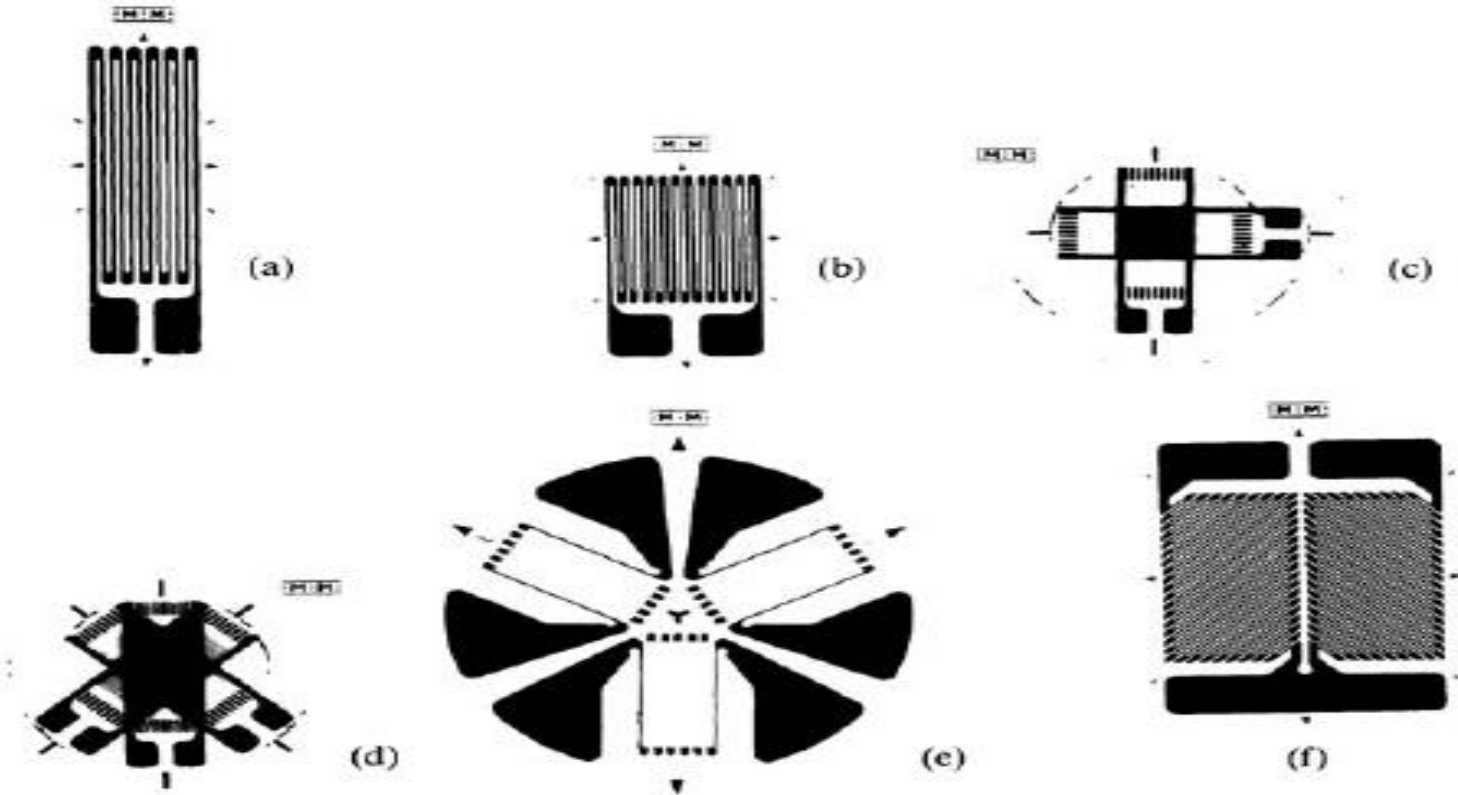
- Vast improvement in the photographic techniques currently used in the photoetching process employed to manufacture foil gages.
- Foil gages are available in various gage lengths from 1/64 in to 6 in, and in a wide variety of grid configurations.
- Standard alloys such as constantan, isoelastic, nichrome, karma, and platinum- tungsten, as well as a number of special proprietary alloys, are used in the sensing elements.



2. Foil strain gages

- a) Single-element gages,
- b) Stacked two-element rectangular rosette
- c) Stacked three-element rectangular rosette
- d) Three-element delta rosette
- e) Two-element rectangular rosette torque gage

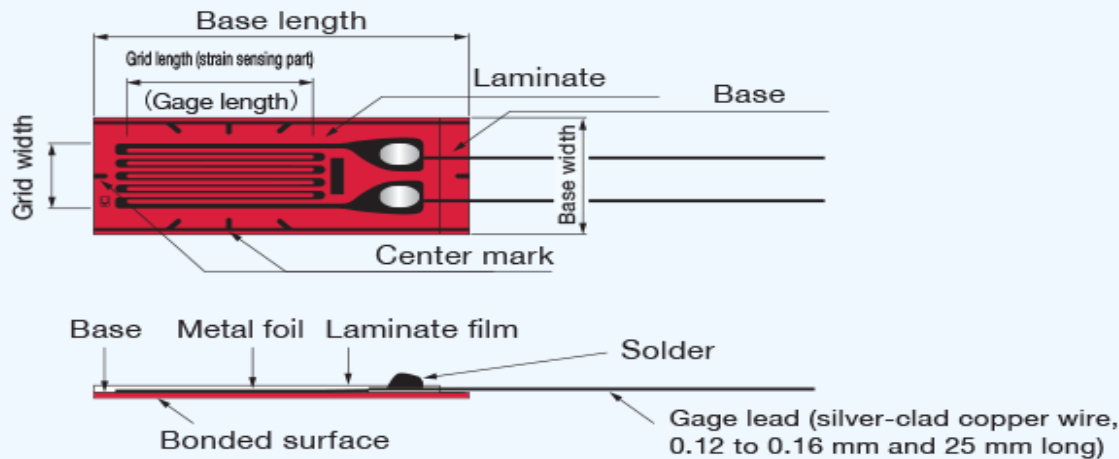
Foil strain gages



Foil strain gages, (a, b) Single-element gages, (c) Stacked two-element rectangular rosette, (d) Stacked three-element rectangular rosette, (e) Three-element delta rosette, (f) Two-element rectangular rosette torque gage. (Courtesy of Measurements Group, Inc.)

Construction

Fig. 2 Example of KFG gage



- The strain gauge is bonded to the measuring object with a dedicated adhesive. Strain occurring on the measuring site is transferred to the strain sensing element via the gauge base.
- For accurate measurement, the strain gauge and adhesive should match the measuring material and operating conditions including temperature.
- The foil strain gauge has metal foil photo-etched in a grid pattern on the electric insulator of the thin resin and gauge leads attached, as shown in Fig.



Strain sensitivity of an Wire

- $R = \rho L / A$ (1)
 - Where, ρ = Specific resistance
 - L = Length of the conductor
 - A = Cross sectional area of the conductor



Types

- Types of strain gauges include foil strain gauge, wire strain gauge, and semiconductor strain gauge



Magnetic sensor

Lecture-11

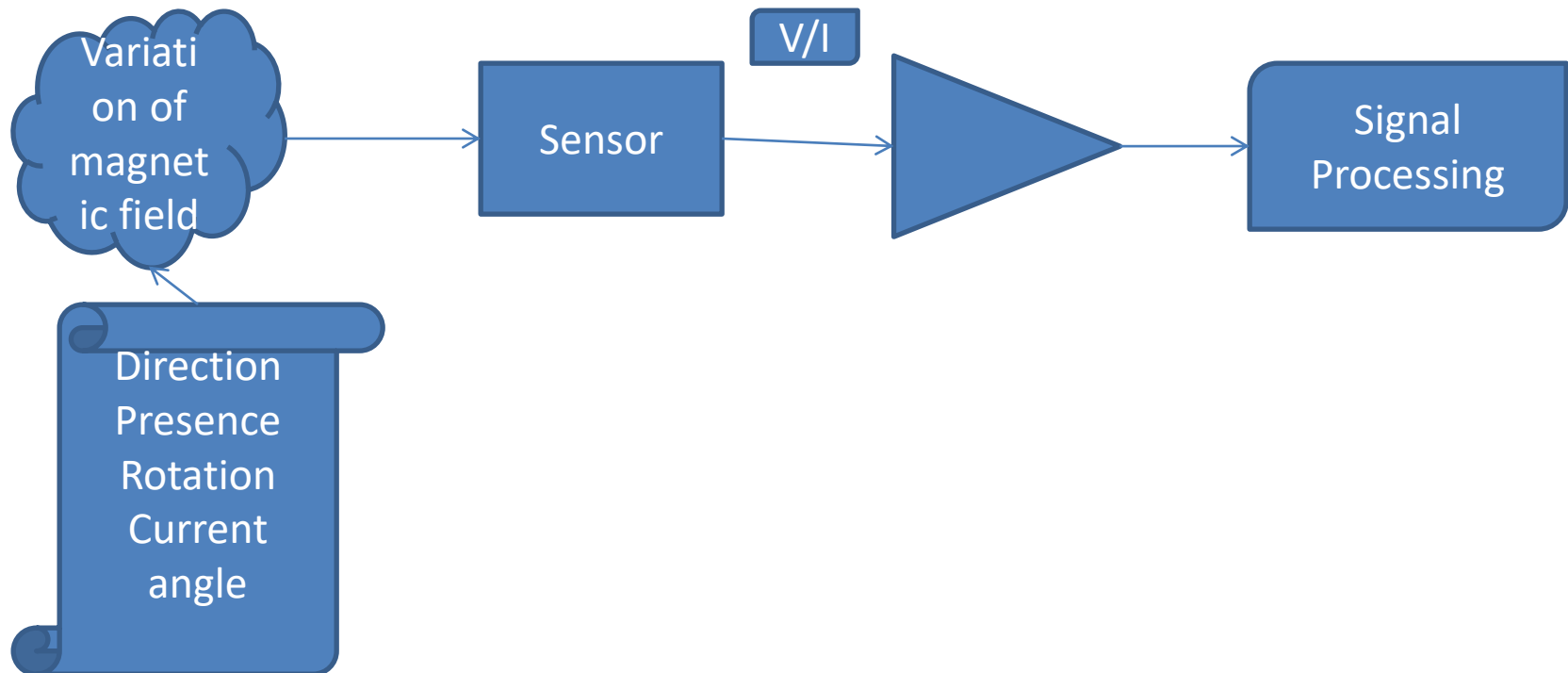
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Magnetic sensor

- The sensors, transducers which uses the changes in magnetic fields for their operation
- Used to measure current, speed, position and displacement
- As the conventional sensors, magnetic sensor does not give output parameters directly
- Signal processing is required for desired signal

Magnetic sensor





History

- In 1831, Michael Faraday in England and Joseph Henry in the United States discovered
- one of the most fundamental effects of electromagnetism: an ability of a varying magnetic field to induce electric current in a wire. It is not important how the field is produced—either by a permanent magnet or by a solenoid—the effect is the same.
- Electric current is generated as long as the magnetic field changes

Magnetic terms and Units

(MKSA-Meter, Kilogram, Seconds, ampere)

Term, quantity	MKSA unit	subunits	CGS unit	conversion
Magnetic field strength H	A/m	$1 \text{ A/cm} = 100 \text{ A/m}$ $1 \text{ mA/cm} = 0.1 \text{ A/m}$ $1 \text{ kA/m} = 1000 \text{ A/m}$	Oe (Oersted)	$1 \text{ Oe} = 79.58 \text{ A/m}$ $= 0.796 \text{ A/cm}$
Magnetization M	A/m	see field strength		
Magnetic induction (flux density) B	T (Tesla) $= \frac{\text{V} \cdot \text{s}}{\text{m}^2}$	$1 \text{ mT} = 10^{-3} \text{ T}$ $1 \mu\text{T} = 10^{-6} \text{ T}$ $1 \text{ nT} = 10^{-9} \text{ T}$ $1 \text{ pT} = 10^{-12} \text{ T}$ $1 \gamma^{1)} = 1 \text{ nT}$	G (Gauss)	$1 \text{ G} = 10^{-4} \text{ T}$ $1 \text{ kG} = 0.1 \text{ T}$ $1 \text{ mG} = 10^{-7} \text{ T}$ $1 \gamma^{1)} = 10^{-5} \text{ G}$
Magnetic flux ϕ	Wb (Weber) $= \text{V} \cdot \text{s}$	—	Mx (Maxwell)	$1 \text{ Mx} = 10^{-8} \text{ Wb}$
Magnetic polarization J	T	see induction		
Permeability (absolute) P	$\frac{\text{T} \cdot \text{m}}{\text{A}}$	—	$\frac{\text{G}}{\text{Oe}}$	—
Permeability of vacuum (magnetic constant) μ_0	$4\pi \cdot 10^{-7} \frac{\text{T} \cdot \text{m}}{\text{A}}$	$0,4\pi \cdot 10^{-4} \frac{\text{T} \cdot \text{cm}}{\text{A}}$	1	—

¹⁾ γ is a special unit used in geomagnetism, there is a necessity to distinguish between γ_H and γ_B (related to H and B)

Most important equations:

The most important basic equations are:

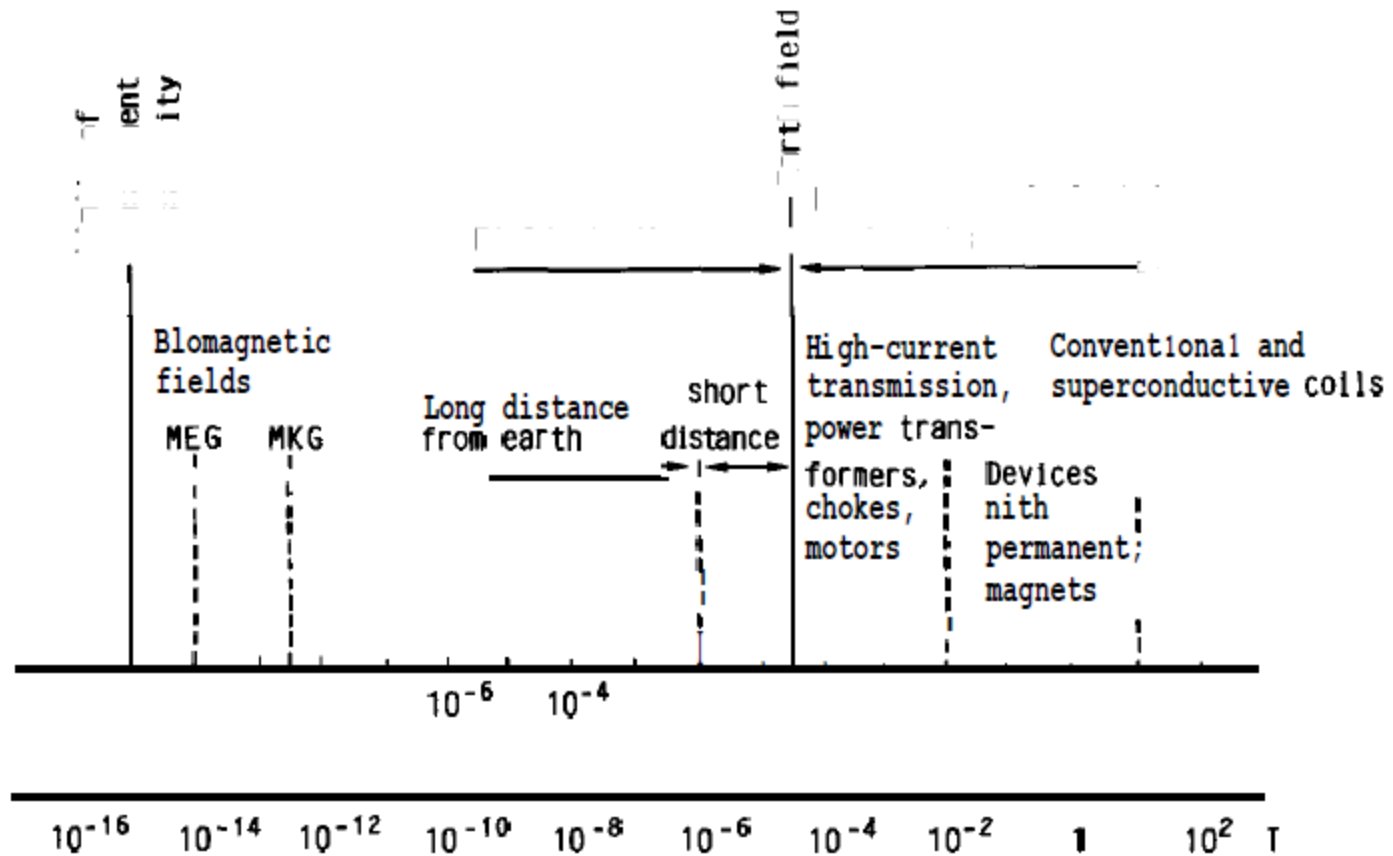
$$\mathbf{B} = \mu_0 \cdot (\mathbf{H} + \mathbf{M}) = \mu_0 \cdot \mathbf{H} + \mathbf{J}$$

$$\mathbf{M} = \frac{\mathbf{B}}{\mu_0} - \mathbf{H} = \frac{\mathbf{J}}{\mu_0}$$

$$\mu = \mu_0 \cdot \mu_r \quad \mu_r = \text{relative permeability}$$

$$\mathbf{B} = \mu_0 \cdot \mu_r \cdot \mathbf{H}$$

Scale of Magnetic Field Strength and Flux Density



Soft Magnetic Materials

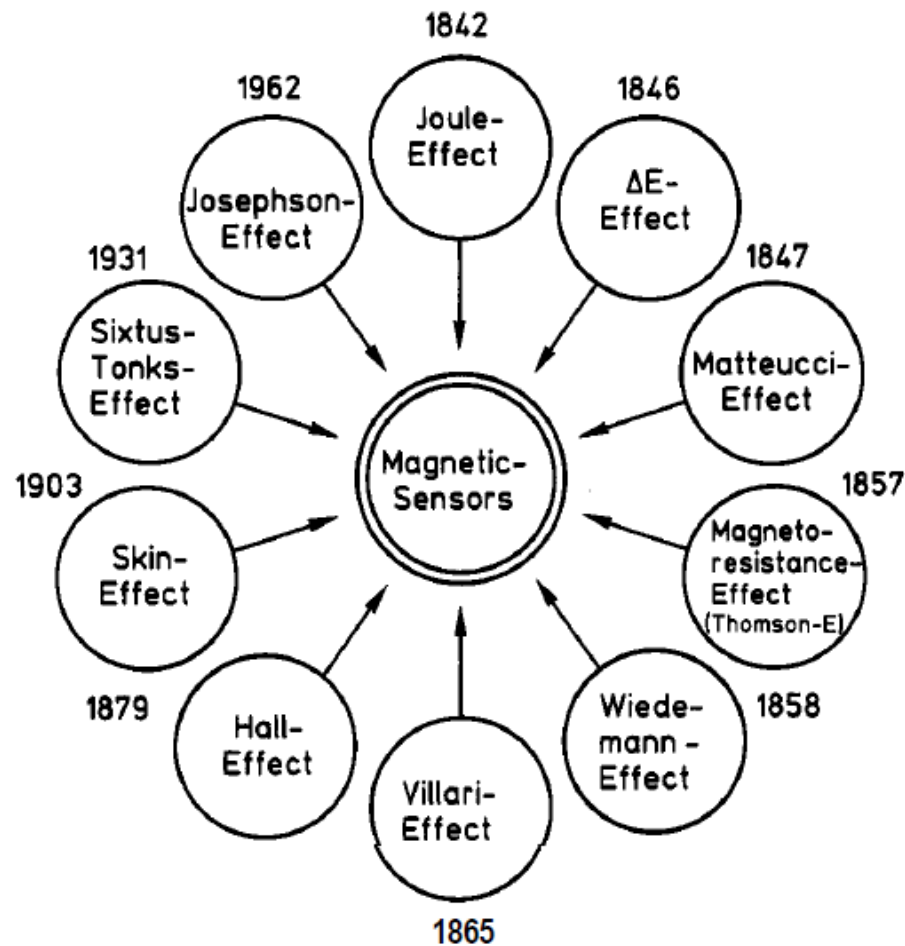
Group	Code
Crystalline metals	A Irons
	B Low carbon mild steel
	C Silicon steel, mainly with 3% Si
	D Other steels
	E Nickel-iron alloys (5 groups E1 ... E5 with 30% ... 83% Ni)
	F Iron-cobalt alloys (3 groups F1 ... F3 with 23% ... 50% Co)
	G Other alloys as AlSiFe-alloys
Oxides	H Soft ferrites as NiZn and MnZn oxides and others
Amorphous metals	I Amorphous alloys (Fe-based and Co-based alloys)
Powder composite metals	— based on Fe and iron alloy powders

Hard Magnetic Materials













Group	Code	
Crystalline metals	R1 ¹⁾	Alloys of AlNiCo-type
	R2	Platinum-cobalt alloys
	R3	Iron-cobalt-vanadium (Chromium) alloys
	R6	Chromium-iron-cobalt alloys
	R5 ¹⁾	Rare earth cobalt alloys
	R7 ¹⁾	Rare earth iron alloys
Amorphous metals	— ¹⁾	Rare earth iron alloys
Oxides	S1	Hard ferrites as Ba- and Sr-ferrites
	T	Other hard magnetic materials, e. g., magnetically semi-hard metals

¹⁾ also as powder composite materials

Physical Effects Used for Sensors and year of discovery



Field range for various Magnetic Field Sensors

Magnetic Sensor	Detectable Field Range			
	1nT	1 μ T	1 mT	1 T
SQUID				
FIBER-OPTIC				
OPTICALLY PUMPED				
NUCLEAR PRECESSION				
SEARCH COIL				
	 EARTH'S FIELD			
AMR SENSORS				
FLUX-GATE				
MAGNETOTRANSISTOR				
MAGNETO-OPTICAL				
HALL-EFFECT				
GMR SENSORS				



Types of magnetic sensors

Based on working principle

The most important galvanomagnetic effects are

- Magneto resistive
- Hall effect sensor

Based on field range

- Low field-can sense very low values of magnetic field($<1\mu\text{gauss}$)-medical and nuclear applications
- Earth Field sensor- $1\mu\text{Gauss}$ to 10Gauss -uses earths magnetic fields-Navigation and vehicle detection
- BIAS Magnetic sensors



Hall effect sensor



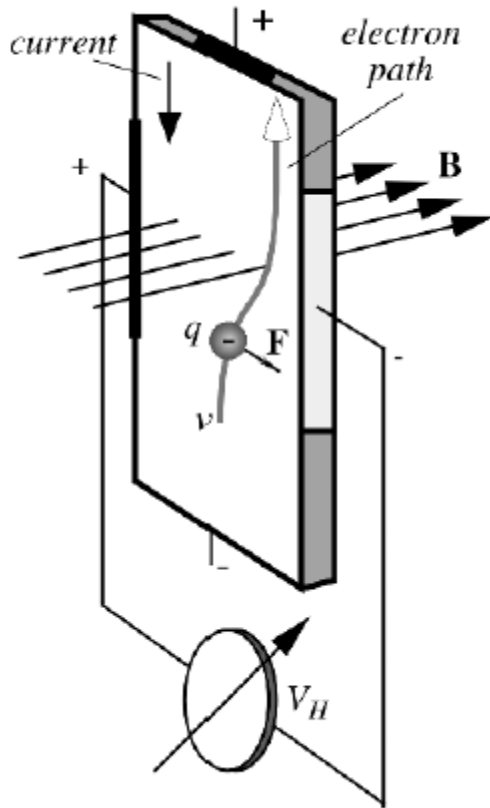
Hall effect sensor

- Physical effect was discovered in 1879 at Johns Hopkins University by E. H. Hall
- The effect had a limited, but very valuable application as a tool for studying electrical conduction in metals, semiconductors, and other conductive materials
- Hall sensors are used to detect magnetic fields and position and displacement of objects
- In **metals**, these **carriers are electrons**. When an electron moves through a magnetic field, a sideways force acts upon it.

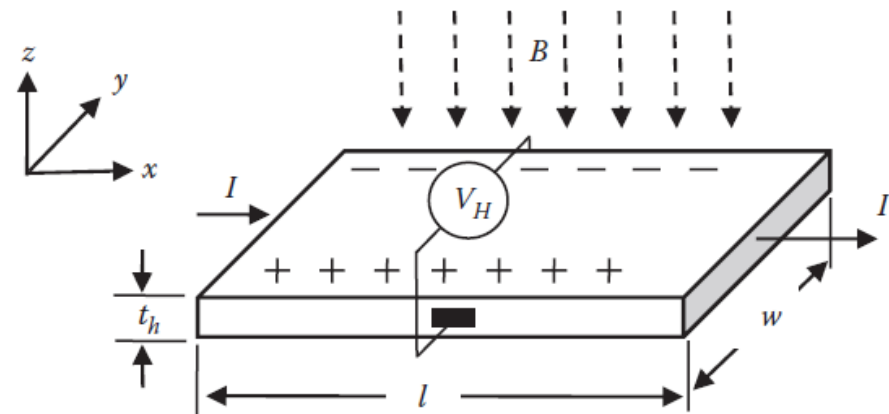
$$\mathbf{F} = q\mathbf{v}\mathbf{B}$$

- where $q = 1.6 \times 10^{-19}$ C is an electronic charge,
 v is the speed of an electron, and \mathbf{B} is the magnetic field

Hall effect sensor working



$$V_H = \frac{IB}{qN_c t_h}$$





Hall voltage

- Due to the magnetic field, the deflecting force shifts moving electrons toward the right side of the strip, which becomes more negative than the left side; that is, the magnetic field and the electric current produce the so-called *transverse Hall potential difference* V_H .
- The sign and amplitude of this potential depends on both the magnitude and directions of magnetic field and electric current

$$V_H = h i B \sin \alpha$$

- where α is the angle between the magnetic field vector and the Hall plate, i -Current, B -Magnetic field density
- h is the coefficient of overall sensitivity whose value depends on the plate material, its geometry (active area), and its temperature



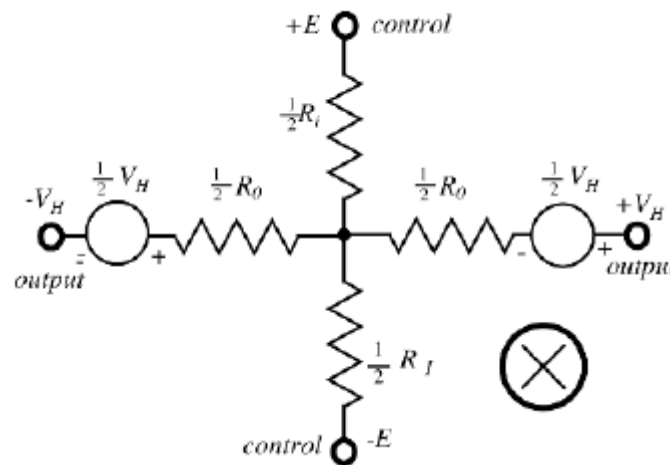
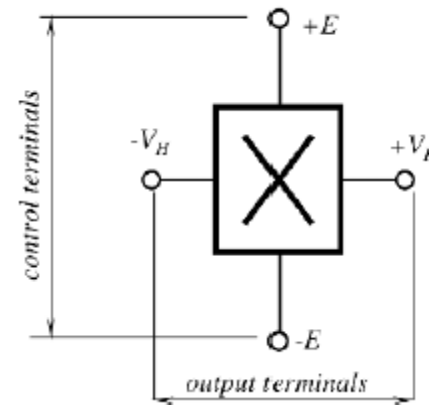
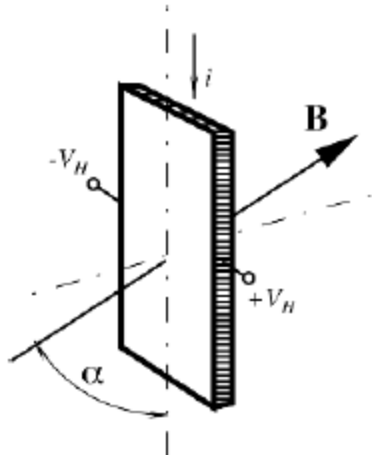
Hall effect sensor sensitivity

- The overall sensitivity depends on the Hall coefficient, which can be defined as the
- transverse electric potential gradient per unit magnetic field intensity per unit current density

$$H = \frac{1}{Ncq}$$

- where N is the number of free electrons per unit volume and c is the speed of light

Equivalent circuit of hall effect sensor

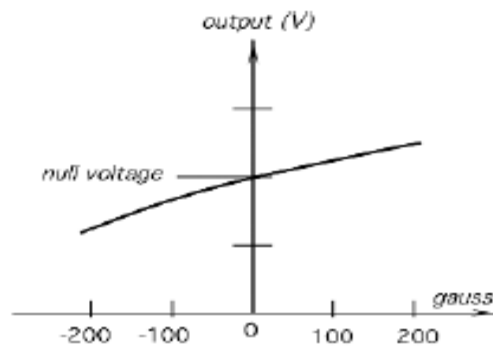
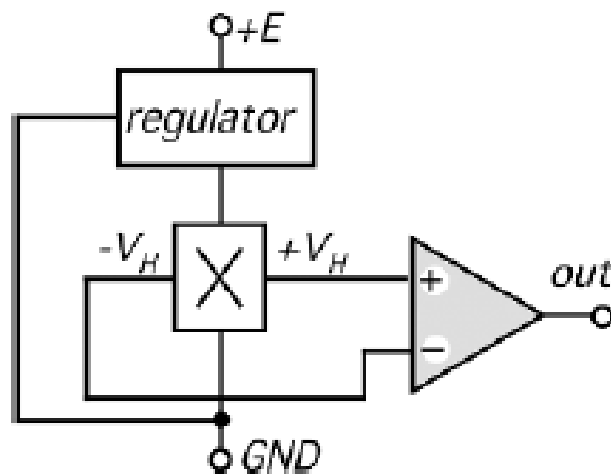




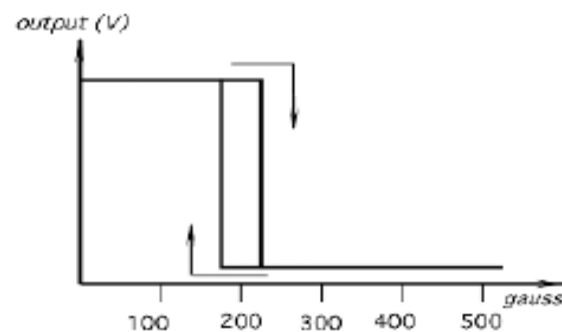
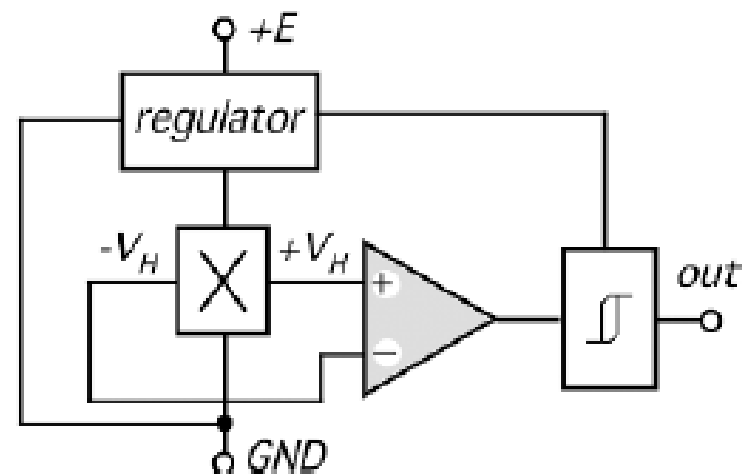
Circuit description

- Terminals for applying the control current are called the *control* terminals and the resistance between them is called the *control resistance* R_i .
- Terminals where the output voltage is observed are called the *differential output terminals* and the resistance between them is called the *differential output resistance*, R_0 .

Circuit diagram of linear and threshold hall effect sensor



(A)



(B)

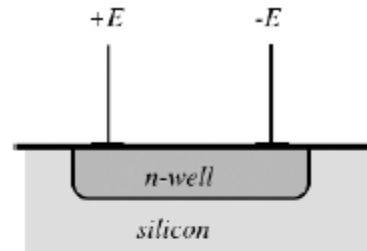
- Many Hall effect sensors are fabricated from silicon and fall into two general categories:
 - The basic sensors
 - The integrated sensors
- Materials used for the element fabrication include InSb, InAs, Ge, and GaAs

- Hall effect sensor contain built in electronics interface circuit which contain threshold device.
- Because of this two states sensor will act as two state device.
 - Output zero when magnetic field below threshold
 - Output one when magnetic field above threshold
- Because of photo resistivity of silicon, all hall effect sensors susceptible to mechanical stress effect.

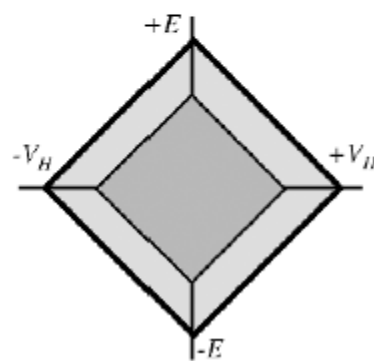


- If the sensor element is supplied with voltage source temperature will change the control resistance.
- It is preferred to connect the control terminal to current source rather than voltage source

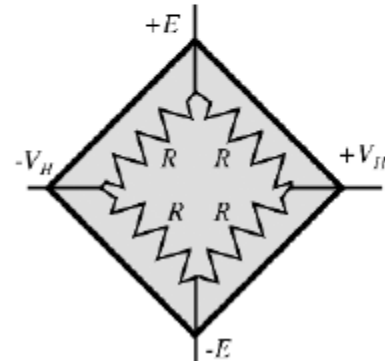
Silicon hall effect sensor with n-well and its equivalent circuit



(A)



(B)



(C)



$$C_H = \frac{1}{qN_C} \quad (5.2)$$

EXAMPLE 5.1

In a typical Hall sensor application, $I = 1 \text{ mA}$, $B = 0.1 \text{ T}$, $t_h = 10 \text{ }\mu\text{m}$, and $C_H = 0.006 \text{ m}^3 \cdot \text{C}^{-1}$ (or $\text{m}^3 \cdot \text{A}^{-1} \cdot \text{s}^{-1}$). Find the Hall voltage V_H .

SOLUTION

Apply Equation 5.1:

$$V_H = \frac{C_H}{t_h} IB = \frac{0.006 \text{ m}^3 \cdot \text{C}^{-1}}{10 \times 10^{-6} \text{ m}} (1 \times 10^{-3} \text{ A})(0.1 \text{ T}) = 0.06 \text{ V or } 60 \text{ mV}$$

A geometry factor, G_H , is introduced to represent this influence:

$$V_H = G_H \frac{C_H}{t_h} IB \quad (5.4)$$

Ideally, $G_H=1$. In real Hall devices, G_H has values between 0.7 and 0.9.

EXAMPLE 5.2

A Hall sensor is made of a copper foil. Its Hall coefficient is $7.42 \times 10^{-11} \text{ m}^3 \cdot \text{C}^{-1}$, thickness is $25 \mu\text{m}$, and geometry factor is 0.8. If a 1 A current flows through the foil and the applied magnetic field is 1 T, find the Hall voltage.

SOLUTION

Apply Equation 5.4:

$$V_H = G_H \frac{C_H}{t_h} IB = (0.8) \frac{7.42 \times 10^{-11} \text{ m}^3 \cdot \text{C}^{-1}}{25 \times 10^{-6} \text{ m}} (1 \text{ A})(1 \text{ T}) = 2.37 \times 10^{-6} \text{ V}$$



5.2.1.1 Hall Effect in Metals

In metals, the number of charge carriers per cubic meter, N_C , can be calculated by

$$N_C = \frac{C_A}{M_m} D_g \quad (5.5)$$

where C_A is the *Avogadro constant* ($6.02 \times 10^{23} \text{ mol}^{-1}$), M_m is the *molar mass* of the metal ($\text{g} \cdot \text{mol}^{-1}$), and D_g is *specific gravity* of the metal ($\text{g} \cdot \text{cm}^{-3}$).

EXAMPLE 5.3

Find the number of charge carriers per cubic centimeter N_C and Hall coefficient C_H for a 25 μm -thick copper foil. If the applied current is 1 A and the magnetic field is 1 T, find the resultant Hall voltage, V_H , on the foil. (The molar mass of copper is $63.55 \text{ g} \cdot \text{mol}^{-1}$ and the specific gravity of copper is $8.89 \text{ g} \cdot \text{cm}^{-3}$.)



SOLUTIONS

Apply Equation 5.5:

$$\begin{aligned} N_C &= \frac{C_A}{M_m} D_g = \frac{6.02 \times 10^{23} \text{ mol}^{-1}}{63.55 \text{ g} \cdot \text{mol}^{-1}} \times 8.89 \text{ g} \cdot \text{cm}^{-3} = 8.42 \times 10^{22} \text{ cm}^{-3} \\ &= 8.42 \times 10^{28} \text{ m}^{-3} \end{aligned}$$

Apply Equation 5.2:

$$C_H = \frac{1}{qN_C} = \frac{1}{(1.602 \times 10^{-19} \text{ C})(8.42 \times 10^{28} \text{ m}^{-3})} = 7.41 \times 10^{-11} \text{ m}^3 \cdot \text{C}^{-1}$$

Apply Equation 5.1:

$$V_H = \frac{IB}{qN_C t_h} = \frac{(1 \text{ A})(1 \text{ T})}{(1.602 \times 10^{-19} \text{ C})(8.42 \times 10^{28} \text{ m}^{-3})(25 \times 10^{-6} \text{ m})} = 2.97 \times 10^{-6} \text{ V}$$

This result shows that the Hall voltage produced by a copper foil is extremely small. For this reason, it is not practical to make Hall-effect sensors with most metals.



Hall Effect in Semiconductors

EXAMPLE 5.4

A Hall sensor made from an n-type silicon has been doped to a level of $4 \times 10^{15} \text{ cm}^{-3}$. If its thickness is $25 \mu\text{m}$, the current is 1 mA , and the magnetic field is 1 T , find the sensor's output voltage V_H .

SOLUTION

$$V_H = \frac{IB}{qN_{ct_h}} = \frac{(1 \times 10^{-3} \text{ A})(1 \text{ T})}{(1.602 \times 10^{-19} \text{ C})(4 \times 10^{21} \text{ m}^{-3})(25 \times 10^{-6} \text{ m})} = 0.0624 \text{ V} = 62.4 \text{ mV}$$

TABLE 5.2

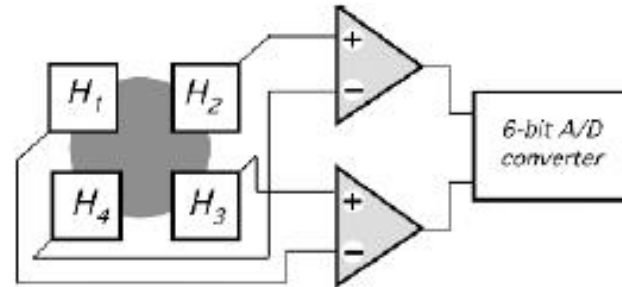
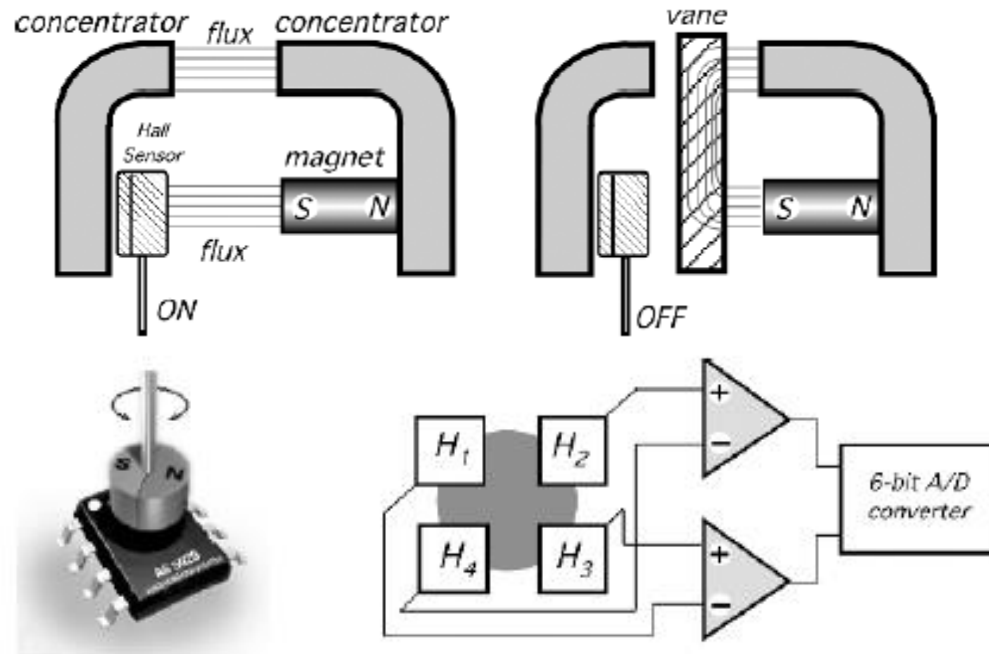
Commonly Accepted Values of Intrinsic Carrier Concentrations at 300 K

Semiconductor Material	Carrier Concentration (m^{-3})
Silicon (Si)	1.4×10^{16} – 1.5×10^{16}
Germanium (Ge)	2.1×10^{19} – 2.4×10^{19}
Gallium-arsenide (GaAs)	1.8×10^{12} – 11.0×10^{12}



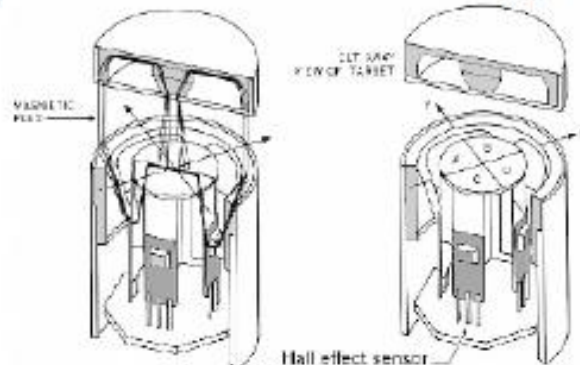
The above result shows that a doped semiconductor Hall sensor can provide 21,000 times ($=0.0624/(2.97 \times 10^{-6})$) of Hall voltage as a copper sensor does. Also the bias current (1 mA) applied is only 1/1000 of the bias current (1 A) used in the copper sensor. Therefore, the doped semiconductor Hall sensors provide more practical functions than metal Hall sensors.

Application



(A)

(B)





Magnetic Material

- Neodymium-Iron-Boron magnets (NdFeB) • affordable price, • high pole strength for size, • almost no demagnetization, • room temperature preferential • sensitive to corrosion in hot environment
- Cobalt-Samarium magnets (SmCo) • relatively expensive, • high pole strength for size, • almost no demagnetization • large range of temperatures
- Aluminium-Nickel-Cobalt (AlNiCo) • magnetically very stable • operation up to 500°C , • demagnetization possible • mechanically sensitive, brittle
- Ceramic magnets from hard ferrite material • only simple shape • temperature range between • low price SmCo and AlNiCo



Jhon.s.wilson, pavel ripka

MAGNETORESISTIVE

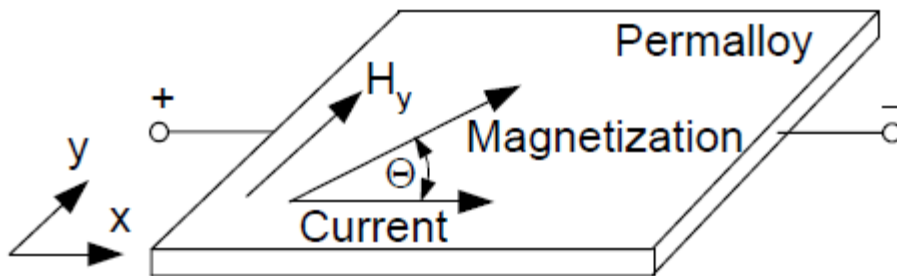


Hall effect Vs Magneto resistive sensor

- A **Hall effect** device derives its output from **magnetic field strength**, while a **magneto resistive** device measures the **angle direction of a magnetic field**, so its output is based on the electrical resistance of the field. Some of the advantages of measuring field direction vs. field strength include:
 - Insensitivity to the temperature coefficient of the magnet,
 - Less sensitivity to shock and vibration, and
 - The ability to withstand large variations in the gap between the sensor and the magnet.

Magneto resistive working

The AMR effect is due to the quantum mechanical scattering of electrons by the magnetized states of the material.



$$\sin \theta = \frac{H_y}{H_x} \quad \text{for } H_y < H_x$$

$$R(H_Y) = R_0 + \Delta R \left[1 - \left(\frac{H_Y}{H_0} \right)^2 \right] = R_0 + \Delta R \cos^2 \Theta$$



History

- [William Thomson \(Lord Kelvin\)](#) first discovered ordinary magnetoresistance in 1856. He experimented with pieces of iron and discovered that the resistance increases when the current is in the same direction as the magnetic force and decreases when the current is at 90° to the magnetic force. He then did the same experiment with nickel and found that it was affected in the same way but the magnitude of the effect was greater. This effect is referred to as anisotropic magnetoresistance (AMR).
- In 2007, Albert Fert and Peter Grünberg were jointly awarded the Nobel Prize for the discovery of Giant Magnetoresistance.



History

- The effect arises from the simultaneous action of magnetization and spin-orbit interaction and its detailed mechanism depends on the material.
- It can be for example due to a larger probability of s-d scattering of electrons in the direction of magnetization (which is controlled by the applied magnetic field).
- The net effect (in most materials) is that the electrical resistance has maximum value when the direction of current is parallel to the applied magnetic field

AMR

In polycrystalline ferromagnetic materials, the AMR can only depend on the angle $\varphi = \psi - \theta$ between the magnetization and current direction and (as long as the resistivity of the material can be described by a rank-two tensor), it must follow^[9]

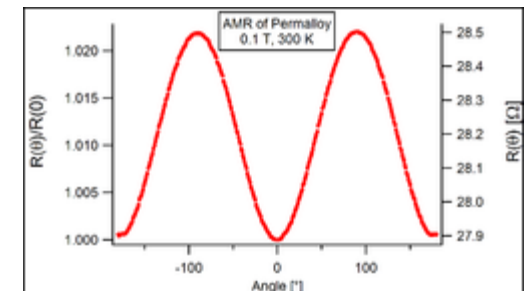
$$\rho(\varphi) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2 \varphi$$

where ρ is the (longitudinal) resistivity of the film and $\rho_{\parallel, \perp}$ are the resistivities for $\varphi = 0$ and 90° , respectively. Associated with longitudinal resistivity, there is also transversal resistivity dubbed (somewhat confusingly^[1]) the planar Hall effect. In monocrystals, resistivity ρ depends also on ψ, θ individually.

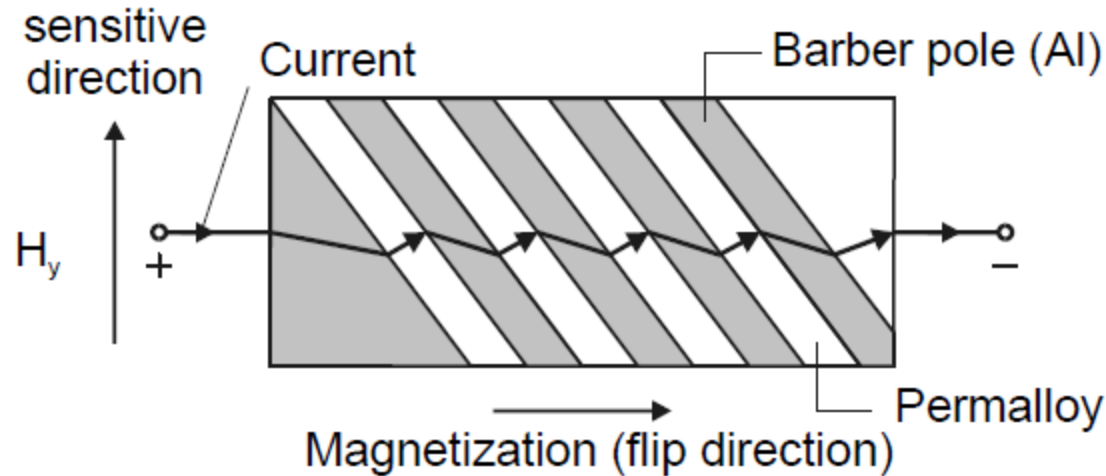
As theoretical aspects, I. A. Campbell, A. Fert, and O. Jaoul (CFJ)^[10] derived an expression of the AMR ratio for Ni-based alloys using the two-current model with s-s and s-d scattering processes, where s is a conduction electron and d is 3d states with the spin-orbit interaction. The AMR ratio is expressed as

$$\frac{\Delta\rho}{\rho} = \frac{\rho_{\parallel} - \rho_{\perp}}{\rho_{\perp}} = \gamma(\alpha - 1),$$

with $\gamma = (3/4)(A/H)^2$ and $\alpha = \rho_{\downarrow}/\rho_{\uparrow}$, where A , H , and ρ_{σ} are a spin-orbit coupling constant (so-called ξ), an exchange field, and a resistivity for spin σ , respectively. In addition, recently, Satoshi Kokado et al.^{[11] [12]} have obtained the general expression of the AMR ratio for 3d transition-metal ferromagnets by extending the CFJ theory to a more general one. The general expression can also be applied to half-metals.



Magneto resistive working



$$R = R_0 + \Delta R \cos^2(\Theta + 45^\circ)$$

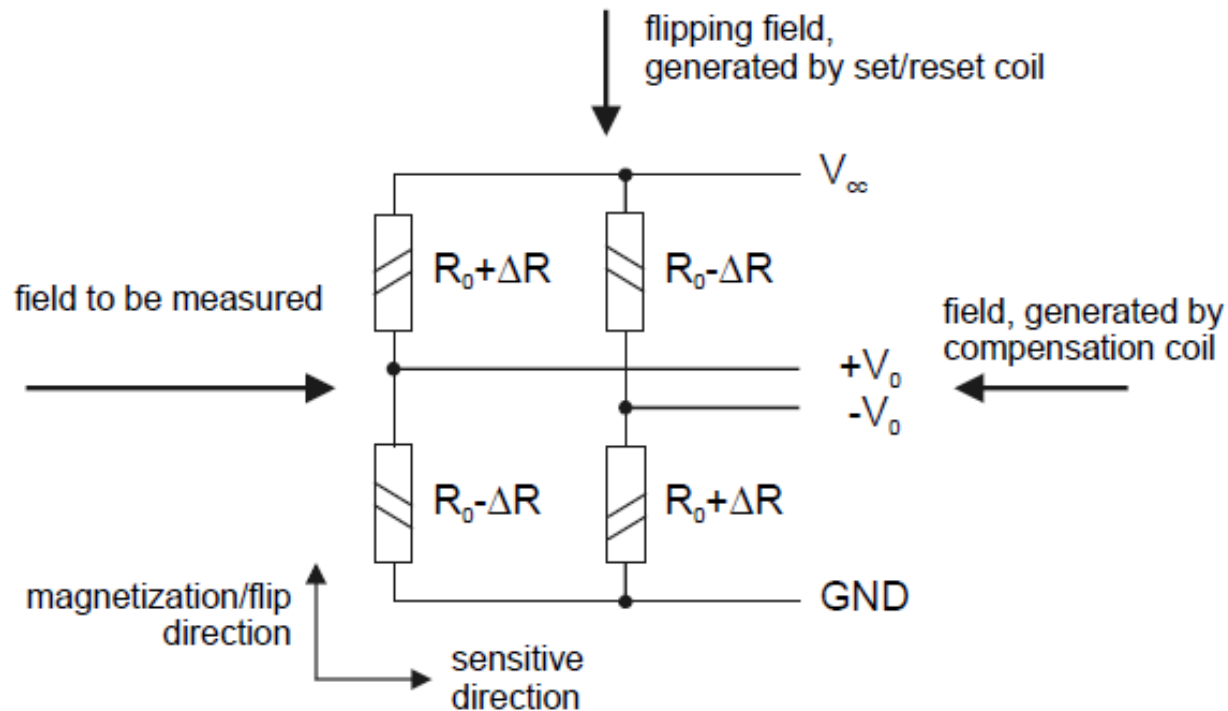
We obtain the result:

$$R = R_0 \pm \Delta R \frac{H_y}{H_0} \sqrt{1 - \left(\frac{H_y}{H_0}\right)^2}$$

When $H_y \ll H_0$

$$R = R_0 \pm \Delta R \frac{H_y}{H_0}$$

Wheatstone bridge



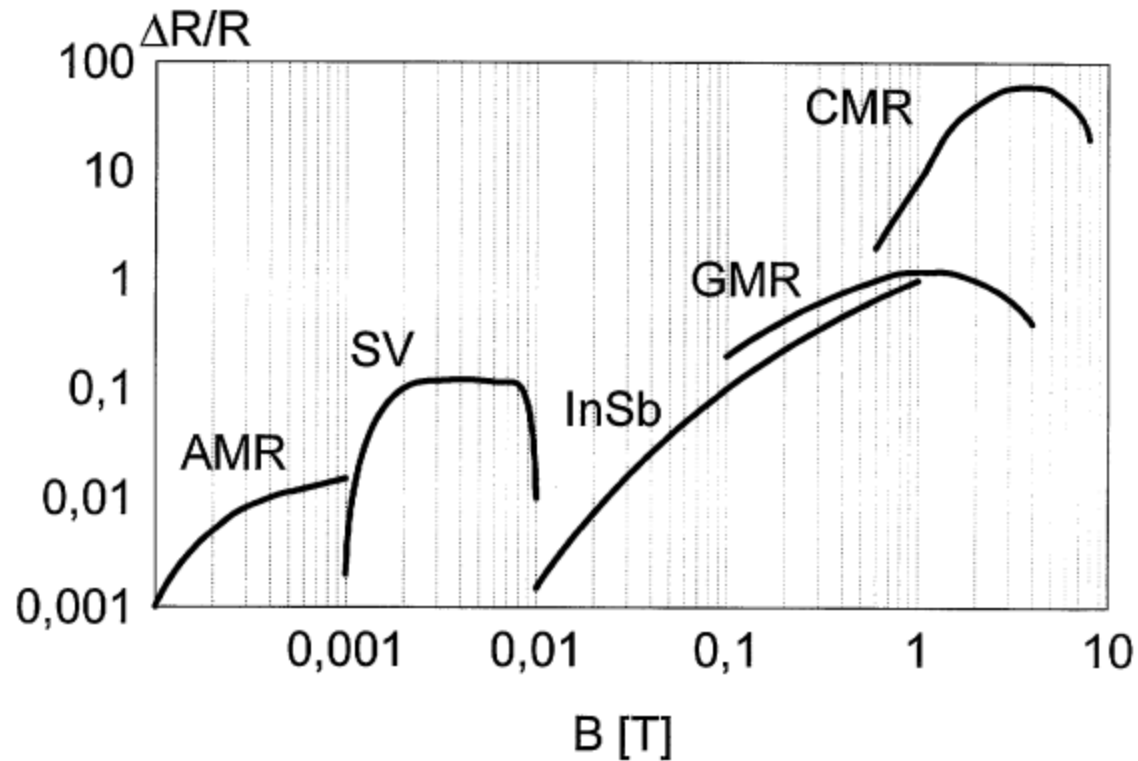
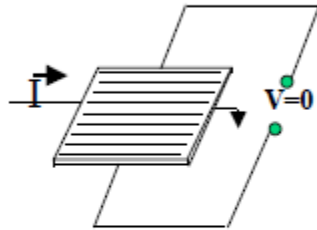


Figure 1.9 The typical field range of various magnetoresistive sensors – AMR: anisotropic magnetoresistance; SV: spin valve sensors; InSb: semiconductor magnetoresistors; GMR: multilayer GMR sensors; CMR: colossal magnetoresistance (Heremans 1993).

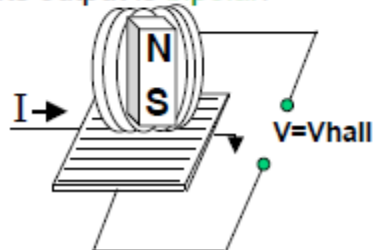
Comparison

Hall-effect Sensing Mechanism

- The current source is applied through a thin sheet of semiconductor material.

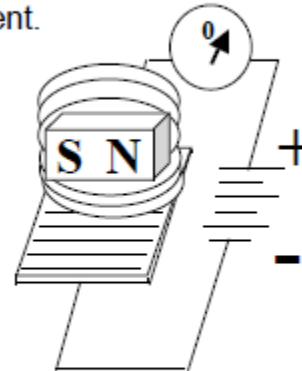


- A magnetic field applied **perpendicular** to the element creates a voltage change = V_{hall} . Its output is **bipolar**.

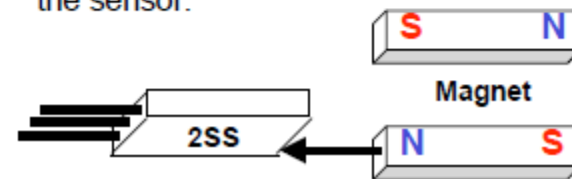


Magnetoresistive Sensing Mechanism

- A magnetic field applied **parallel** to the element changes its resistance and creates a current.



- MR is **omnipolar**—either pole will operate the sensor.



Source: Honeywell technologies



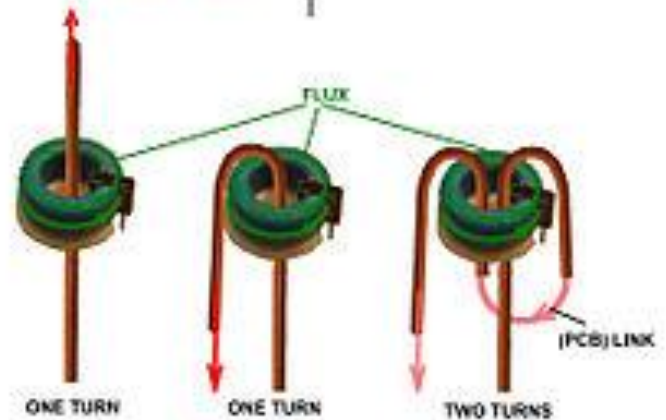
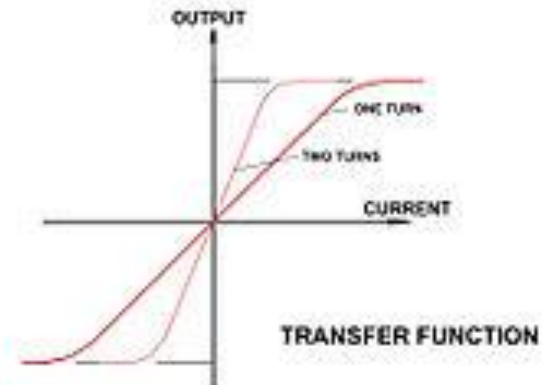
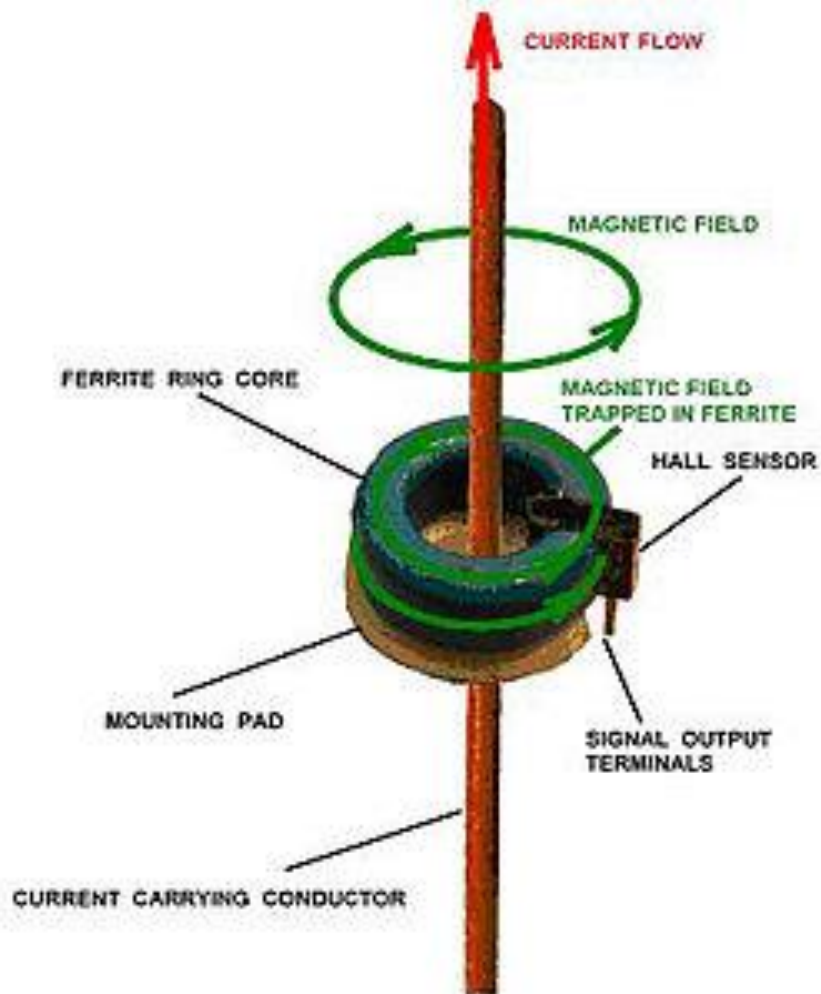
Design Factor-magnetic types

- **Unipolar:** Only a south pole will operate the sensor. The sensor turns on with the south pole(+) and off when the south pole is removed.
- **Bipolar:** Sensor output is pole-dependent. A south pole (+) is designed to activate the sensor; a north pole(-) is designed to deactivate. It's possible that the sensor could turn off and still be within a positive Gauss level.
- **Latching:** Specifications are tighter on latching. Sometimes it is designed to make certain that when the south pole(+) is removed from the sensor, it will stay on until it sees the opposite pole(-).
- **Omnipolar:** The sensor is designed to operate with either magnetic pole(+ or -).
- **Ratiometric linear:** Output is proportional to magnetic field strength. Output sensitivity range is 2.5 – 3.75 mV per unit of Gauss.



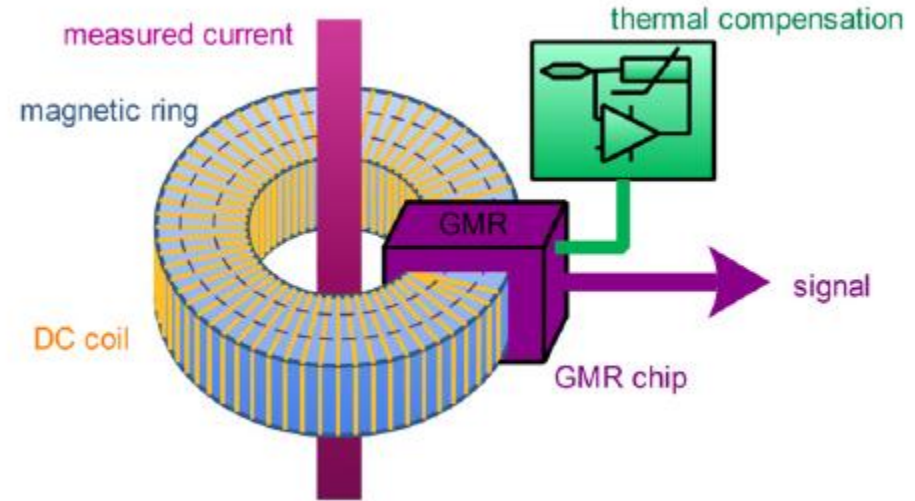
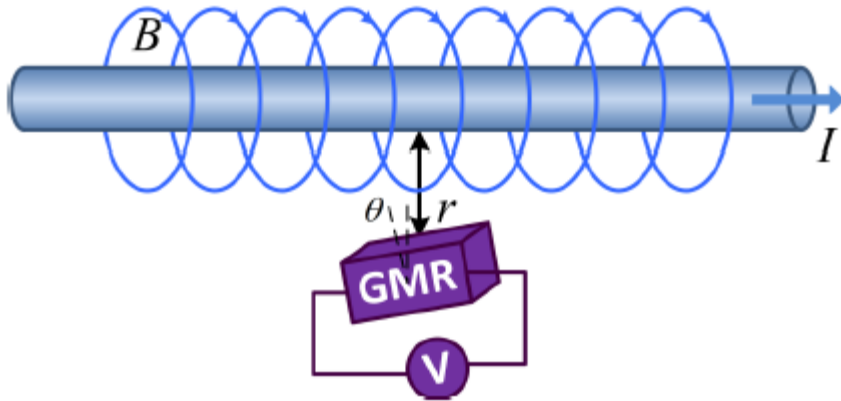
CURRENT SENSOR

Hall current sensor



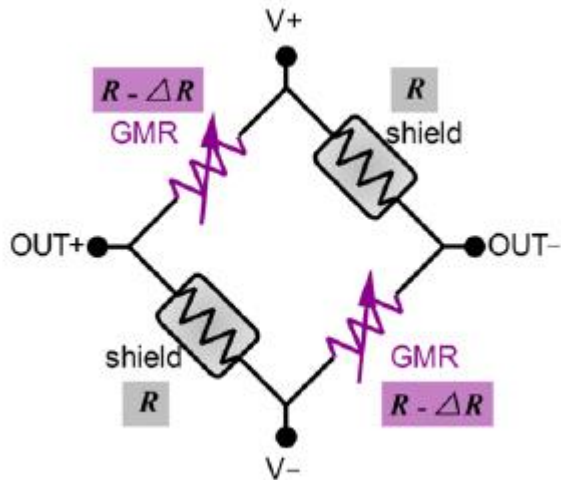
EFFECT OF CONDUCTOR PASSES THROUGH CORE

Magnetoresistive current sensor



Output voltage:

$$V = F_{GMR}(I, f, T, V_S, \phi, \Pi, r, B_D)$$



$$V_{out+} = \frac{R}{2R - \Delta R}(V_+ - V_-) + V_-$$

$$V_{out-} = \frac{R - \Delta R}{2R - \Delta R}(V_+ - V_-) + V_-$$

$$V_{out+} - V_{out-} = \frac{\Delta R}{2R - \Delta R}(V_+ - V_-) \approx \frac{\Delta R}{2R}(V_+ - V_-)$$



Giant magnetic resistance

- Giant magnetoresistance (GMR) is a quantum mechanical magnetoresistance effect observed in thin-film structures composed of alternating ferromagnetic and non-magnetic conductive layers. The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grünberg for the discovery of GMR.
- The effect is observed as a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment. The overall resistance is relatively low for parallel alignment and relatively high for antiparallel alignment. The magnetization direction can be controlled, for example, by applying an external magnetic field. The effect is based on the dependence of electron scattering on the spin orientation.
- The main application of GMR is magnetic field sensors, which are used to read data in hard disk drives, biosensors, microelectromechanical systems (MEMS) and other devices. GMR multilayer structures are also used in magnetoresistive random-access memory (MRAM) as cells that store one bit of information.



Heading Sensor

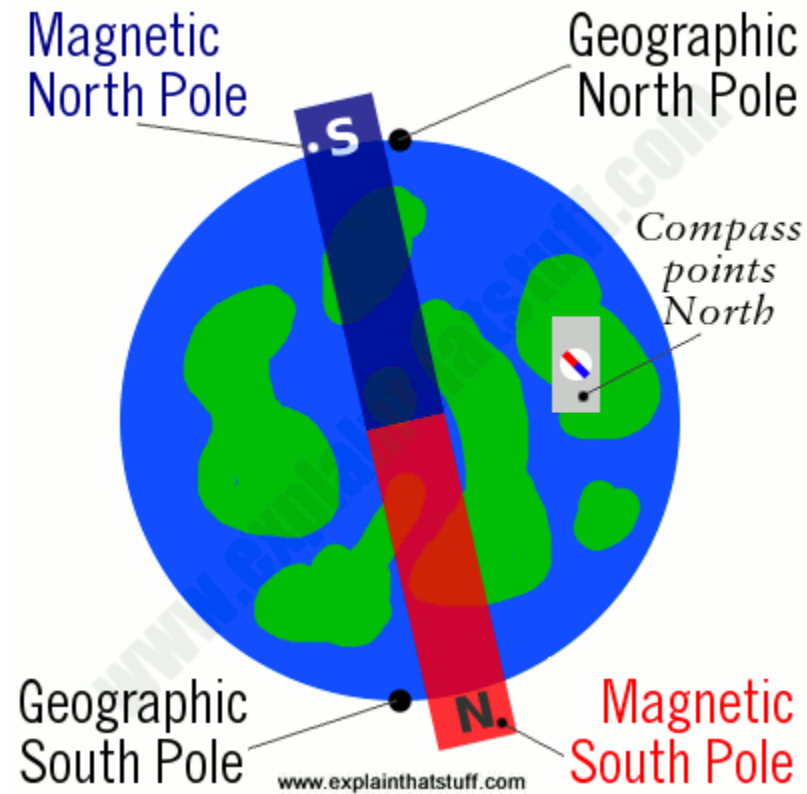
Lecture-12

R.MATHIAZHAGAN

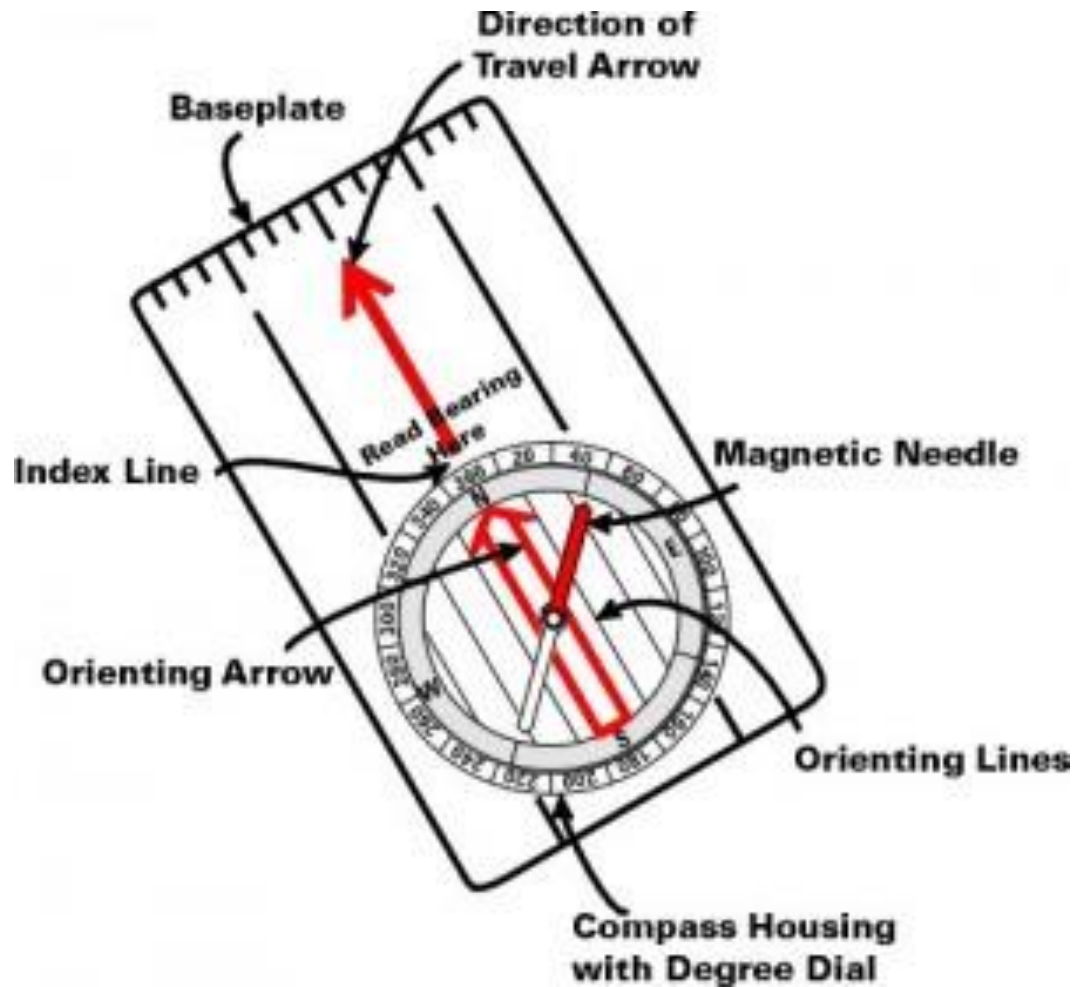
TEACHING FELLOW

DEPARTMENT OF PRODUCTION
TECHNOLOGY, MIT

How Compass works?



compass

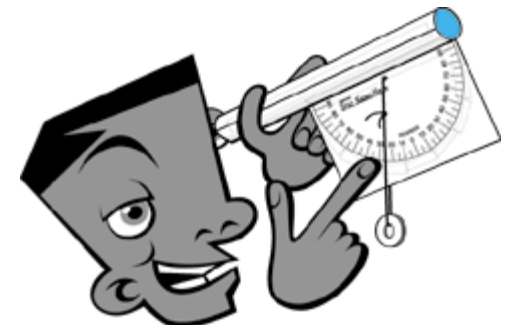
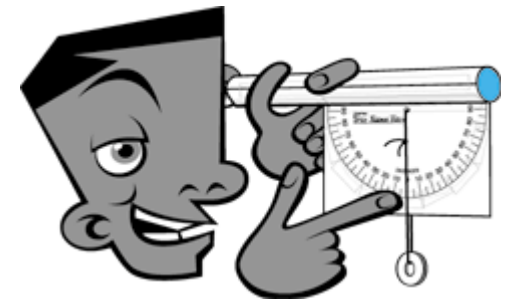




Types of compass

- Magnetic compass
- Gyro compass
- Astrocompass
- Solid state compass
- GPS compass
- Marine compass
- Thumb compass
- Prismatic compass

Inclinometer



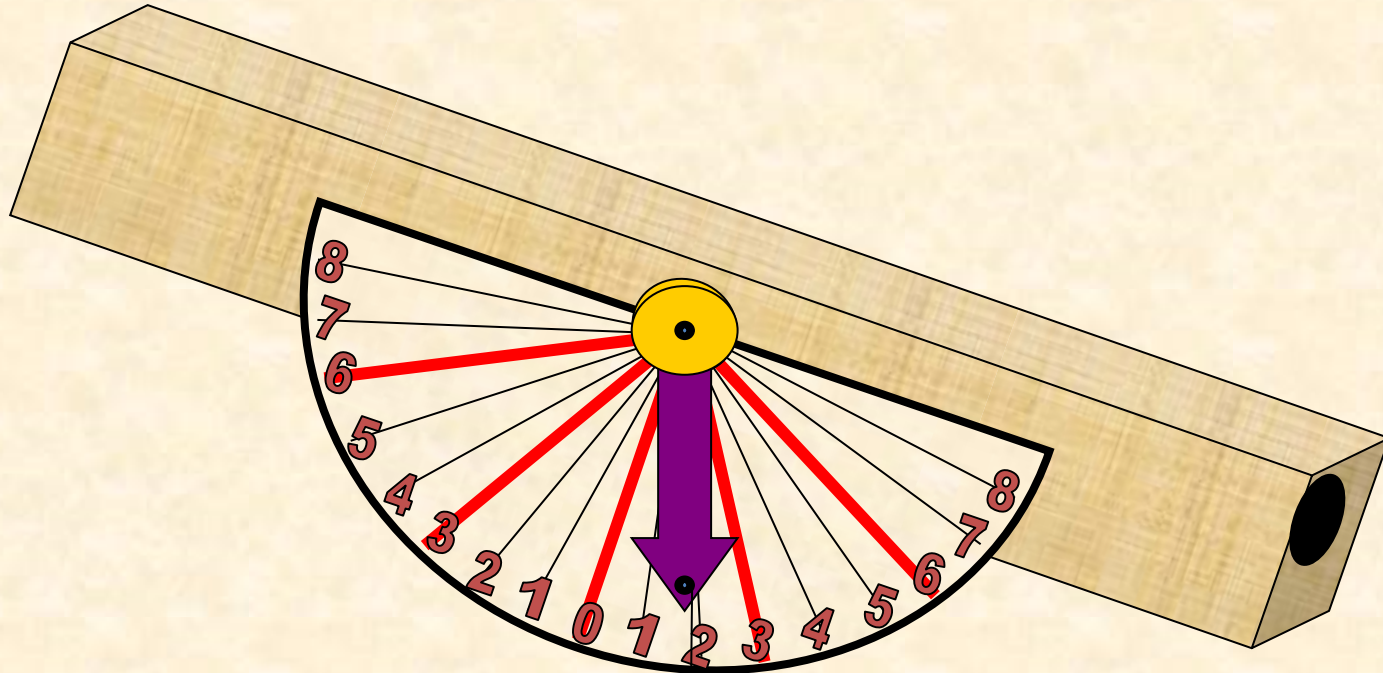


Definition

-https://www.exploratorium.edu/math_explorer/howHigh_useInclino.html

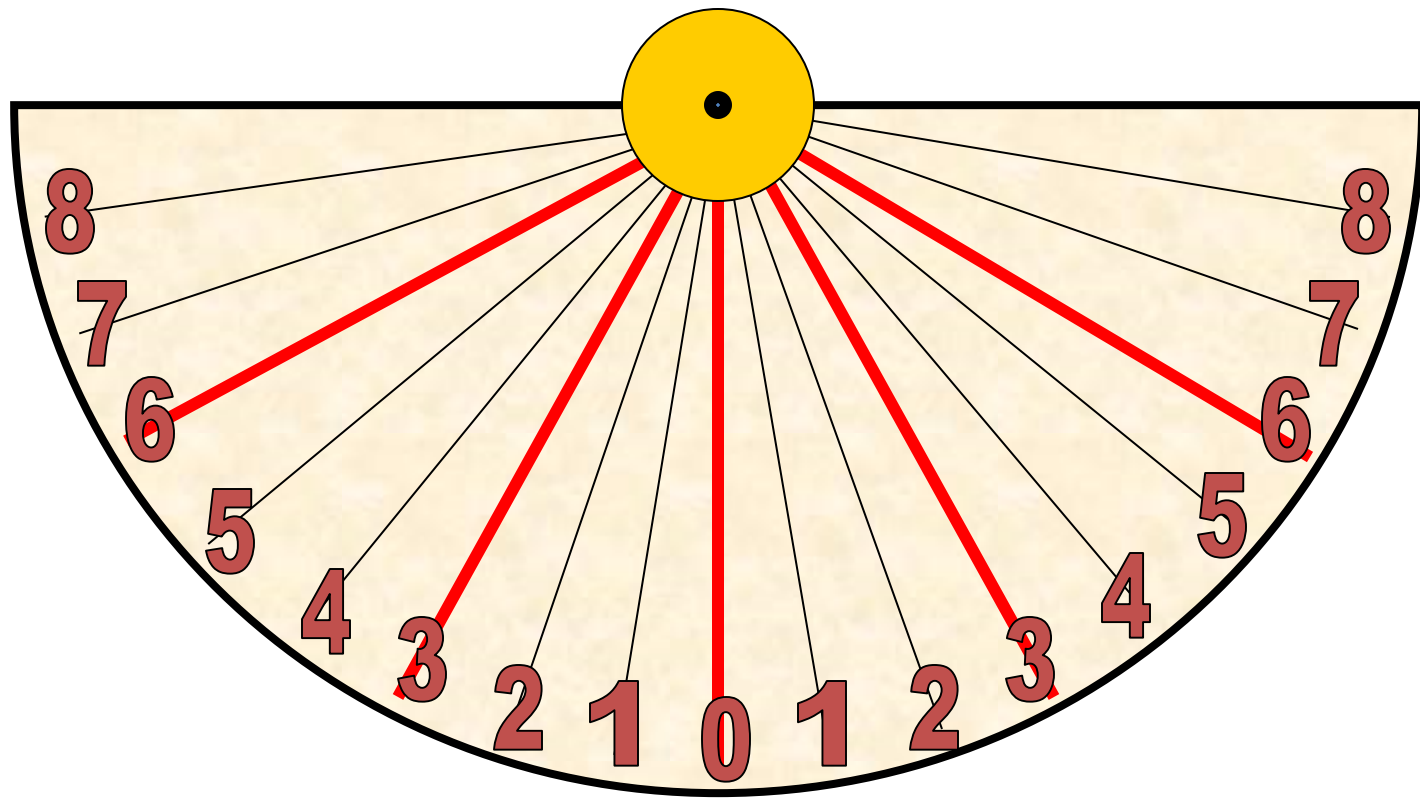
An inclinometer or clinometer is an instrument for measuring angles of slope (or tilt), elevation or depression of an object with respect to gravity. It is also known as a tilt meter, tilt indicator, slope alert, slope gauge, gradient meter, gradiometer, level gauge, level meter, declinometer, and pitch & roll indicator

-wikipedia

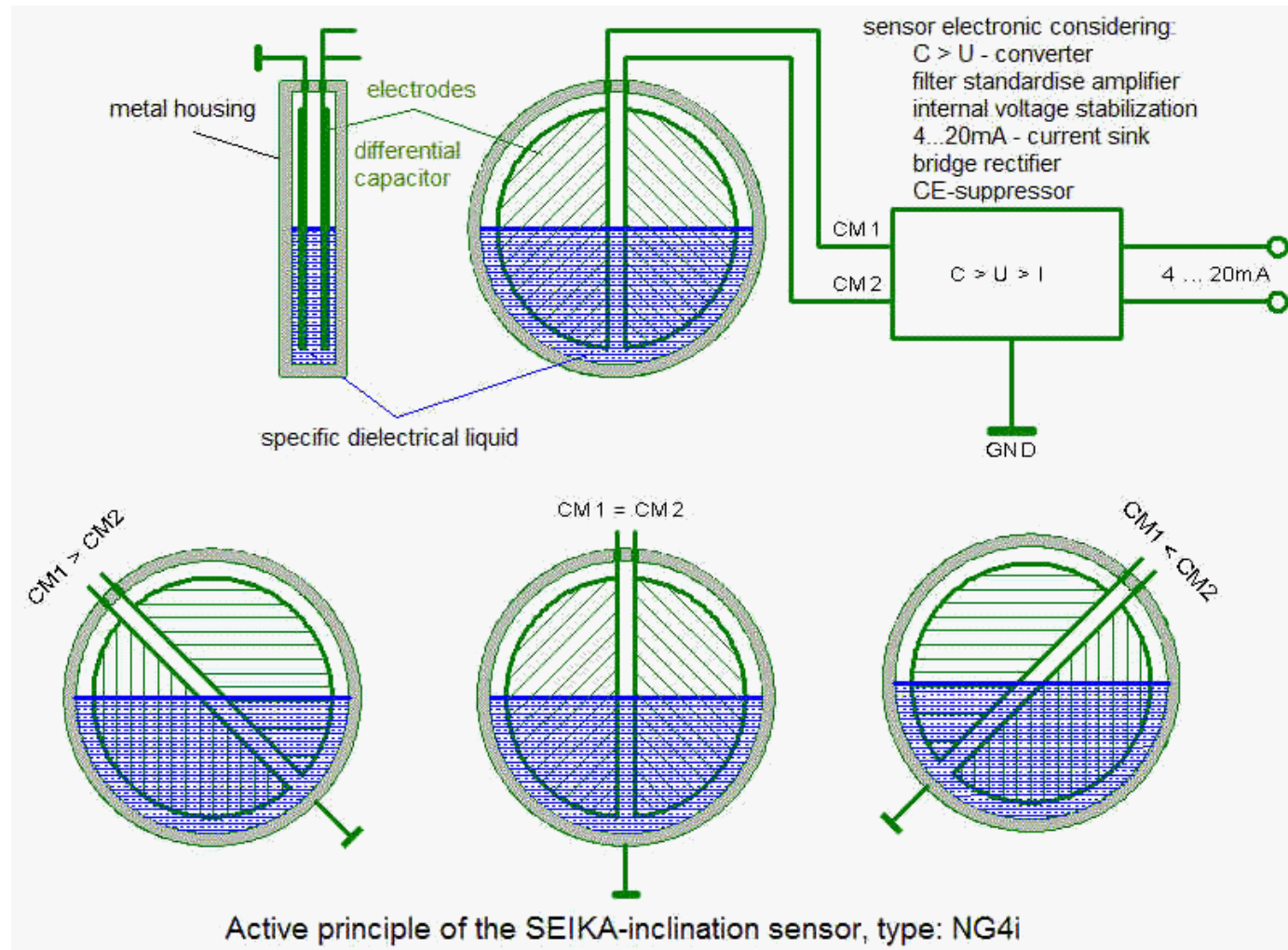


**The
Inclinometer**





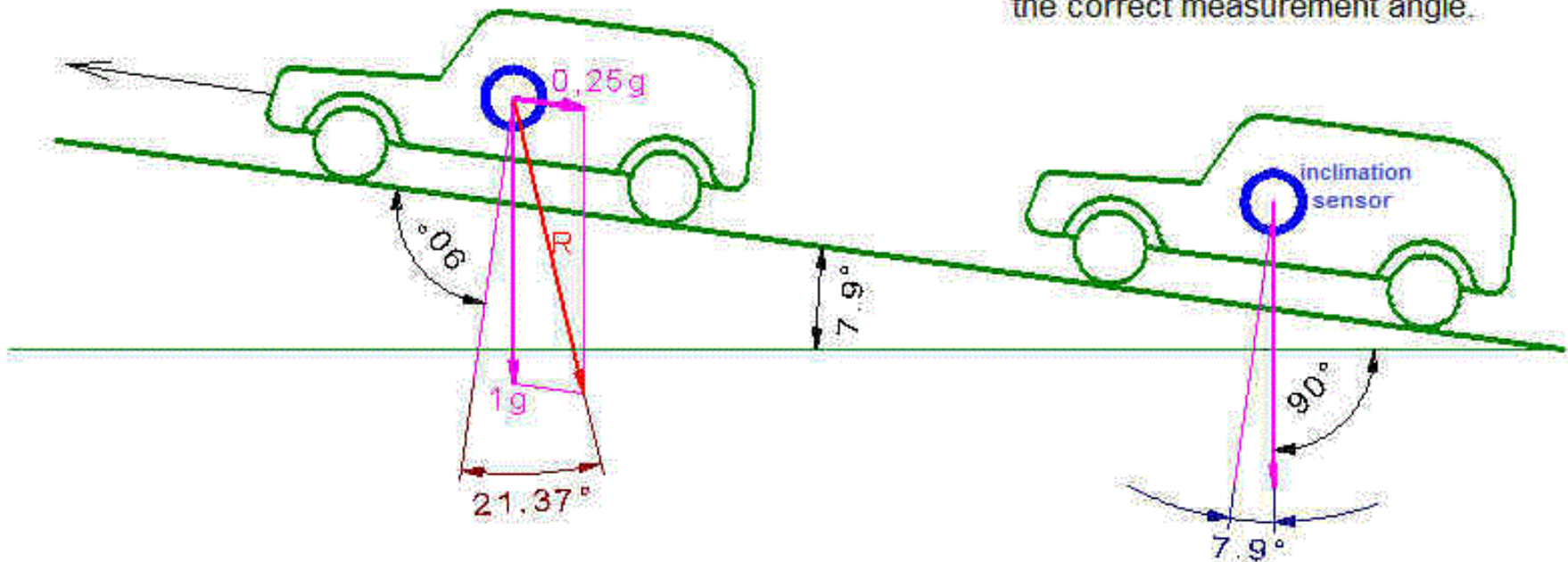
Capacitive inclinometer



error

The automobile accelerates with $0.25g$, for example. The measured inclination of the automobile is incorrect, because the sensor reacts to the resultant vector (R)!

This automobile stands or moves with constant speed, so only the earth acceleration appears. The inclination sensor is measuring the correct measurement angle.





Optical Sensor

-Jacob Fraden

Light Detectors(Electromagnetic
Radiation Detector)

R.MATHIYAZHAGAN

TEACHING FELLOW

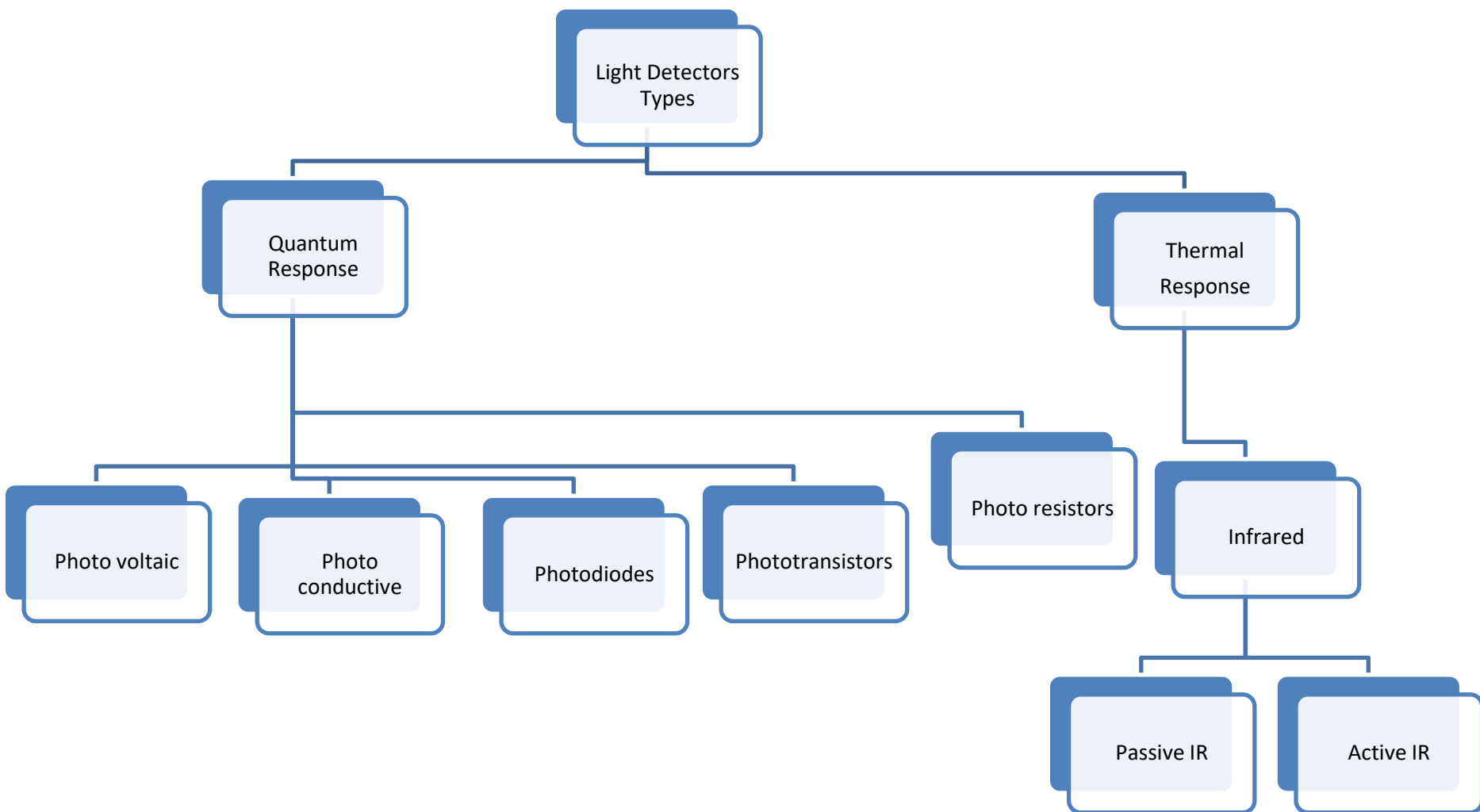
DEPARTMENT OF PRODUCTION
TECHNOLOGY, MIT



Photo detectors

- Detectors of electromagnetic radiation in the spectral range from ultraviolet to far infrared are called light detectors

Types





Quantum response

Principle:

- *“Solid-state quantum detectors (photovoltaic and photoconductive devices) rely on the interaction of individual photons with a crystalline lattice of semiconductor materials”*
- In certain circumstances light energy was concentrated into bundles and it is named as photons. The energy of single photon is given by

$$E = h\nu$$

- ν is the frequency of light and $h=6.626075 \times 10^{-34} \text{ J s}$ (or $4.13567 \times 10^{-15} \text{ eVs}$) is Planck's constant

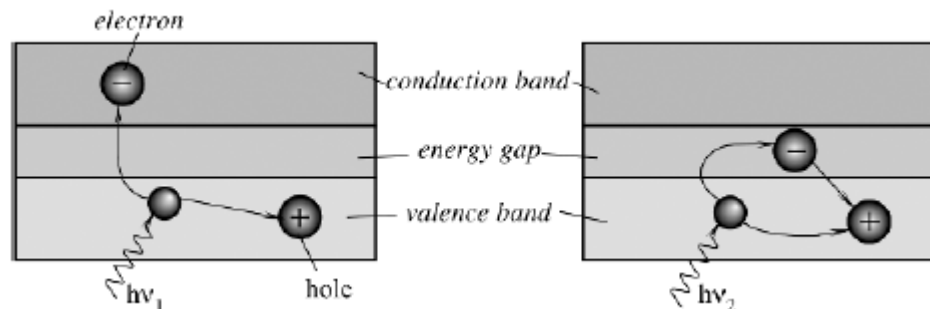
Quantum response

- All devices that **directly convert photons of electromagnetic radiation into charge carriers** are called *quantum detectors* and are generally produced in a form of photodiodes, phototransistors, and photoresistors.
- The photoelectric effect can be described as

$$h\nu = \phi + K_m$$

Where, ϕ -(work function) this part used to detach electron from surface

K_m -(maximum kinetic energy) This part used to give kinetic energy for the electron



Quantum response for high and low energy



Conductivity

- Light of a proper wavelength [sufficiently high energy of photons strikes a semiconductor crystal, the concentration of charge carriers (electrons and holes) in the crystal increases, which manifests in the increased conductivity of a crystal

$$\sigma = e(\mu_e n + \mu_h p)$$

where, e is the electron charge,

μ_e is the electron mobility,

μ_h is the hole mobility, and

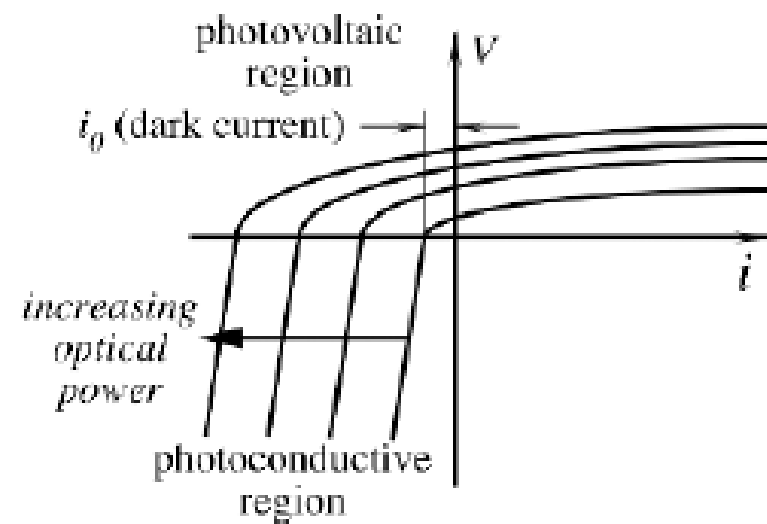
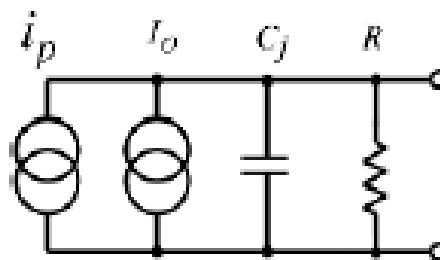
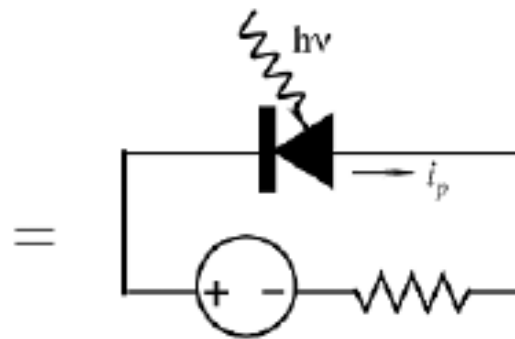
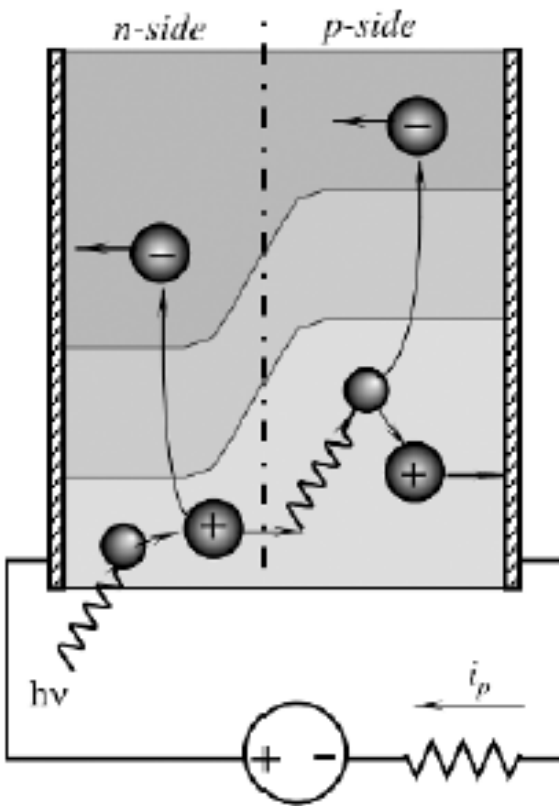
n and p are the respective concentrations of electrons and holes



Characteristics of Photo detector

- Noise equivalent power
- IR cutoff wavelength
- Maximum current
- Maximum reverse voltage
- Radiation responsivity
- Field of view
- Junction capacitance

Photodiode



Equivalent circuit of Photodiode

Structure of Photo diode

Optical power Vs electric current

- Average rate of production of electrons(r)

$$\langle r \rangle = \frac{\eta P}{h\nu}$$

Where, P = optical power

η = probability that a photon
of energy $h\nu$ will produce an electron

- The probability of the production of m electrons in some measurement interval τ is given by

$$p(m, \tau) = (\langle r \rangle \tau)^m \frac{1}{m!} e^{-\langle r \rangle \tau}$$

- *Electrical current is proportional to the optical power incident on the detector*

$$i = \langle r \rangle e = \frac{\eta e P}{h\nu},$$

Current voltage relation

The current-to-voltage response of the photodiode

$$i = i_0(e^{eV/k_bT} - 1) - i_s$$

Where, i_0 is a reverse “dark current” which is attributed to the thermal generation of electron–hole pairs, i_s is the current due to the detected optical signal, k_b is Boltzmann constant, and T is the absolute temperature

$$i = i_0(e^{eV/k_bT} - 1) - \frac{\eta e P}{h\nu}$$

Efficiency of the direct conversion
of optical power into electric power is quite low(5-10%)



Types of Photodiodes

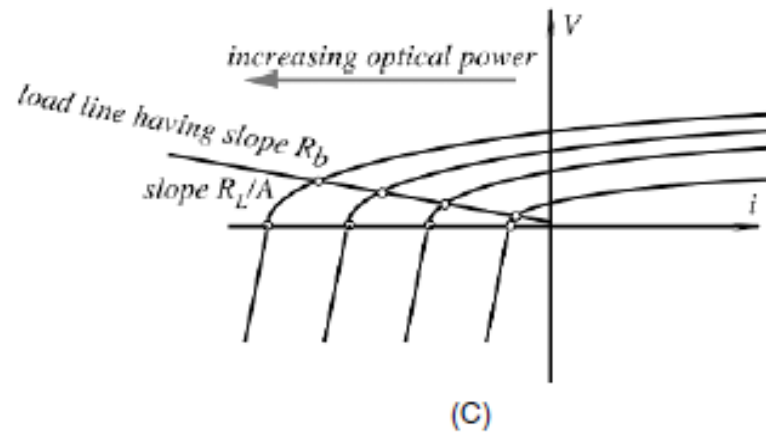
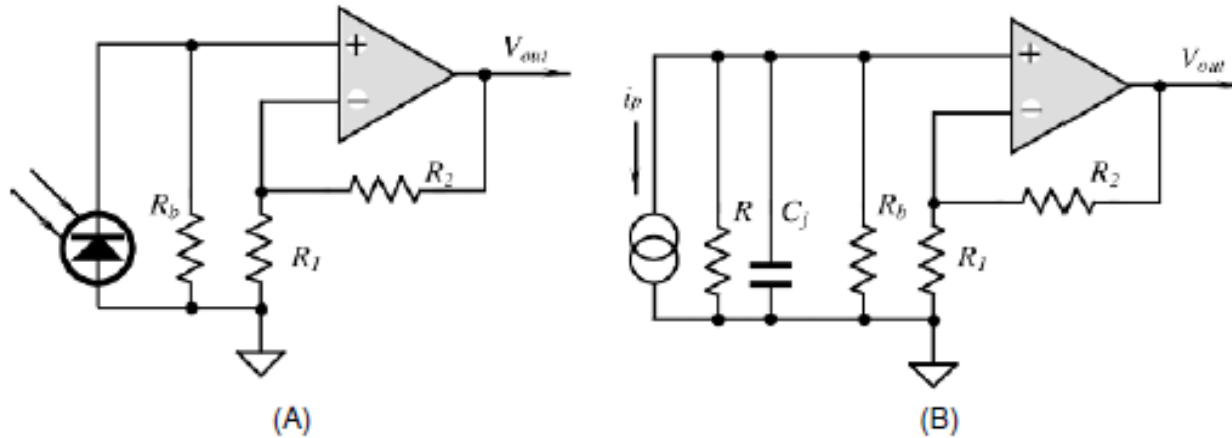
- PN Photodiode
- PIN Photodiode
- Schottky Photodiode
- Avalanche Photodiode



Photo diode Modes of operation

- Photovoltaic(PV)
- Photoconductive(PC)

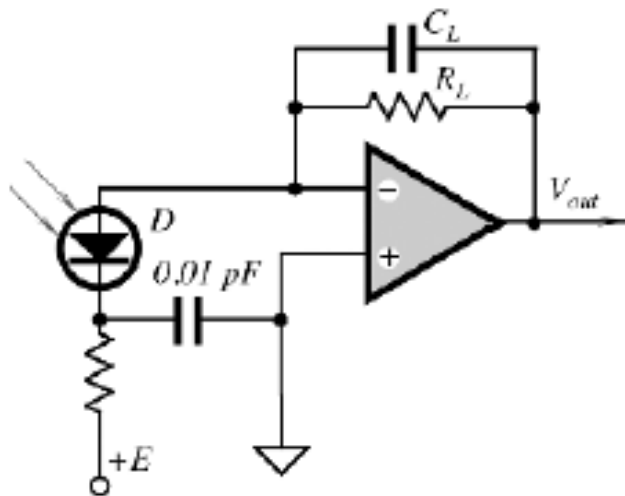
Photodiode connected in Photovoltaic mode



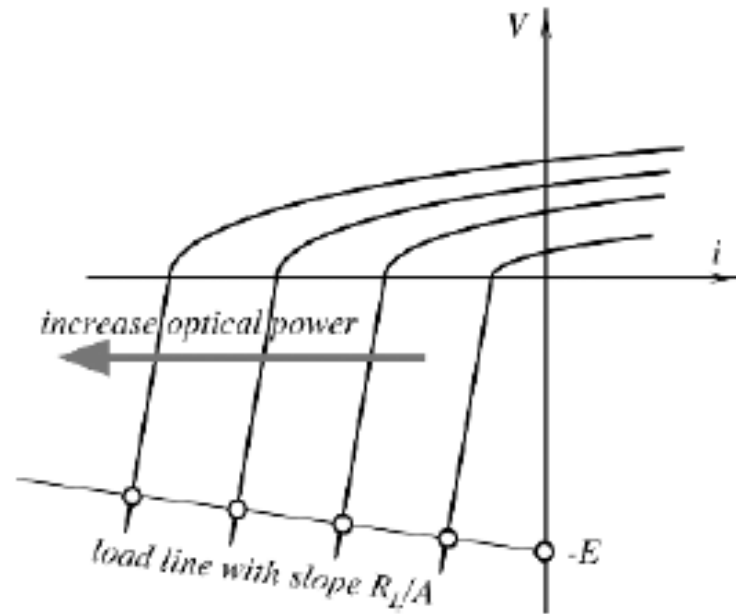
$$V_{out} = \frac{-R_L i_p}{1 + j \frac{f}{f_1}}$$

$$f_1 = 1/2\pi R_L C$$

Photoconductive mode operation

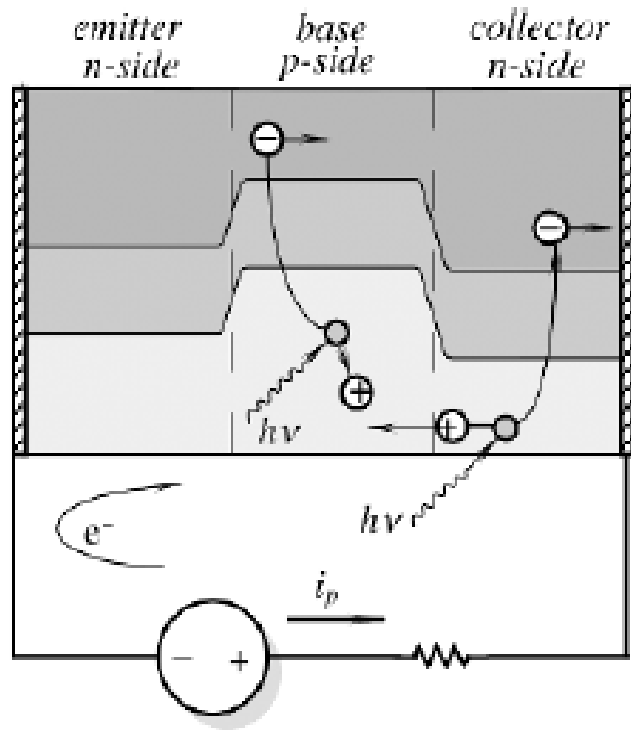


(A)



(B)

Phototransistor



=

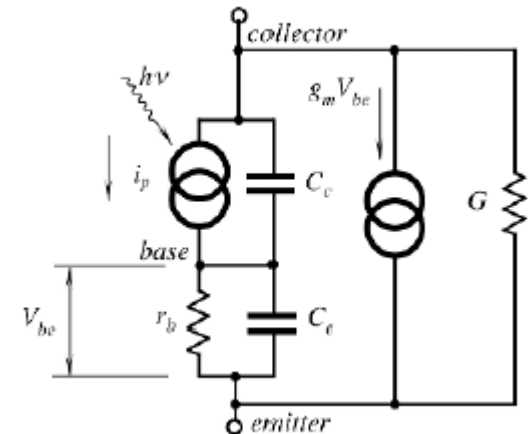
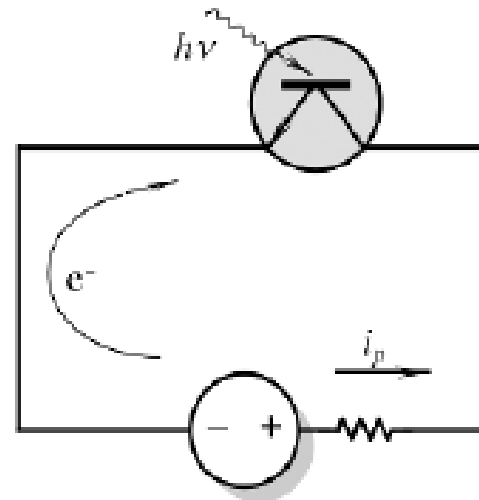
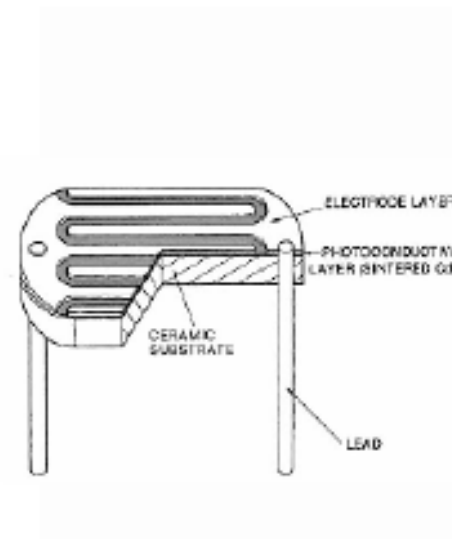
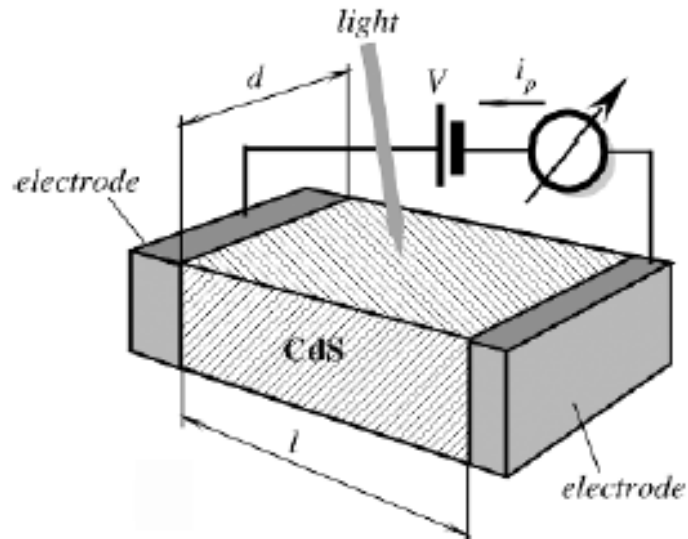


Photo resistive cell



The most common materials for its fabrication are cadmium sulfide¹ (CdS) and cadmium selenide (CdSe).



Fiber optic sensor

- Material used
- Construction
- Fabrication
- Working principle
- Characteristics
- application



THERMAL DETECTOR



Radiation Thermometry

- Thermal infrared detectors are primarily used for detecting infrared radiation in mid and far-infrared spectral ranges and noncontact temperature measurements.
- Their operating principle is based on a sequential conversion of thermal radiation into heat and, then, conversion of heat level or heat flow into an electrical signal by employing conventional methods of heat detection

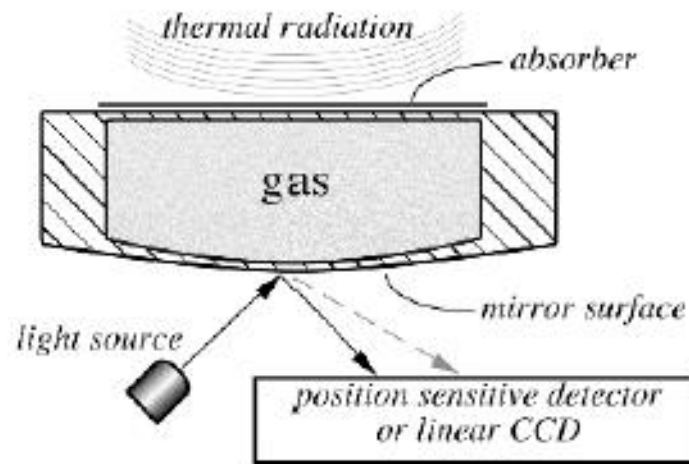


Infrared

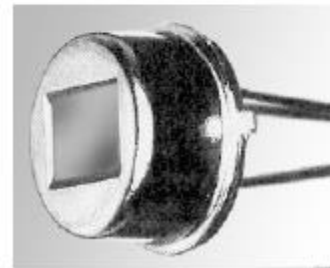
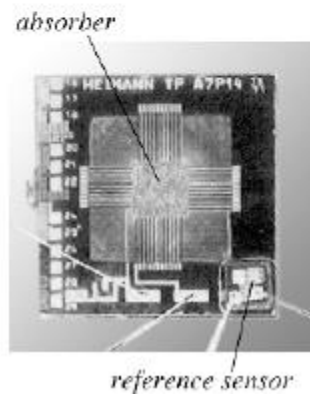
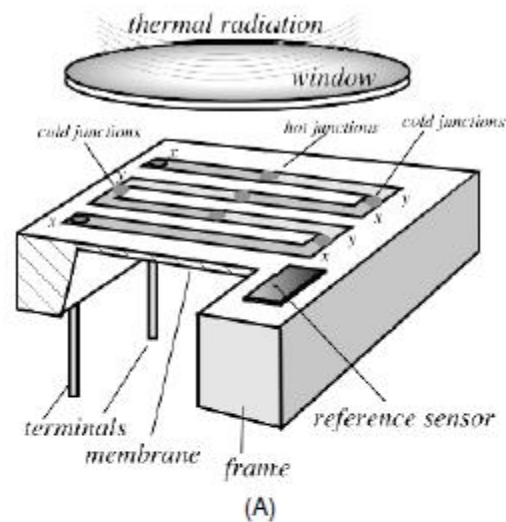
- All thermal radiation detectors can be divided into two classes: *passive infrared (PIR)* and *active far-infrared (AFIR)* detectors.
- Passive detectors absorb incoming radiation and convert it to heat, whereas
- Active detectors generate heat from the excitation circuit.

Golay cell(Thermopneumatic detectors)

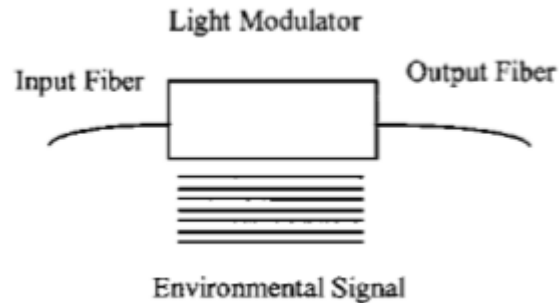
- The operating principle of the cell is based on the detection of a thermal expansion of gas trapped inside an enclosure



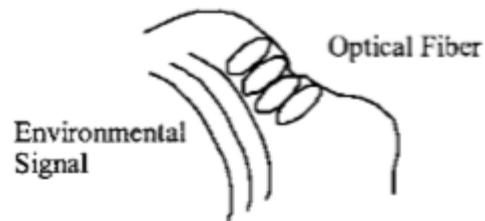
Thermopile for detecting thermal radiation



Fiber optics

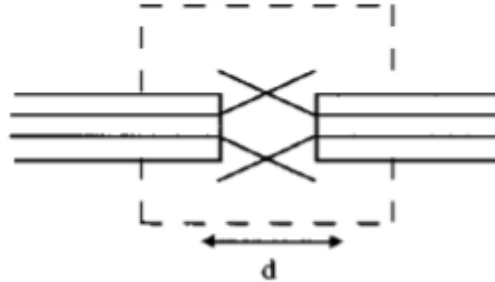


Extrinsic fiber optic sensors consist of optical fibers that lead up to and out of a “black box” that modulates the light beam passing through it in response to an environmental effect

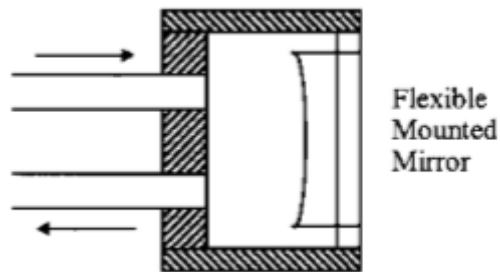


Intrinsic fiber optic sensors rely on the light beam propagating through the optical fiber being modulated by the environmental effect either directly or through environmentally induced optical path length changes in the fiber itself

INTENSITY-BASED FIBER OPTIC SENSORS

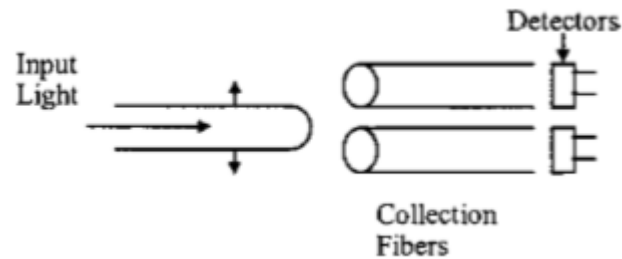


Closure and vibration fiber optic sensors based on numerical aperture can be used to support door closure indicators and measure levels of vibration in machinery.

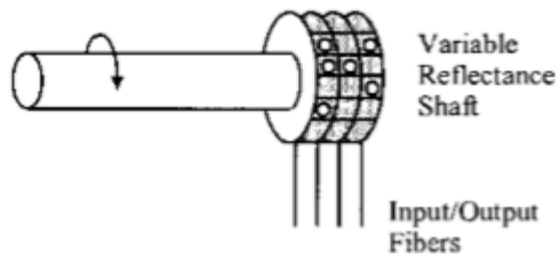


A numerical aperture fiber sensor based on a flexible mirror can be used to measure small vibrations and displacements

Fiber optics



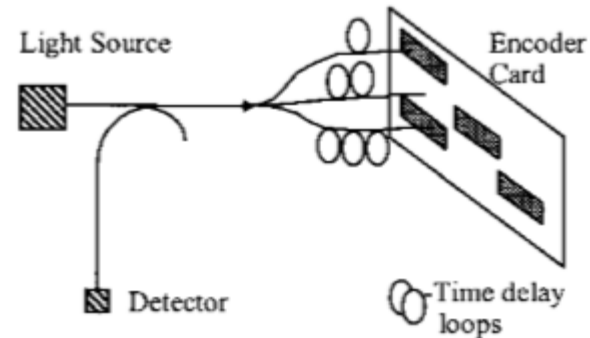
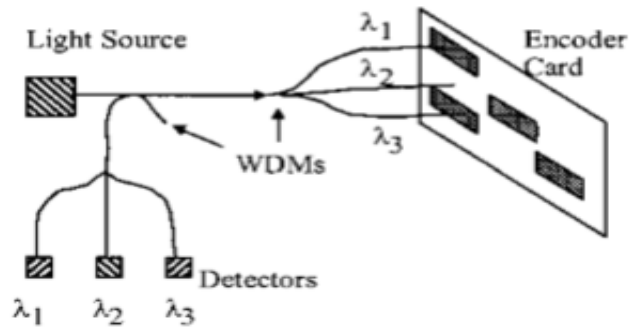
A fiber optic translation sensor based on numerical aperture uses the ratio of the output on the detectors to determine the position of the input fiber



Fiber optic rotary position sensor based on reflectance used to measure the rotational position of the shaft via the amount of light reflected from dark and light patches

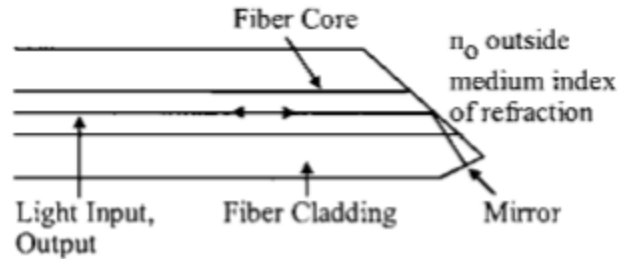
Fiber optics

A linear position sensor using wavelength division multiplexing decodes position by measuring the presence or absence of a reflective patch at each fiber position as the card slides by via independent wavelength separated detectors

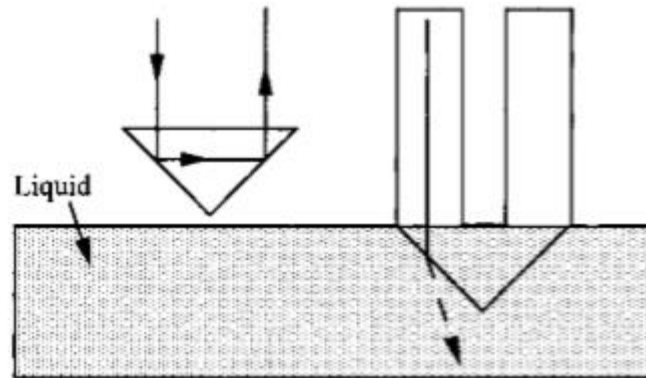


A linear position sensor using time division multiplexing measure decodes card position via a digital stream of on's and off's dictated by the presence or absence of a reflective patch

Fiber optics

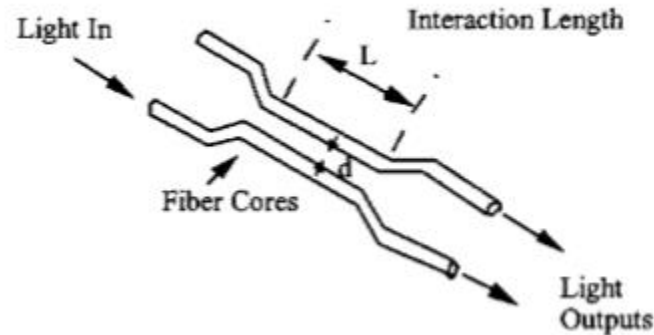


Fiber sensor using critical angle properties of a fiber for pressure=index of refraction measurement via measurements of the light reflected back into the fiber

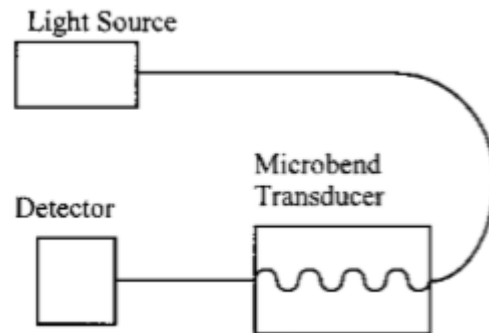


A liquid-level sensor based on the total internal reflection detects the presence or absence of liquid by the presence or absence of a return light signal

Fiber optics

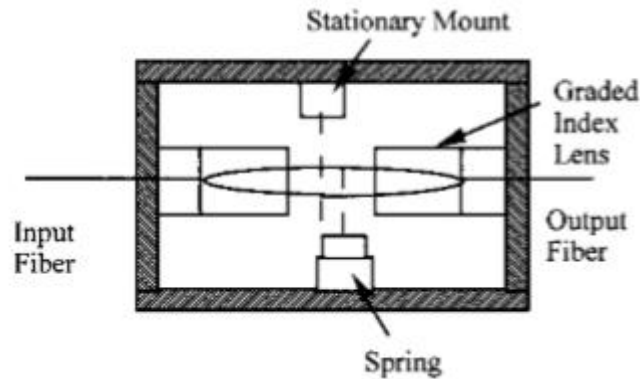


Evanescence-based fiber optic sensors rely on the cross-coupling of light between two closely spaced fiber optic cores. Variations in this distance due to temperature, pressure, or strain offer environmental sensing capabilities

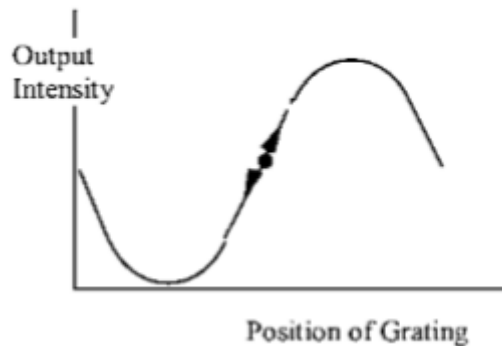


Microbend fiber sensors are configured so that an environmental effect results in an increase or decrease in loss through the transducer due to light loss resulting from small bends in the fiber

Fiber optics



Grating-based fiber intensity sensors measure vibration or acceleration via a highly sensitive shutter effect



Dynamic range limitations of the grating-based sensor of Fig. are due to smaller grating spacing increasing sensitivity at the expense of range

Fiber optics



Dual grating mask with regions 90 out of phase to support quadrature detection, which allows grating-based sensors to track through multiple lines

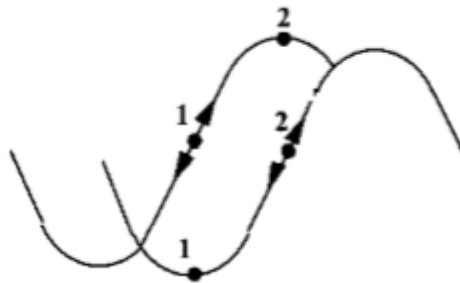
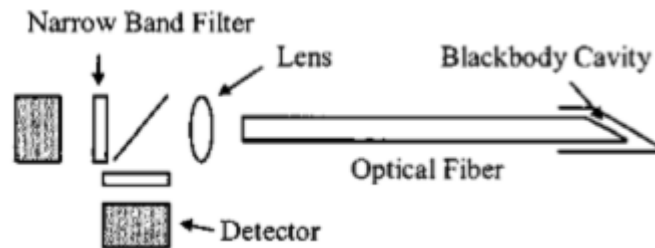
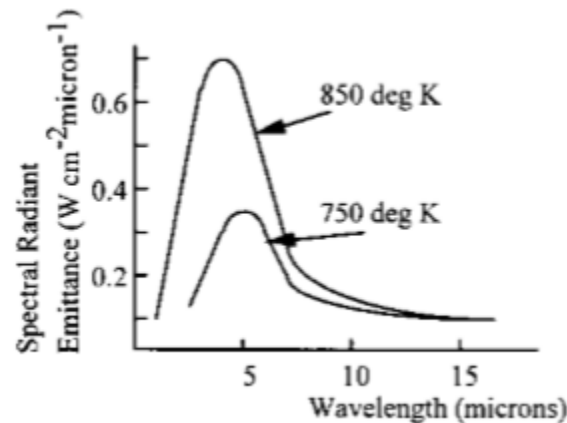


Diagram of a quadrature detection method that allows one area of maximum sensitivity while the other reaches a minimum, and vice versa, allowing uniform sensitivity over a wide dynamic range

SPECTRALLY BASED FIBER OPTIC SENSORS

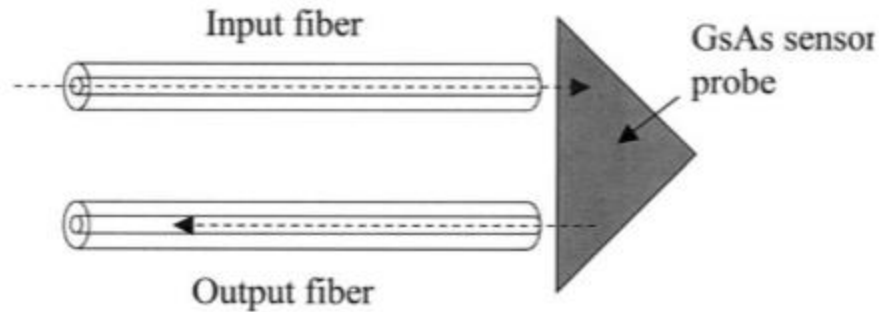


Blackbody fiber optic sensors allow the measurement of temperature at a hot spot and are most effective at temperatures of higher than 300C.



Blackbody radiation curves provide unique signatures for each temperature.

SPECTRALLY BASED FIBER OPTIC SENSORS



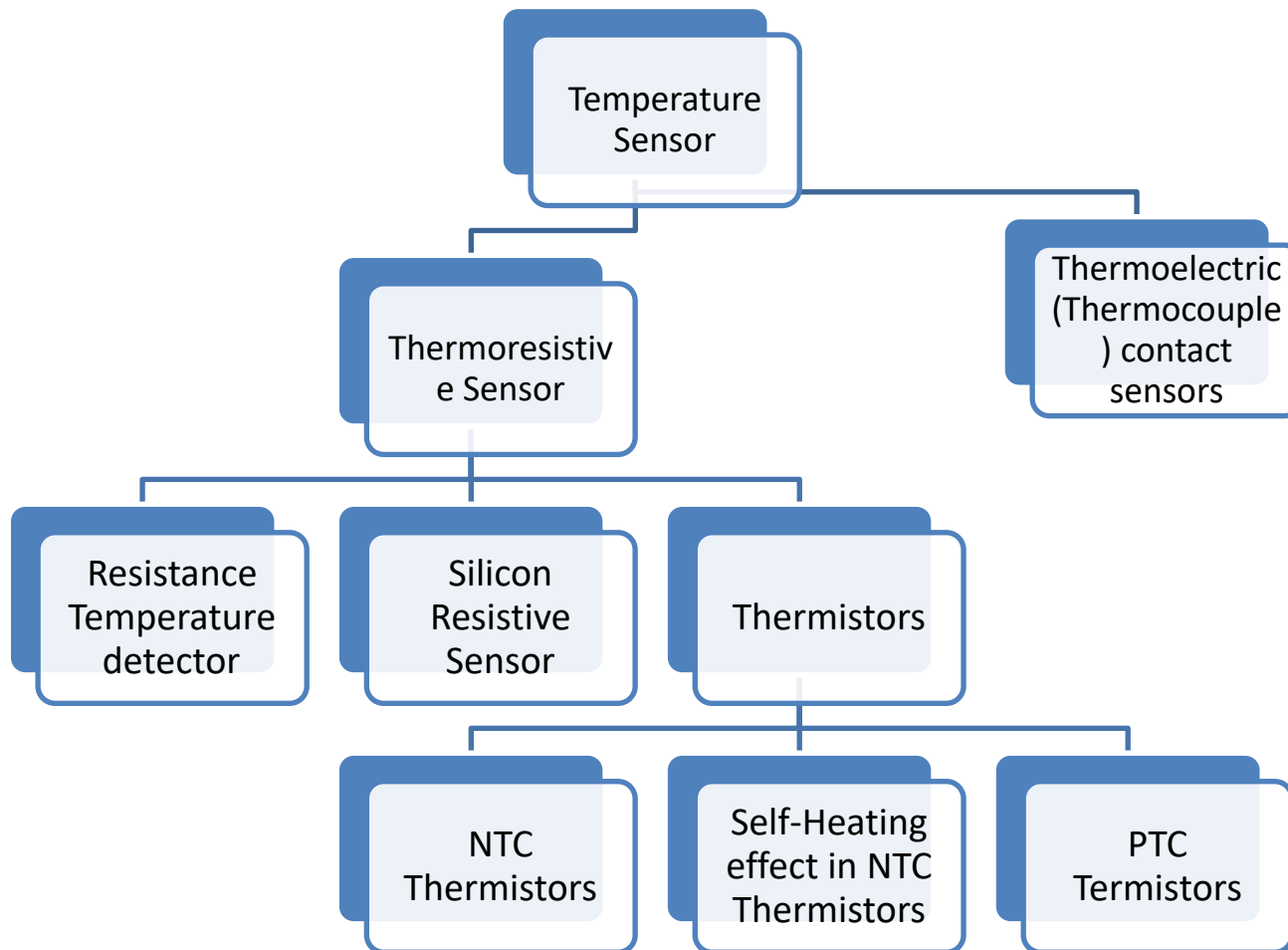
Fiber optic sensor based on variable absorption of materials such as GaAs allow the measurement of temperature and pressure



Temperature sensor

R.MATHIAZHAGAN
TEACHING FELLOW
DEPARTMENT OF PRODUCTION
TECHNOLOGY, MIT

Classification





Resistance

The conductivity of a material changes with temperature, t , and in a relatively narrow range, it may be expressed by α , which is temperature coefficient of resistance (TCR)

$$\rho = \rho_0[1 + \alpha(t - t_0)]$$

where ρ_0 is resistivity at the reference temperature t_0 (commonly either 0°C or 25°C). In a broader range, resistivity is a nonlinear function of temperature

- Contact type
- Non contact type

Absolute sensor: An absolute temperature sensor measures temperature which is referenced to the absolute zero or any other point on a temperature scale, such as 0°C (273.15°K), 25°C , and so forth. The examples of the absolute sensors are thermistors and resistance temperature detectors (RTDs).

Relative sensor: A relative sensor measures the temperature difference between two objects where one object is called a reference. An example of a relative sensor is a thermocouple.



RTD construction

- **Wire Wound :-**

Wire-wound RTDs are made by winding a very fine strand of metal wire (platinum, typically 0.0005–0.0015 in. diameter) into a coil and packaged inside a ceramic mandrel, or wound around the outside of a ceramic housing and coated with an insulating material to prevent the sensor from shorting. Larger lead wires (typically 0.008–0.015 in. diameter) are connected to the wound wires. Wire-wound RTDs provide superior interchange ability and stability to the highest temperatures.

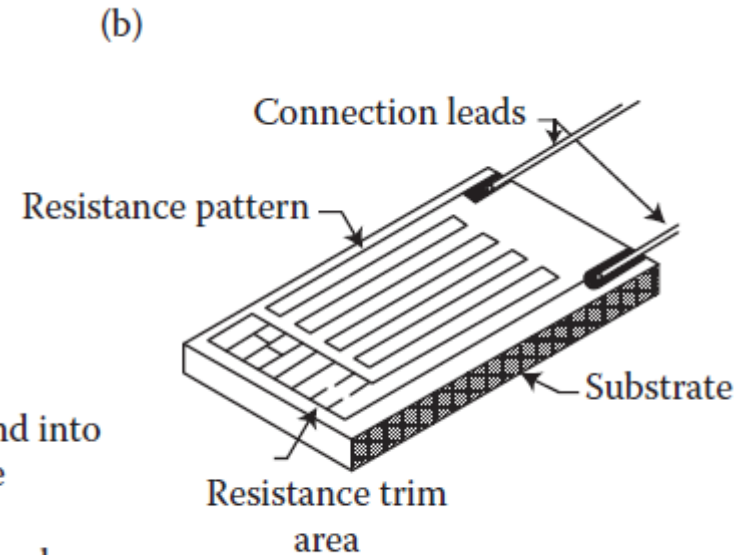
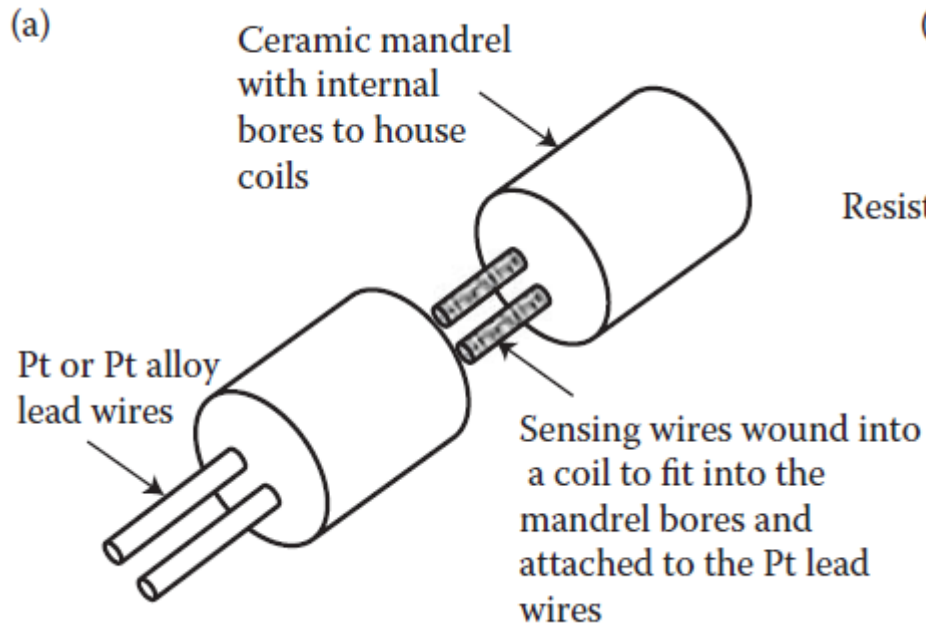


RTD Construction

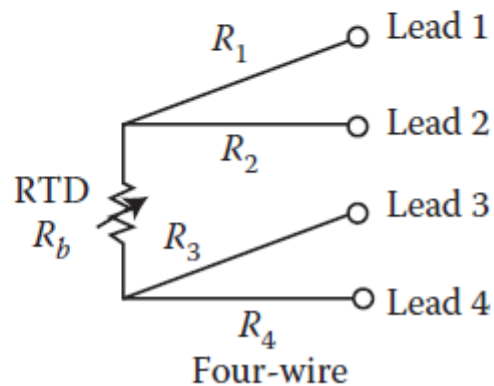
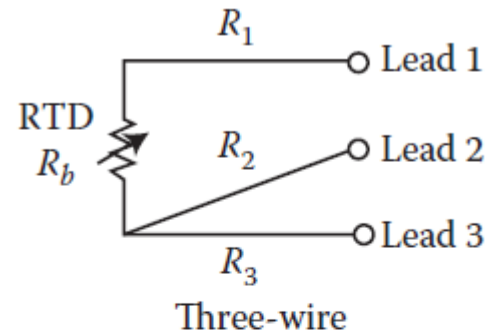
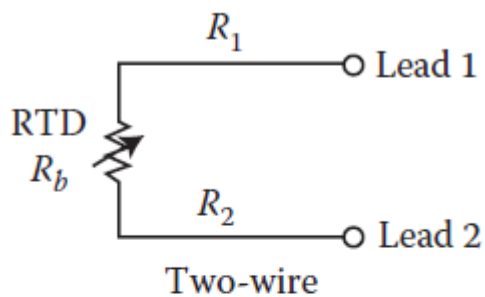
- **Thin flim RTD:-**

Thin-film RTDs are produced using thin-film lithography that deposits a thin film of metal (e.g., 1 μm platinum) onto a ceramic substrate through the cathodic atomization or sputtering process

RTD Construction (Wire Wound and Thin film RTD)



Two, Three and Four Wire Configuration



RTD

- Types
 - Thin film RTD
 - Wire Wound RTD
- For the range from -200°C to 0°C (Callendar–van Dusen approximations represent the platinum)

- transfer functions

$$R_t = R_0[1 + At + Bt^2 + Ct^3(t - 100)]$$

- For the range from 0°C to 630°C

$$R_t = R_0(1 + At + Bt^2)$$

- The constants A , B , and C are determined by the properties of platinum used in the construction of the sensor



RTD equation

The Callendar-Van-Dusen equation describes the relationship between the Ohmic Resistance and Temperature of Platinum based temperature instruments. This equation is commonly used in commercial applications in RTD thermometers and RTD Transmitters. In its original form, the Callendar-Van-Dusen Equation is given by:

$$R_t = R_0 + R_0\alpha[t - \delta(0.01t - 1)(0.01t) - B(0.01t - 1)(0.01t)^3]$$

Where:

R_t = Resistance at Temperature t ($^{\circ}\text{C}$)

R_0 = Resistance at $t = 0^{\circ}\text{C}$

α = Sensor specific constant

δ = Sensor specific constant

B = Sensor specific constant (0 at $t > 0^{\circ}\text{C}$, 0.11 at $t < 0^{\circ}\text{C}$)

The above equation has been used in the EN/IEC 60751 standard in the format below:

$$R_t = R_0(1 + At + Bt^2) \quad \text{for } t \geq 0^{\circ}\text{C}, \text{ for a Platinum resistor, } t \text{ is in the range } -200^{\circ}\text{C to } 0^{\circ}\text{C}$$

$$R_t = R_0(1 + At + Bt^2 + C(t - 100)t^3) \quad \text{for } t \leq 0^{\circ}\text{C}, \text{ for a Platinum resistor, } t \text{ is in the range } 0^{\circ}\text{C to } 850^{\circ}\text{C}$$

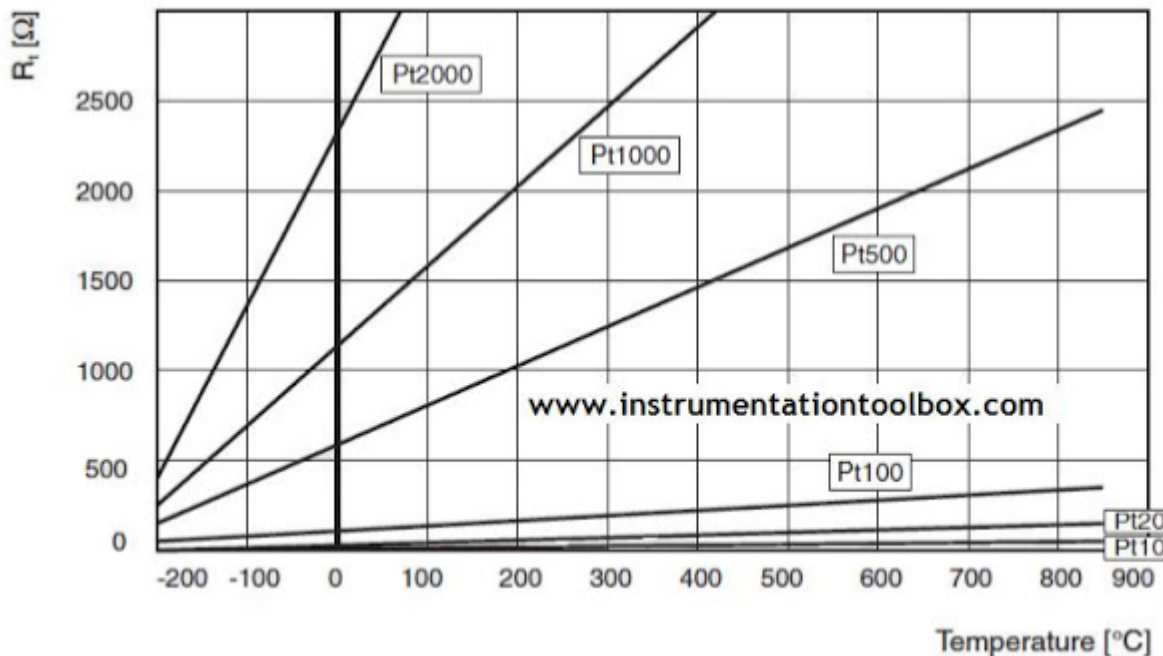
The value R_0 is the resistance of the Platinum resistor at 0°C . The coefficients A , B , C as well as all other properties which the platinum resistance based temperature instrument must satisfy are contained in the EN/IEC 60751 standard.

RTD equation

Nominal Values of Platinum Used as Temperature Measurement Devices.

For industrial temperature measurement, Platinum is the most used resistors followed by Nickel. Platinum measurement resistors with a nominal value of 100 ohms known as Pt 100 have been established as the industrial standard for temperature measurement.

Temperature resistors are identified by their resistance at 0°C also called the nominal value. Pt 100 and Ni 100 the most common types of resistors used have a resistance of 100 ohms at 0°C. Pt 2000, Pt 1000, Pt 500, Pt 20, Pt 10 have 2000 ohms, 1000 ohms, 500 ohms, 20 ohms and 10 ohms respectively at 0°C. The relationship between resistance and temperature for various types of Platinum resistance is shown in the chart below:





RTD equation

In the IEC/EN 60751 standard, the constants A, B & C are given the following values:

$$A = 3.9083 \times 10^{-3} \text{ K}^{-1}$$

$$B = -5.775 \times 10^{-7} \text{ K}^{-2}$$

$$C = -4.183 \times 10^{-12} \text{ K}^{-4}$$

Application of the Callendar - Van - Dusen Equation

It is used in transmitter-sensor matching to create a curve that closely approximates an RTD's resistance versus temperature relationship. This curve can be generated for any RTD by plugging the RTD's specific constants (A, B & C) into either version of the Callendar-Van Dusen equation, which is programmed into many smart transmitters. In this way, the transmitter uses the actual RTD curve rather than an ideal curve to translate the sensor's resistance signal into a temperature value thus providing extraordinary system accuracy.

Although transmitter-sensor matching is typically not required for all process measurements, it is the clear choice for those measurements requiring the best possible accuracy.



How to Convert RTD Resistance to Temperature?



An RTD resistance can be converted into temperature using standard tables that gives values of temperatures for any given resistance value of the RTD.

The table below shows temperature versus resistance data in degree celsius with temperature coefficient of resistance of: 0.003916 ohm/ohm/°C.

Fundamental Interval 39.16 ohms

°C	0	100	200	300	400	500	600	°C
0	100	139.16	177.14	213.95	249.59	284.04	317.33	0
10	103.97	143.01	180.88	217.57	253.09	287.43	320.59	10
20	107.93	146.85	184.60	221.17	256.57	290.79	323.84	20
30	111.87	150.68	188.31	224.77	260.05	294.15	327.08	30
40	115.81	154.49	192.01	228.35	263.51	297.50		40
50	119.73	158.30	195.70	231.92	266.96	300.83		50
60	123.64	162.09	199.37	235.47	270.40	304.15		60
70	127.54	165.87	203.03	239.02	273.83	307.47		70
80	131.42	169.64	206.69	242.55	277.25	310.76		80
90	135.30	173.40	210.33	246.08	280.65	314.05		90
100	139.16	177.14	213.95	249.59	284.04	317.33		100
Ω/°C Ave	0.390	0.380	0.368	0.356	0.345	0.333	0.325	



Problem

Example 1:

Calculate the resistance of an RTD thermometer when the temperature is:

- a) 0 degree Celsius
- b) 100 degree Celsius
- c) 50 degree Celsius
- d) 75 degree Celsius

Solution:

(a) From the Temperature vs Resistance data tables,

At 0 degree Celsius, Resistance = 100 ohms

(b) At 100 degree Celsius, Resistance = 139.16 ohms

(c) At 50 degree Celsius, Resistance = 119.73 ohms

(d) At 700C, resistance = 127.54ohms

At 800C, resistance = 131.42ohms

At 750C, let resistance = X

Using interpolation method, we have:

$$(70 - 80)/(75 - 80) = (127.54 - 131.42)/(X - 131.42)$$

$$-10/-5 = -3.88/(X - 131.42)$$

$$-10(X - 131.42) = 19.4$$

$$X = 131.42 - 1.94 = 129.48$$



Problem

Example 2:

An RTD with a temperature coefficient of resistance of 0.390 has a resistance of 100Ω at 00°C and a resistance of 139.16Ω at 100°C . If the RTD is used to measure the temperature of water in a water bath heater, what is the temperature of the water bath if the resistance of the RTD is 120Ω ?

Solution:

At

0°C , RTD resistance = 100Ω

100°C , RTD resistance = 139.16Ω

Let X be the temperature of the water when RTD resistance is 120Ω

Using interpolation, we have:

$$(X - 0)/(100 - 0) = (120 - 100)/(139.16 - 100)$$

$$X/100 = 20/39.16$$

$$X = (20 \times 100)/(39.16)$$

$$X = 51.0725^\circ\text{C}$$

Hence temperature of the water bath is 51°C



Problem

Callendar–Van Dusen Coefficients Corresponding to Standard RTDs

Standard	A'	B'	C' ($C' = 0$ for $T > 0^\circ\text{C}$)
DIN 43760	3.9080×10^{-3}	-5.8019×10^{-7}	-4.2735×10^{-12}
American	3.9692×10^{-3}	-5.8495×10^{-7}	-4.2325×10^{-12}
ITS-90	3.9848×10^{-3}	-5.8700×10^{-7}	-4.0000×10^{-12}

Source: From Measuring temperature with RTDs—A tutorial, Application Note 046, National Instruments Corporation, Austin, Texas, USA, 1996. With permission.

$$R_T = R_0[1 + A'T + B'T^2 + C'(T - 100)T^3]_{(-200^\circ\text{C} < T < 850^\circ\text{C})} \quad (2.8)$$



Problem

A Pt100 sensor is used to measure the temperature of a chamber. What is its resistance under a -80°C temperature? If the chamber's temperature is increased to $+80^{\circ}\text{C}$, what is the sensor's new resistance value? Assume the American standard Pt100.

SOLUTIONS

From the second row in Table 2.3, $A' = 3.9692 \times 10^{-3}$ and $B' = -5.8495 \times 10^{-7}$. Thus:

For $T = -80^{\circ}\text{C}$, $C' = -4.2325 \times 10^{-12}$:

$$R_{-80} = R_0[1 + A'T + B'T^2 + C'(T - 100)T^3]$$

$$\begin{aligned} R_{-80} &= 100[1 + (3.9692 \times 10^{-3})(-80) + (-5.8495 \times 10^{-7})(-80)^2 \\ &\quad + (-4.2325 \times 10^{-12})(-80 - 100)(-80)^3] = 67.83 \, \Omega \end{aligned}$$

For $T = 80^{\circ}\text{C}$, $C' = 0$:

$$\begin{aligned} R_{80} &= R_0[1 + A'T + B'T^2] = 100[1 + (3.9692 \times 10^{-3})(80) \\ &\quad + (-5.8495 \times 10^{-7})(80)^2] = 131.38 \, \Omega \end{aligned}$$

These results show that as the temperature increases, the resistance of the Pt100 RTD increases.



- If a sensor's coefficient A , B and C are not available, one can measure the sensor's resistance values at a number of known temperatures, and then solve for A , B and C or determine them using



Problem

- Determine the temperature coefficient A, B and C for a Pt100 sensor using the Callendar-Van Dusen equation.



Problem

Measure resistance at the four known temperatures:

R_0 at $T_0 = 0^\circ\text{C}$ (the freezing point of water)

R_{100} at $T_{100} = 100^\circ\text{C}$ (the boiling point of water)

R_h at T_h —a high temperature (e.g., the melting point of zinc, 419.53°C)

R_l at T_l —a low temperature (e.g., the boiling point of oxygen, -182.96°C)

Step 1: Calculate linear parameter α

The linear parameter α is determined as the normalized slope between 0°C and 100°C :

$$\alpha = \frac{R_{100} - R_0}{100R_0} \quad (2.9)$$

Then, the resistance at other temperatures can be calculated as

$$R_T = R_0(1 + \alpha T) \quad (2.10)$$

The temperature as a function of the resistance value is

$$T = \frac{R_T - R_0}{\alpha R_0} \quad (2.11)$$

Problem

Step 2: Calculate the Callendar constant δ

The Callendar constant, δ (introduced by Callendar), is determined based on the disparity between the actual temperature, T_h , and the temperature calculated in Equation 2.11:

$$\delta = \frac{T_h - (R_h - R_0)/(\alpha R_0)}{((T_h/100) - 1)(T_h/100)} \quad (2.12)$$

With the introduction of δ into the equation, the resistance value R_T at a positive temperature T ($T > 0^\circ\text{C}$) can be calculated with a great accuracy:

$$R_T = R_0 + R_0\alpha \left[T - \delta \left(\frac{T}{100} - 1 \right) \left(\frac{T}{100} \right) \right] \quad (2.13)$$

Step 3: Calculate the Van Dusen constant β

At negative temperatures ($T < 0^\circ\text{C}$), Equation 2.12 will still give a small deviation. Van Dusen therefore introduced a term of the fourth order, β (only applicable for $T < 0^\circ\text{C}$). β is calculated based on the disparity between the actual temperature, T_l , and the temperature that would result from employing only α and δ :

$$\beta = \frac{T_l - [(R_l - R_0)/(\alpha R_0) + \delta((T_l/100) - 1)(T_l/100)]}{((T_l/100) - 1)(T_l/100)^3} \quad (2.14)$$

With the introduction of both Callendar and van Dusen constants, the resistance value can be calculated accurately for the entire temperature range (set $\beta = 0$ for $T > 0^\circ\text{C}$):



Problem

$$R_T = R_0 + R_0 \alpha \left[T - \delta \left(\frac{T}{100} - 1 \right) \left(\frac{T}{100} \right) - \beta \left(\frac{T}{100} - 1 \right) \left(\frac{T}{100} \right)^3 \right] \quad (2.15)$$

Step 4: Convert the results to A , B , and C

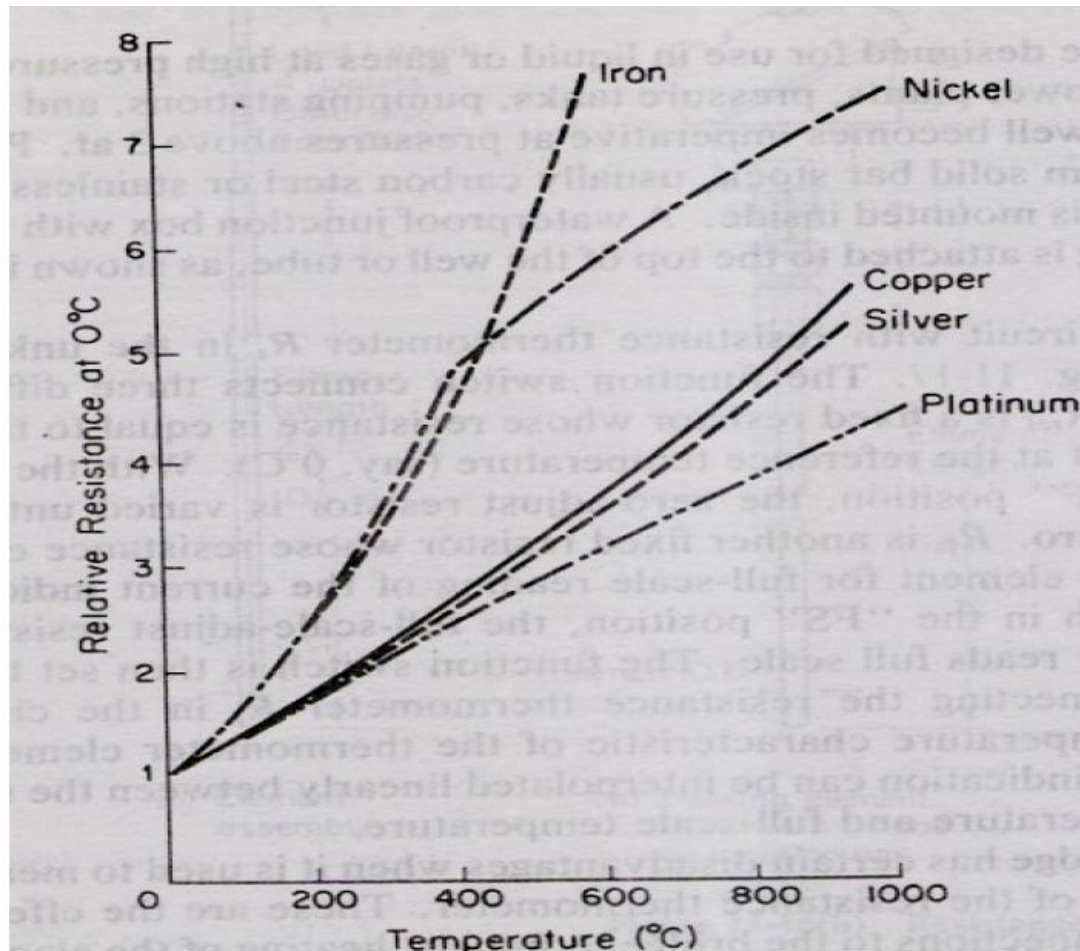
Conversion can be accomplished by simple coefficient comparison of Equations 2.8 and 2.15, resulting in

$$A = \alpha \left(1 + \frac{\delta}{100} \right) \quad (2.16)$$

$$B = -\frac{\alpha \delta}{100^2} \quad (2.17)$$

$$C = -\frac{\alpha \beta}{100^4} \quad (2.18)$$

RTD characteristics



Calibration of RTD

The RTD transmitter is usually factory calibrated to the temperature range shown on the device name plate. When the performance deteriorate and the transmitter needs recalibration, the transmitter is normally calibrated by using a resistance decade box.

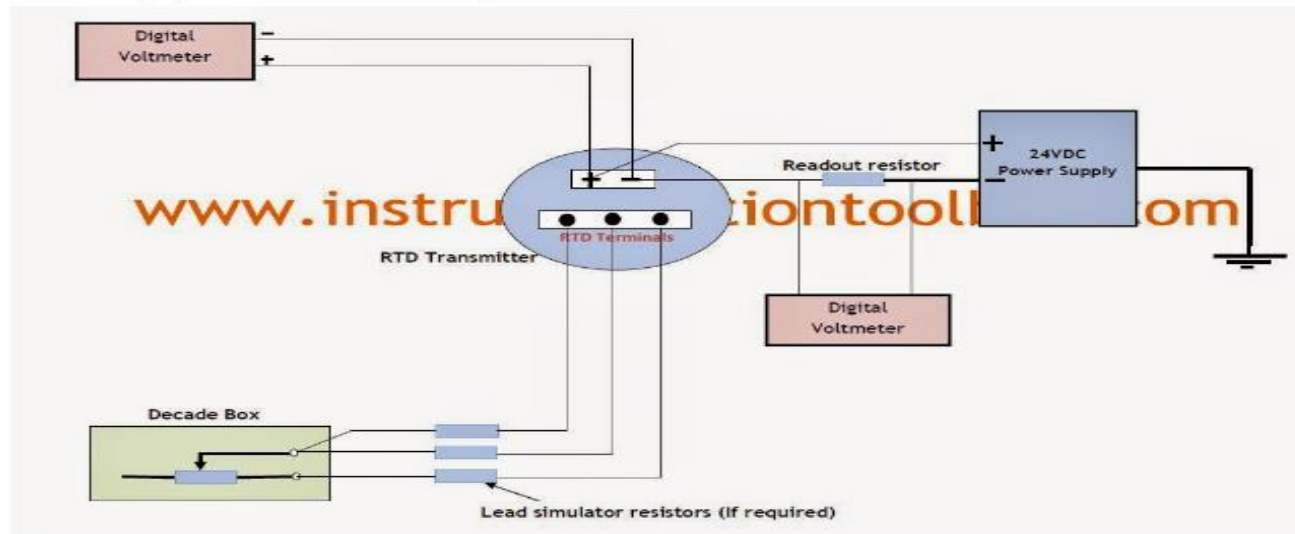
Materials Required for Calibration

To calibrate the RTD transmitter, the following equipment will be required:

1. Voltmeters (digital) of suitable accuracy and very high resolution - 1mv
2. A 24VDC power source
3. A 5 dial Resistance Decade Box with high precision providing 100 Ω steps

Calibration Steps:

Connect the above equipment as in the setup below:



How to Calibrate RTD Transmitter



Calibration of RTD

1. Locate the RTD transmitter terminal by removing the housing cover
2. If an RTD is already connected, remove all the RTD lead connections
3. Determine the RTD resistance at the desired base(0°C) and full scale temperatures
4. Turn the power supply on
5. Set resistance decade box to the resistance that corresponds to the desired base temperature. Adjust the zero pot (potentiometer) of transmitter until the output is 4mA
6. Set resistance decade box to the resistance that corresponds to the desired full scale temperature. Adjust the span pot (potentiometer) of transmitter until the output is 20mA
7. Repeat the above steps until both 4 and 20mA readings are obtained without readjusting span and zero potentiometers.



Silicon Resistive Sensor

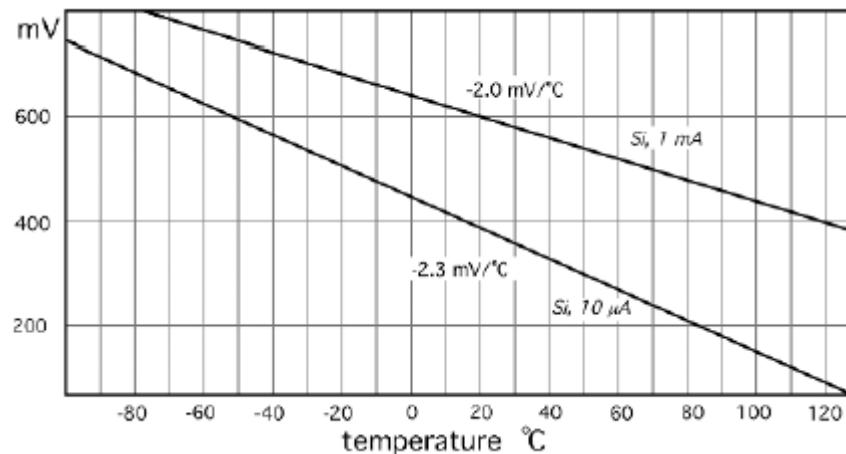
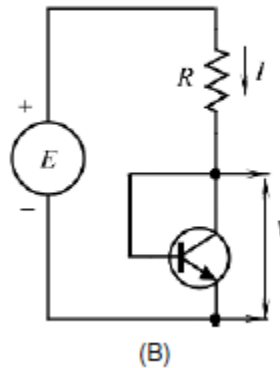
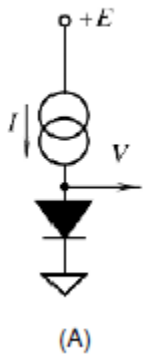
- Conductive properties of bulk silicon have been successfully implemented for the fabrication of temperature sensors with positive temperature coefficient (PTC) characteristics
- Pure silicon, either polysilicon or single-crystal silicon, intrinsically has a negative temperature coefficient of resistance (NTC)

Semiconductor pn junction sensor

The current-to-voltage equation of a p-n junction diode can be expressed as

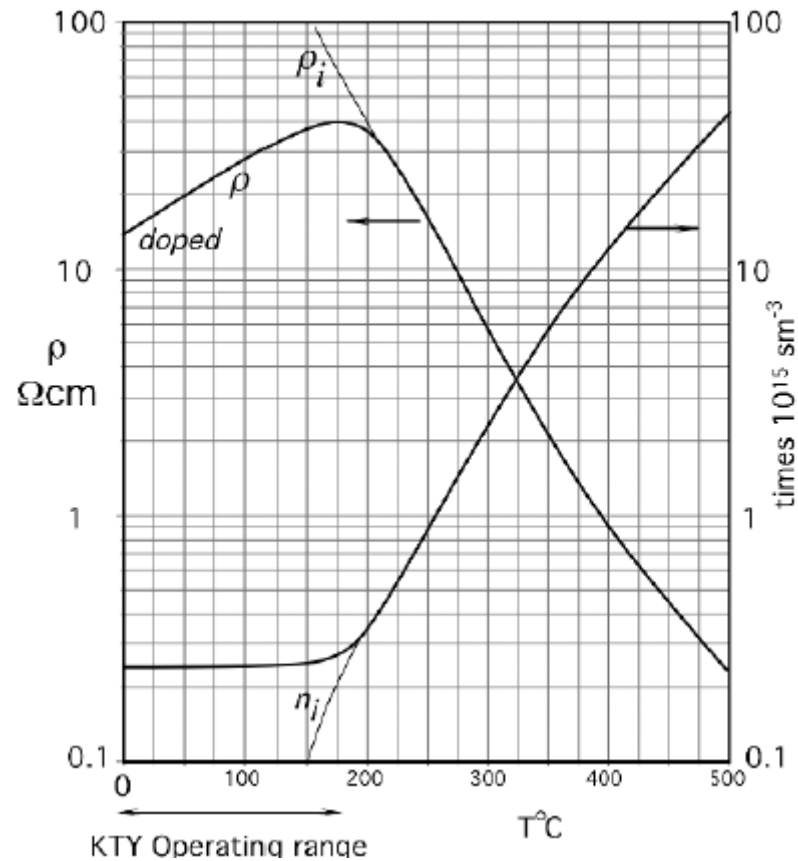
$$I = I_0 \exp\left(\frac{qV}{2kT}\right),$$

$$V = \frac{E_g}{q} - \frac{2kT}{q}(\ln K - \ln I),$$



Forward-biased p-n junction temperature sensors: (A) diode; (B) diode-connected transistor.

Resistivity and number of free charge carriers for n-doped silicon





Calibration and Calibration error

$$V_{\text{out}} = (T_n + 273.15 \text{ K})(10 \text{ mV/K})$$

One-point calibration procedures for an LM335 temperature sensor

One-point calibration is to determine the offset (intercept) of a sensor's transfer function, b , with the assumption that the slope of the transfer function, a , is known (e.g., $a = 1$).

Step 1: Let the temperature being measured by the sensor, T_s , be equal to

$$T_s = aT_n + b = T_n + b \quad (1.16)$$

where T_n is the nominal value of the temperature being measured, a ($=1$) is the known slope, and b is the offset before calibration.

Step 2: Expose the LM335 sensor to a known and stable temperature, T_a (e.g., $T_a = 35^\circ\text{C}$). Read and record the temperature measured by the sensor, T_s (e.g., $T_s = 34.6^\circ\text{C}$).

Step 3: Determine the new offset value b' using the formula

$$b' = b + T_a - T_s = b + 35^\circ\text{C} - 34.6^\circ\text{C} = b + 0.4^\circ\text{C}$$

Step 4: Replace b with b' in Equation 1.16:

$$T_s = aT_n + b + 0.4^\circ\text{C} = T_n + b + 0.4^\circ\text{C}$$

Two-point calibration procedures for an LM335 temperature sensor

Two-point calibration is to determine both the slope a and the offset b of a sensor's transfer function.

Step 1: Let the temperature being measured by the sensor, T_s , be equal to

$$T_s = aT_n + b \quad (1.17)$$

where T_n is the nominal value of the temperature being measured, and a and b are the slope and the offset, respectively, before calibration.

Step 2: Expose the sensor to an accurately known and stable temperature, T_{a1} (e.g., $T_{a1} = 35^\circ\text{C}$). Read and record the sensor output T_{s1} (e.g., $T_{s1} = 34.6^\circ\text{C}$).

Step 3: Expose the sensor to another accurately known and stable temperature, T_{a2} (e.g., $T_{a2} = 75^\circ\text{C}$). Read and record the sensor output T_{s2} (e.g., $T_{s2} = 75.3^\circ\text{C}$).

Step 4: Determine the new slope value a' and the new offset value b' using the formula

$$a' = m a$$

$$b' = n + m b$$

where the intermediate values m and n are

$$m = \frac{T_{a1} - T_{a2}}{T_{s1} - T_{s2}} \quad n = T_{a1} - mT_{s1}$$

Thus

$$a' = m a = \frac{T_{a1} - T_{a2}}{T_{s1} - T_{s2}} a = \frac{35 - 75}{34.6 - 75.3} a = 0.98a$$

$$\begin{aligned} b' &= n + m b = (T_{a1} - mT_{s1}) + mb = T_{a1} + \frac{T_{a1} - T_{a2}}{T_{s1} - T_{s2}}(b - T_{s1}) \\ &= 35 + \frac{35 - 75}{34.6 - 75.3}(b - 34.6) = 1.00 + 0.98b \end{aligned}$$

Step 5: Replace a with a' and b with b' :

$$T_s = (0.98a)T_n + (1.00 + 0.98b) = 0.98(aT_n + b) + 1.00$$



Thermistors

- The term thermistor is a contraction of the words thermal and resistor. The name is usually applied to metal-oxide sensors fabricated in the form of droplets, bars, cylinders, rectangular flakes, and thick films
- NTC(sintered mixture of metallic oxides, which include nickel, cobalt, manganese, and sometimes other oxides) and PTC-NTC is preferred for precise measurement.
- Construction: droplets, bars, cylinders, rectangular flakes, and thick films



Thermistors

- In semiconductor materials, the valence electrons are bonded in covalent bonds with their neighbors. As temperature increases, thermal vibration of the atoms breaks up some of these bonds and releases electrons. These “free” electrons are able to move through the material under applied electric fields and the material appears to have a smaller resistance.
- Thus, electrical resistance R of semiconductor materials decreases as temperature T increases

$$R_T = R_0 e^{\left[\beta \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]}$$



Thermistors

- where R_0 is the resistance at the reference temperature T_0 (in kelvin, K), usually 298 K (25°C), and β is the temperature coefficient (in K) of the material. Since resistance decreases as the temperature increases, β is a negative temperature coefficient (NTC). Most thermistors (a contraction of the words thermal and resistor), made of semiconductor materials, are NTC sensors.

Thermistor

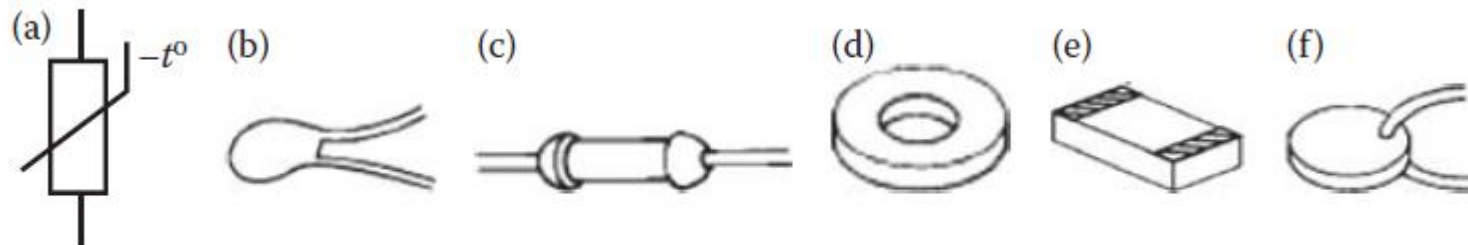
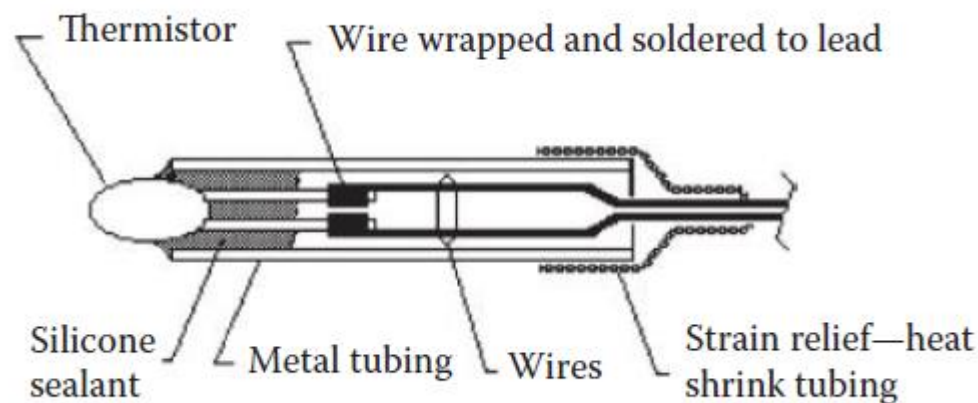
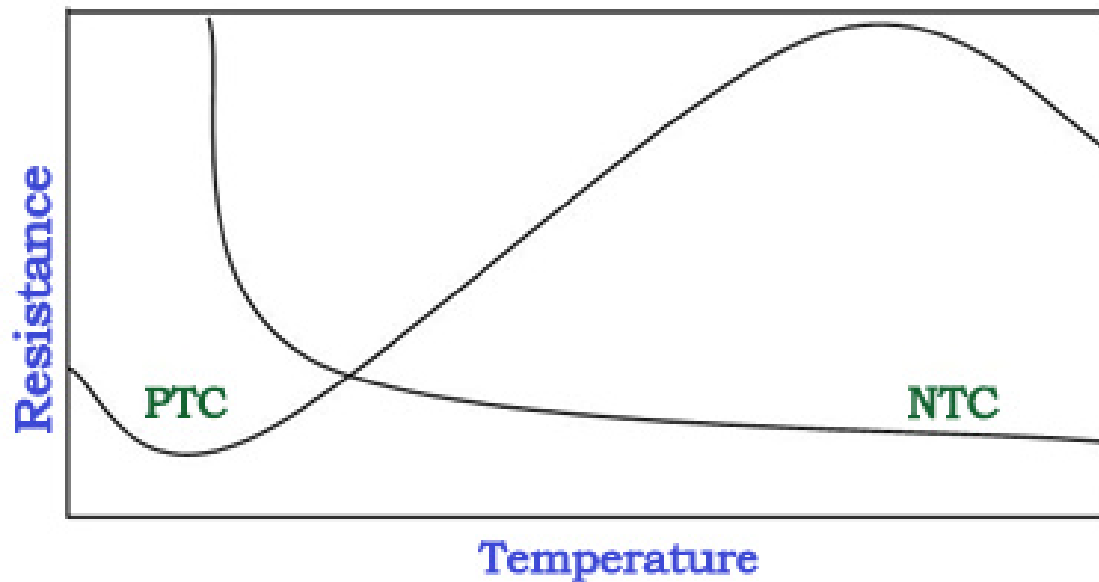
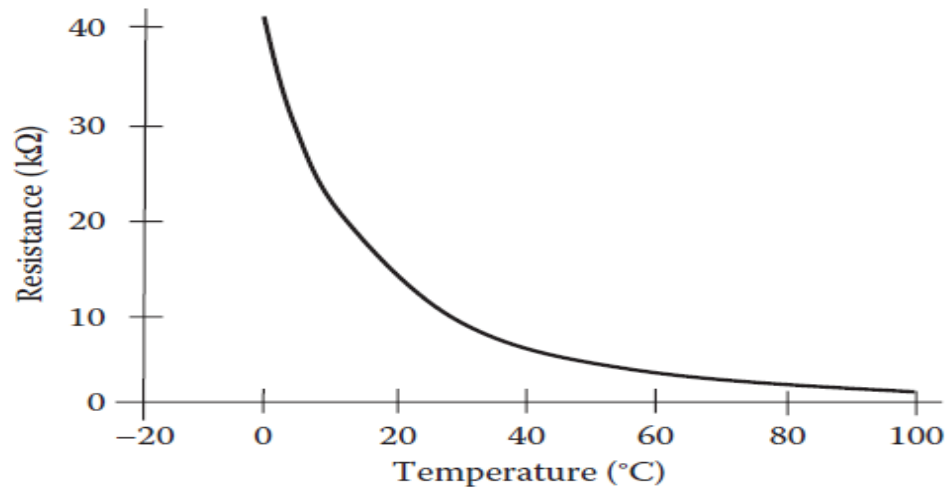


FIGURE 2.16 Thermistors: (a) circuit symbol for NTC type (with negative sign); (b) bead; (c) rod; (d) washer; (e) surface mount; (f) disk.

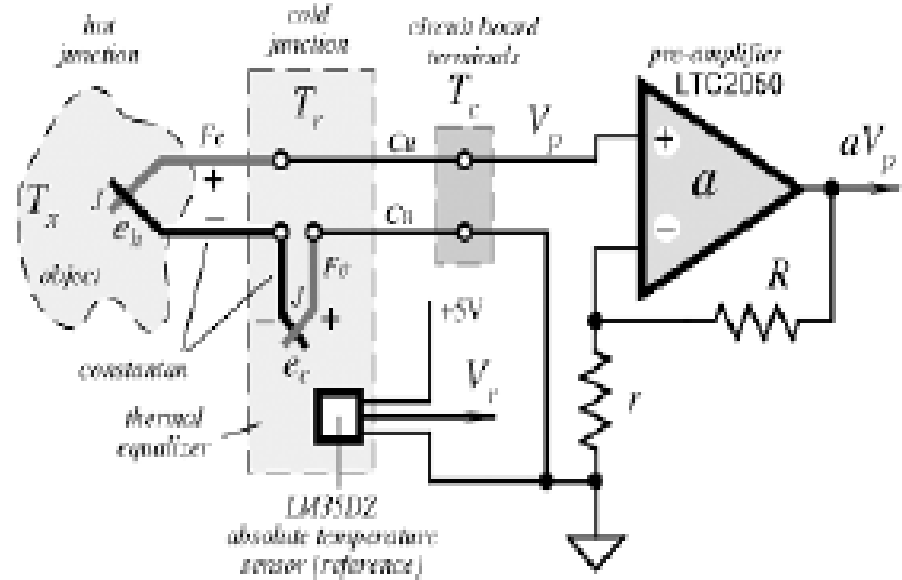
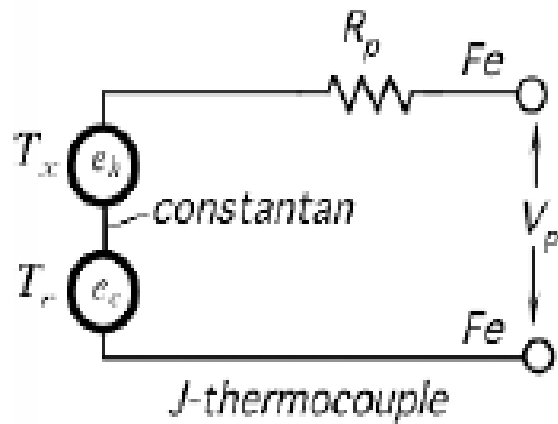


Internal structure of a bead-type thermistor

Thermistor characteristics



Thermocouple





Principles

- The Seebeck effect causes a thermoelectric EMF to appear between the differentially heated junctions of a loop made from two dissimilar conductors.



Principles

- If an electric current is allowed or caused to flow around a loop, then of course Joule (i^2R) heating will occur. In addition, it will be found that the current flowing through the junctions causes temperature increase at one junction and temperature decrease at the other - this is called the Peltier effect.
- A final phenomenon is that a current travelling in a conductor that is subject to a temperature gradient causes either an evolution or an absorption of heat depending on the direction of the current and the temperature gradient. This effect, which is very small, is called the Thompson effect.



Materials

The ideal characteristics of the metals constituting a thermocouple would be:

- high sensitivity and linearity
- time-invariant behaviour
- no device-to-device variability
- physical strength and stability at high temperatures
- resistance to effects of corrosive agents
- low cost



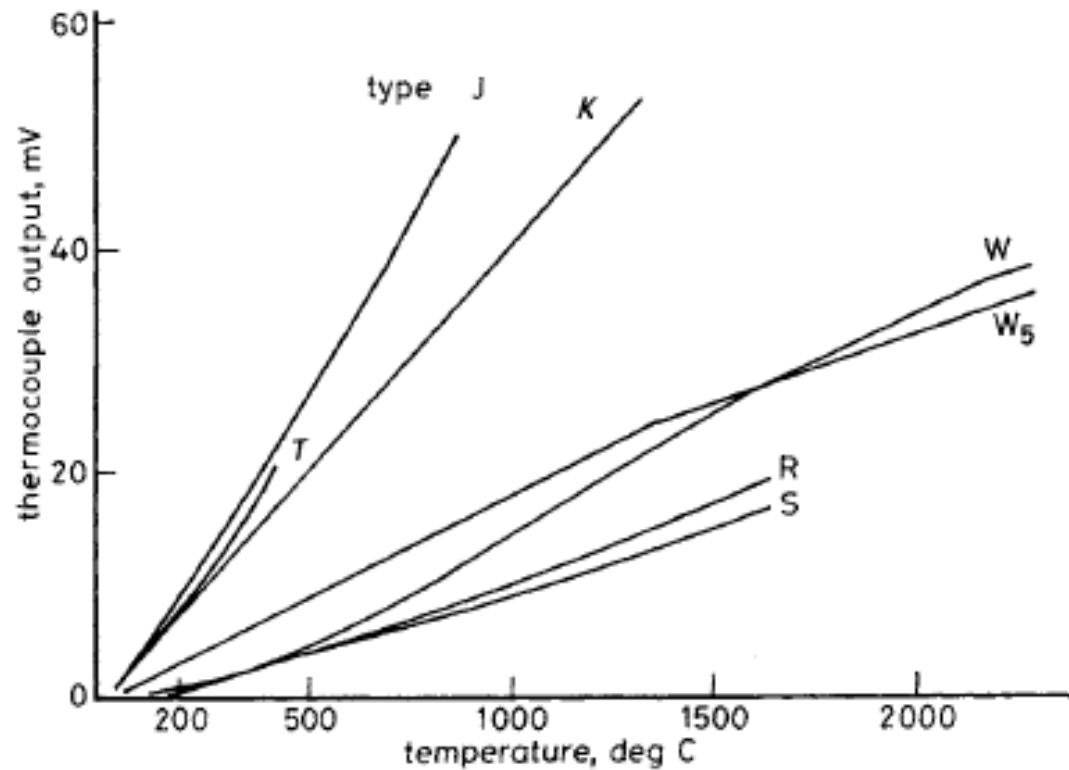
Materials

- Popular base metal thermocouple materials include:
- Type K: nickel-chromium (Chromel) v. nickel-aluminium (Alumel)
- Type J: iron v. copper-nickel
- Type T: copper v. copper-nickel (Constantan)

Temperature range

Standard	Thermocouple		Maximum temperature	defined up to
EN 60 584	Fe-Con	J	750°C	1200°C
	Cu-Con	T	350°C	400°C
	NiCr-Ni	K	1200°C	1370°C
	NiCr-Con	E	900°C	1000°C
	NiCrSi-NiSi	N	1200°C	1300°C
	Pt10Rh-Pt	S	1600°C	1540°C
	Pt13Rh-Pt	R	1600°C	1760°C
	Pt30Rh-Pt6Rh	B	1700°C	1820°C


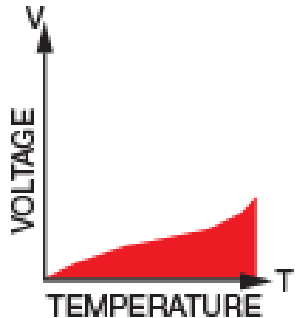

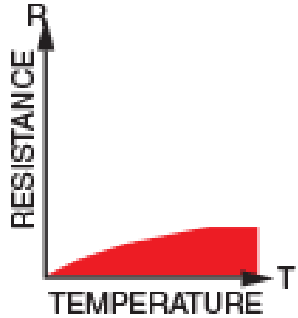

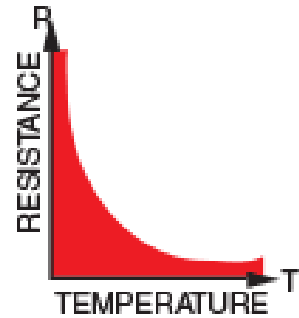

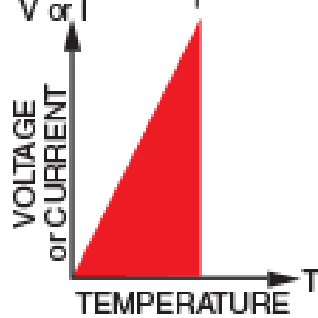
EMF temperature for selected thermocouple materials





Calibration of Thermocouple

- Calibration may be carried out either against absolute standards established locally (such as are specified in the fixed points table) or, alternatively, the thermocouple to be calibrated may be compared with a standard thermocouple whose calibration is traceable back to the primary standard.
- The second (comparison) method is the more widely used. Usually, a thermocouple that is already installed and working will be checked at a single temperature by inserting the standard thermocouple so that the two hot junctions are as close as possible to each other. The output voltages of both thermocouples are then measured by an accurate millivoltmeter whose temperature is measured by a built-in thermometer to allow correction to be made for ambient temperature.

	Thermocouple  	RTD  	Thermistor  	I. C. Sensor  
Advantages	<ul style="list-style-type: none"> Self-powered Simple Rugged Inexpensive Wide variety Wide temperature range 	<ul style="list-style-type: none"> Most stable Most accurate More linear than thermocouple 	<ul style="list-style-type: none"> High output Fast Two-wire ohms measurement 	<ul style="list-style-type: none"> Most linear Highest output Inexpensive
Disadvantages	<ul style="list-style-type: none"> Non-linear Low voltage Reference required Least stable Least sensitive 	<ul style="list-style-type: none"> Expensive Current source required Small ΔR Low absolute resistance Self-heating 	<ul style="list-style-type: none"> Non-linear Limited temperature range Fragile Current source required Self-heating 	<ul style="list-style-type: none"> $T < 200^{\circ}\text{C}$ Power supply required Slow Self-heating Limited configurations

Comparison of Characteristics for RTDs, NTC Thermistors, and Thermocouples

Characteristics	RTD	NTC Thermistor	Thermocouple
Measured parameters	Resistance	Resistance	Voltage
Resolution	Poor	Good	Moderate
Linearity	Linear	Nonlinear	Nonlinear
Temperature range	$-250^{\circ}\text{C} \sim 850^{\circ}\text{C}$	$-100^{\circ}\text{C} \sim 300^{\circ}\text{C}$	$0^{\circ}\text{C} \sim 1600^{\circ}\text{C}$
Current source	Necessary	Necessary	Not necessary
Compensation for environments	Not necessary	Not necessary	Necessary
Response	Relatively slow	Fast	Fast
Cost	Expensive	Inexpensive	Varies

Source: The data in the table are compiled based on several manufacturers' data sheets.



Pressure sensor

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DEPARTMENT OF PRODUCTION
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Measurement of pressure and the transmission of force by a fluid depend are briefly stated

- Density
- Specific gravity
- Free Surface of Liquid(rest is horizontal; or, liquids find their own level)
- Liquid in boundary(produces a force at right angles to that boundary)
- The pressure due to the liquid at any point in a liquid is proportional to the depth of the point below the surface of the liquid.



METHODS OF MEASUREMENT OF PRESSURE

- Pressure may be measured directly in two ways. In the first place, the pressure due to a fluid may be balanced by the pressure produced by a column of liquid of known density. In the second place, the pressure may be permitted to act over a known area, and since

$$\text{Pressure} = \text{Force} / \text{Area or,}$$

- $\text{Force} = \text{Pressure} \times \text{Area}$, a force will be produced whose magnitude depends upon the pressure.



METHODS OF MEASUREMENT OF PRESSURE

- Pressure measurement by balancing against a column of liquid of known density,

Simple U tube with vertical or inclined limb,

The simple U tube in practice.

Absolute pressure measurement.

Differential pressure measurement.

Vernier reading manometer.

Precision calibrating standard manometer.

Sonar manometer.

Industrial types of manometer.

- Pressure measurement by balancing against a known force,

Piston type pressure gauge.

Ring balance type pressure gauge.

Bell type pressure gauge.

Pressure measurement by balancing the force produced on a known area against the stress in an elastic medium

Bourdon tubes,

The 'C type Bourdon tube.

The spiral Bourdon tube.

The helical Bourdon tube.

- Diaphragm types,

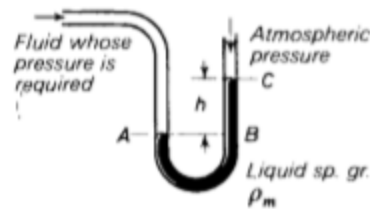
Stiff metallic diaphragm or bellows.

Slack diaphragm and drive plate.

- Other methods.

Simple U tube

Pressure at A = pressure at B
 Fluid pressure at A = atmospheric pressure + pressure due to column of liquid BC
 = atmospheric pressure + $h\rho_m$ mm H₂O
 $h\rho_m$ mm H₂O is the 'gauge pressure' and is written $h\rho_m$ mm H₂O gauge.



Principle

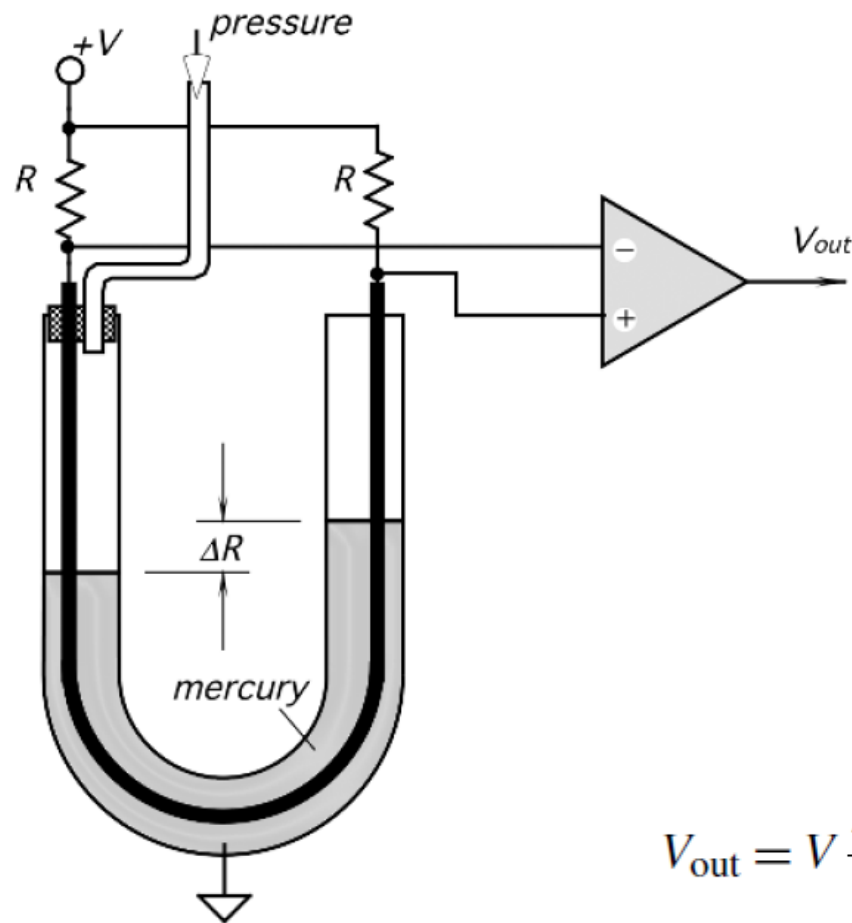
- The conversion of a result of the pressure exertion on a sensitive element into an electrical signal
- For a fluid at rest, pressure can be defined as the force F exerted perpendicularly on a unit area A of a boundary surface.

$$p = \frac{dF}{dA}$$

$$dp = -w \, dh$$

- 1 atm = 760 torr = 101,325 Pa
- 1 Pascal = 0.00001 Bar
- 1 Pascal = Newton / m² or 1 Pascal = Kilogram / meter * second²
- **Bar** is the atmospheric pressure at the sea level and equals to 100 000 pascals or 100 kilopascals
- 1 psi = 6.89 × 10³ Pa = 0.0703 atm.
- W-weight of the medium, h-vertical height
- Pascal SI unit

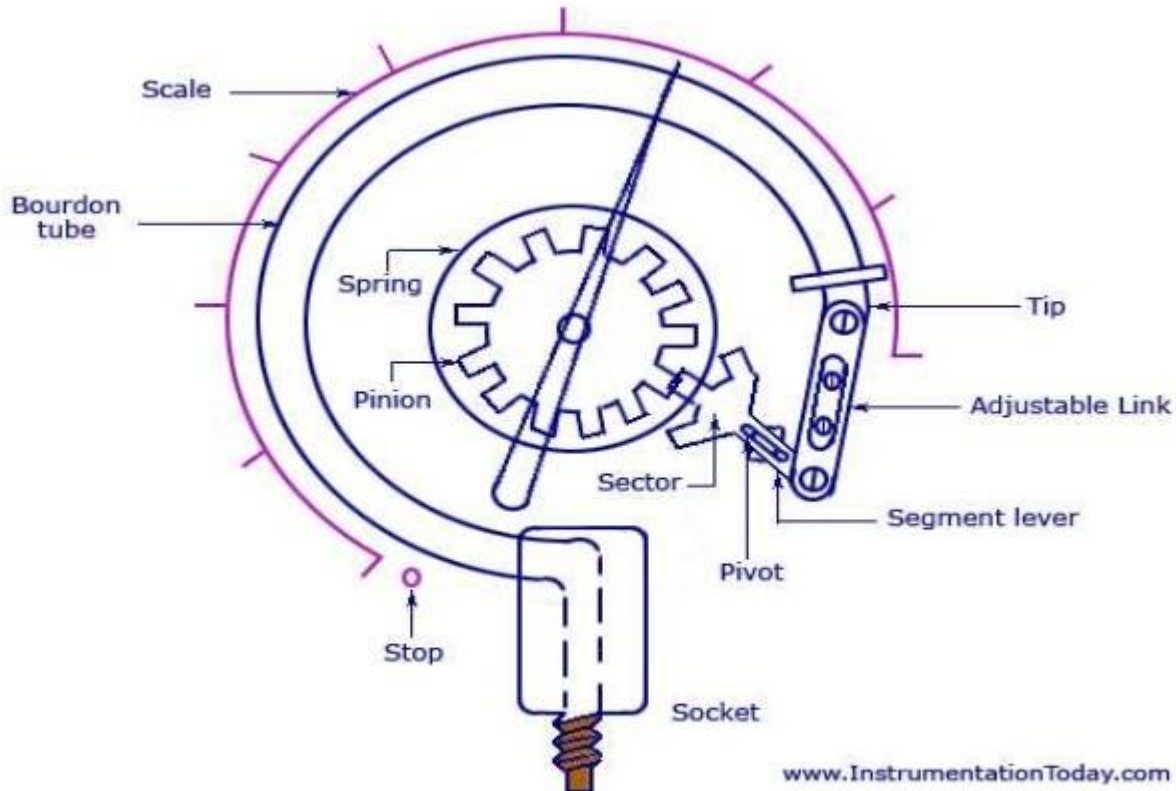
Mercury-filled U-shaped sensor for measuring gas pressure



$$V_{out} = V \frac{\Delta R}{R} = V \beta \Delta p$$

- A U-shaped wire is immersed into mercury, which shorts its resistance in proportion with the height of mercury in each column.
- The resistors are connected into a Wheatstone bridge circuit, which remains in balance as long as the differential pressure in the tube is zero

Bourdon Tube pressure gauge



Bourdon Tube Pressure Gauge

THE 'C' TYPE BOURDON TUBE



Bourdon Tube pressure gauge

Principle:-

- The bourdon tube works on a simple principle that a bent tube will change its shape .
- As pressure is applied internally, the tube straightens and returns to its original form when the pressure is released .
- The tip of the tube moves with the internal pressure change and is easily converted with a pointer onto a scale.



Bourdon Tube pressure gauge

Advantages:-

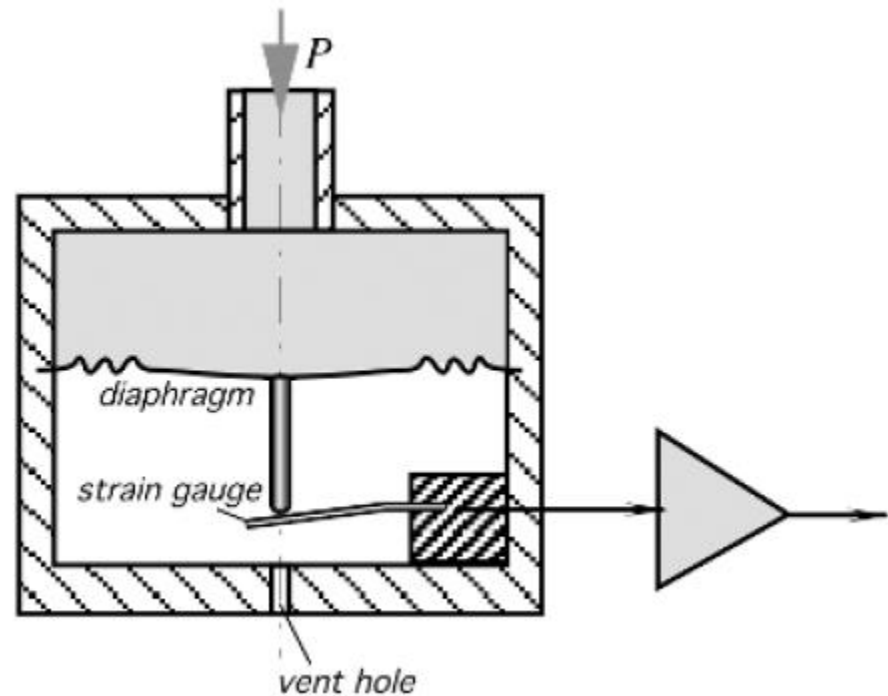
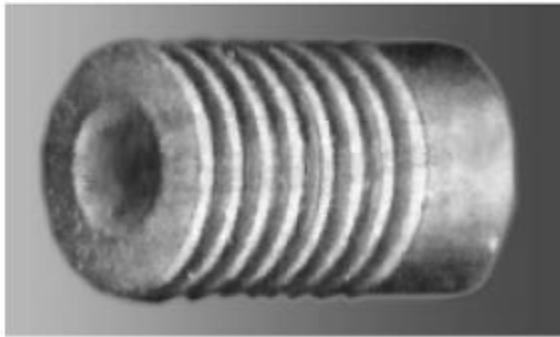
- Inexpensive
- Wide operating range
- Fast response
- Good sensitivity
- Direct pressure measurements

Disadvantages:-

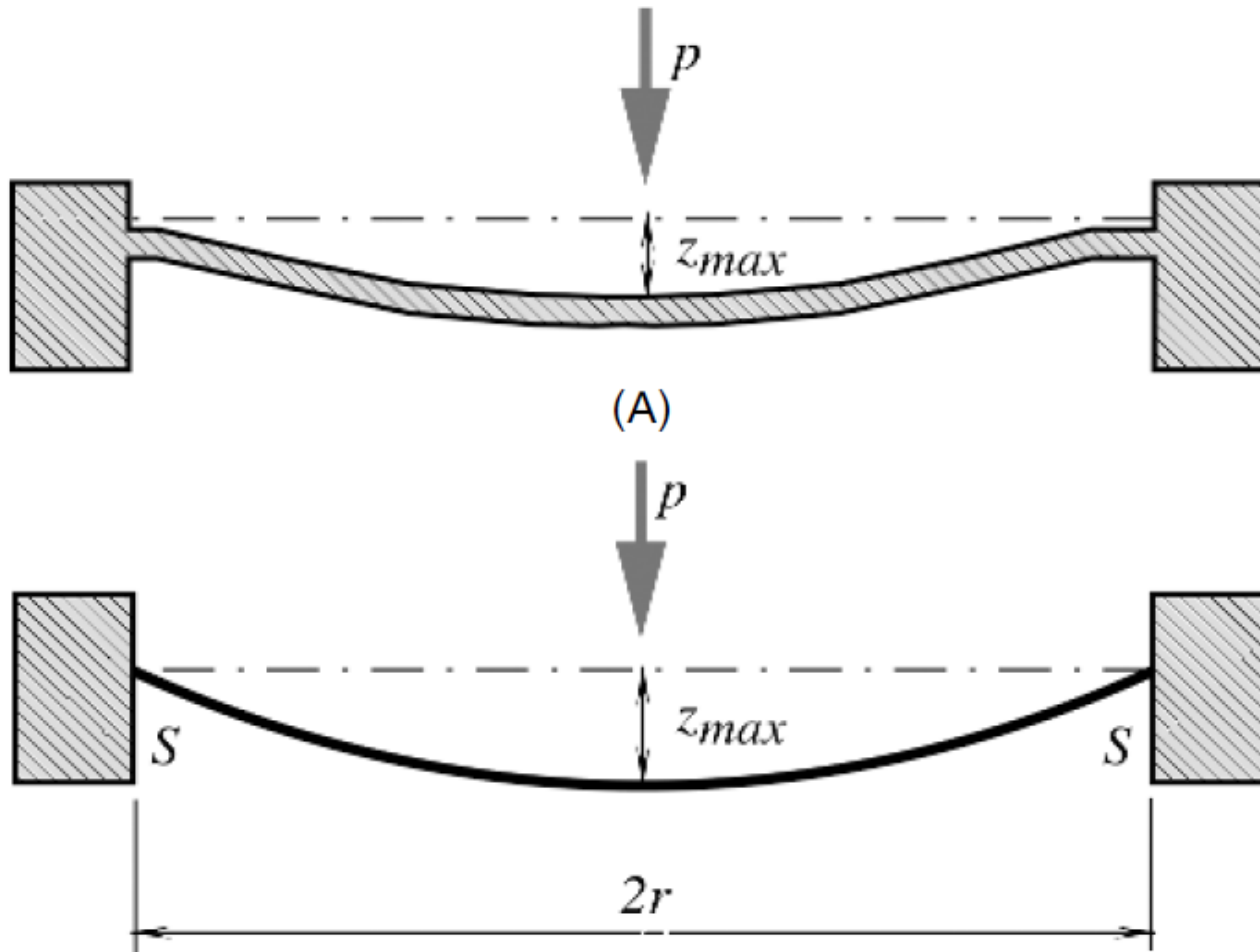
- Hysteresis on cycling
- Sensitive to temperature variations
- Limited life when subjected to shock and vibrations

Applications:- These devices should be used in air if calibrated for air and in liquid if calibrated

Steel bellows for a pressure transducer, metal corrugated diaphragm for conversion of pressure into linear deflection



Thin Plate and Membrane under pressure



Quasi linear function of pressure

Majority of pressure sensors are fabricated with silicon membranes by using micromachining technology

A membrane is a thin diaphragm under radial tension S which is measured in Newtons per meter

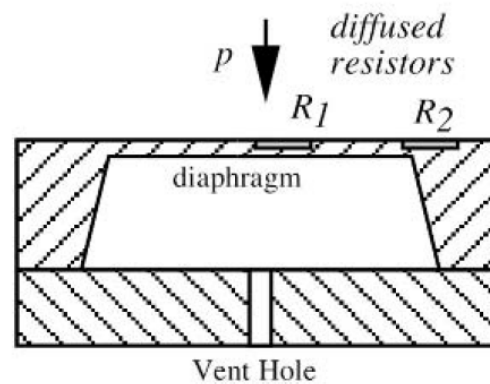
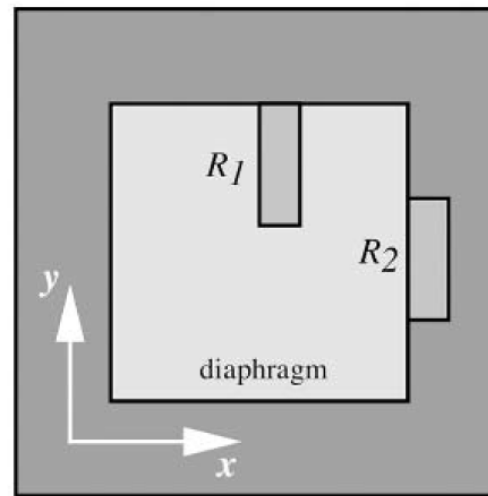
At low-pressure p differences, the center deflection z_m and the stress σ_m are quasilinear functions of pressure.

$$z_{\max} = \frac{r^2 p}{4S},$$

$$\sigma_{\max} \approx \frac{S}{g},$$

where r is the membrane radius and g is the thickness. Stress is generally uniform over the membrane area.

Piezoresistive sensor



$$\frac{\Delta R}{R} = \pi_1 \sigma_1 + \pi_t \sigma_t$$



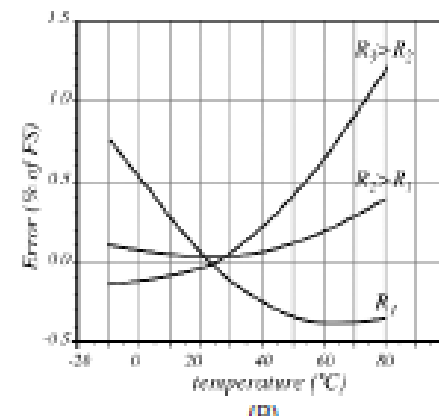
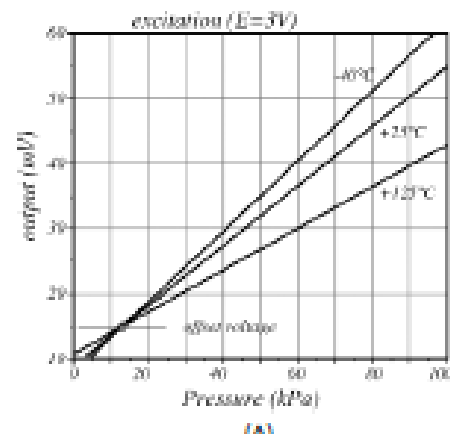
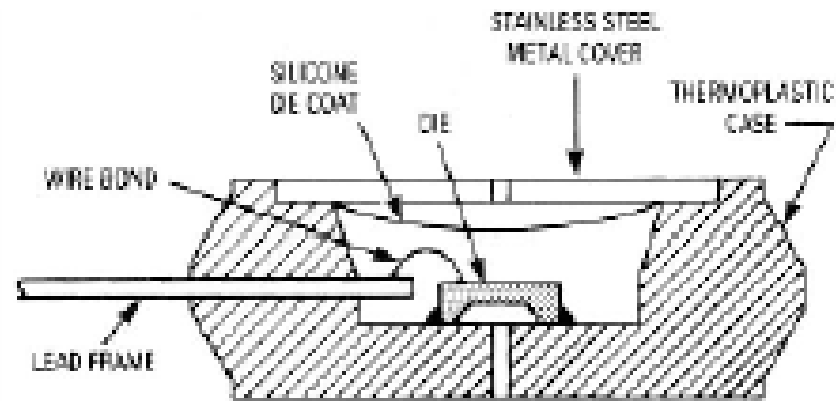
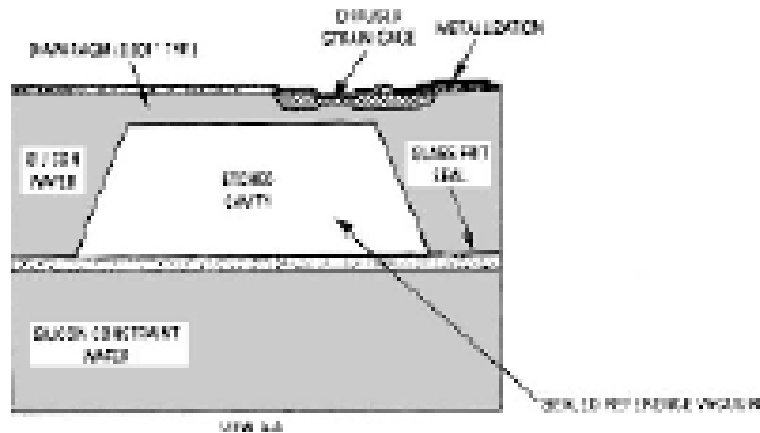
Piezoresistive sensor

- When stress is applied to a semiconductor resistor, having initial resistance R , piezoresistive effect results in change in the resistance .
- where π_l and π_t are the piezoresistive coefficients in the longitudinal and transverse direction, respectively.
- Stresses in longitudinal and transverse directions are designated σ_l and σ_t .
- The π coefficients depend on the orientation of resistor on the silicon crystal

Piezoresistive sensor

- When connecting R1 and R2 in a half-bridge circuit and exciting the bridge with E, the output voltage Vout is
- $V_{out} = \frac{1}{4} E \pi \frac{44}{4} (\sigma_{1y} - \sigma_{1x})$

Absolute and differential pressure packaging

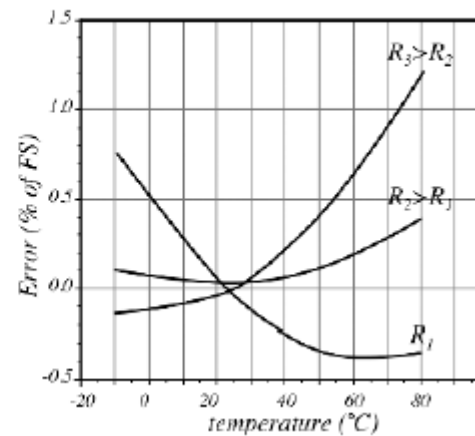
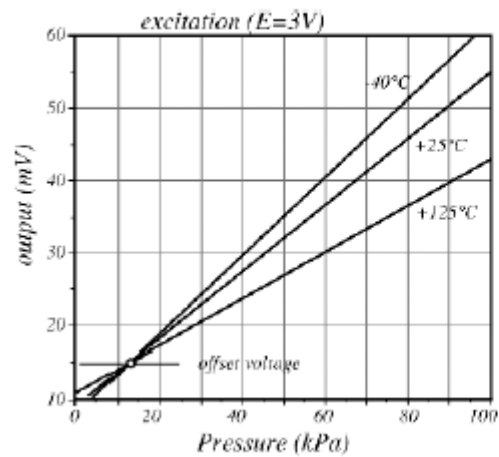




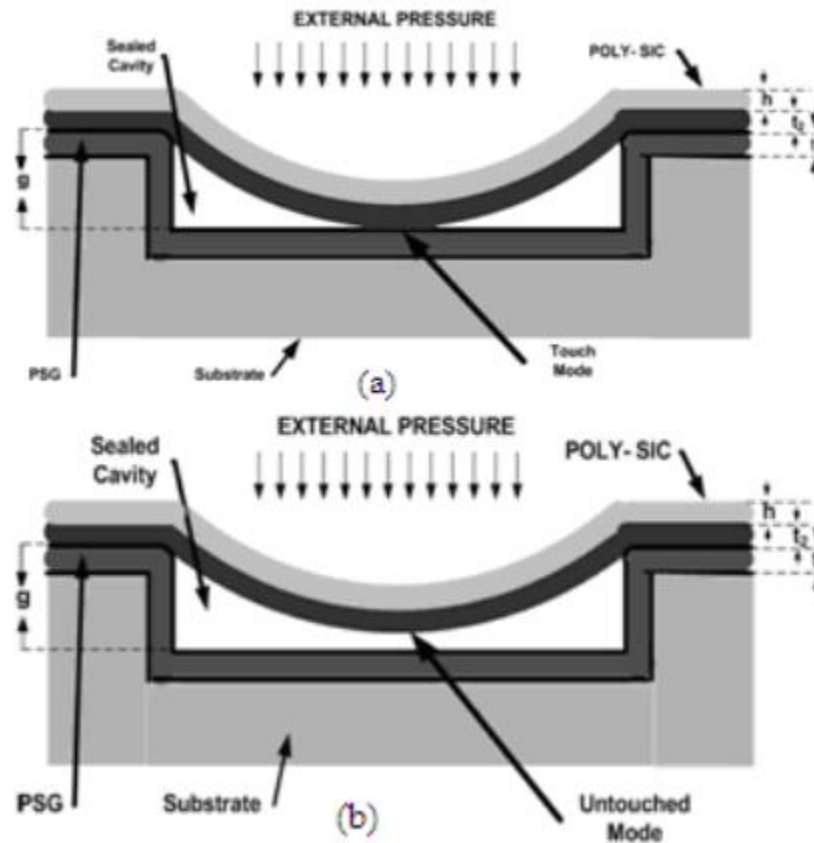
Absolute and differential pressure packaging

- Absolute pressure, such as a barometric pressure, is measured with respect to a reference vacuum chamber. The chamber may be either external or it can be built directly into the sensor .
- A differential pressure, such as the pressure drop in a pressure-differential flowmeter, is measured by applying pressure to opposite sides of the diaphragm simultaneously. Gauge pressure is measured with respect to some kind of reference pressure.
- An example is a blood pressure measurement which is done with respect to atmospheric pressure

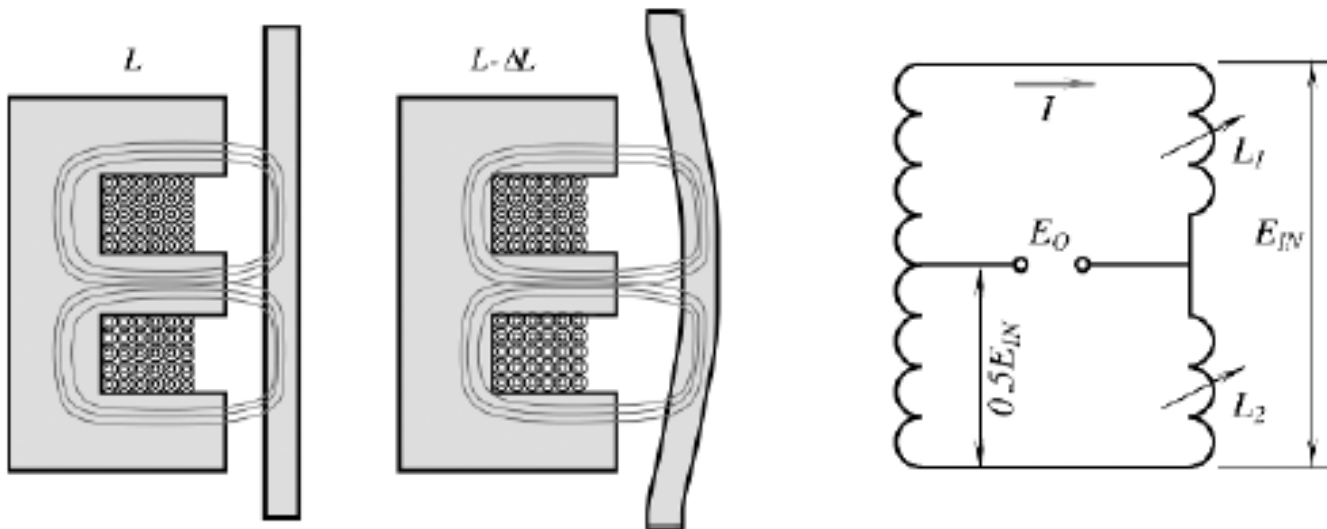
characteristics



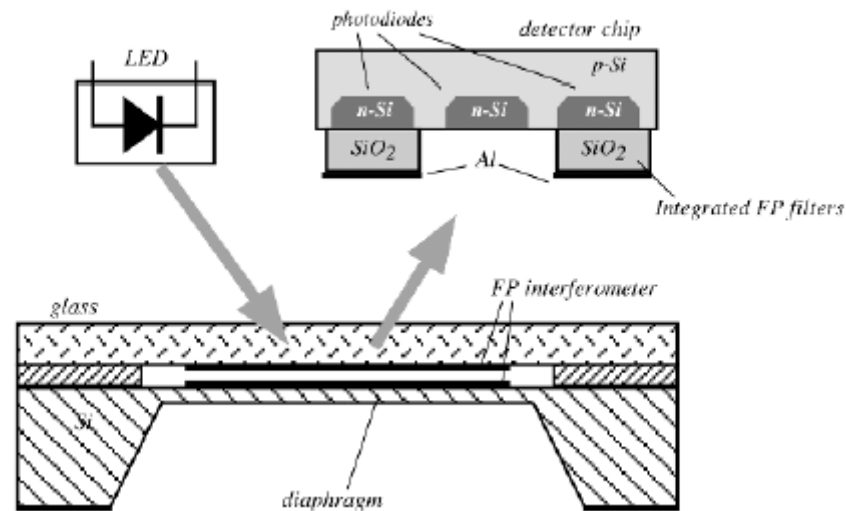
Capacitive pressure sensor



Variable reluctance pressure sensor



Opto electric pressure sensor





Dynamic pressure measurement

- Piezoelectric pressure sensors measure dynamic pressure. They are typically not suited for static pressure measurements. Dynamic pressure measurements including turbulence, blast, ballistics, and engine combustion require sensors with special capabilities. These capabilities include fast response, ruggedness, high stiffness, extended ranges, and the ability to measure quasi static pressures. These are standard features associated with PCB[®] quartz pressure sensors.

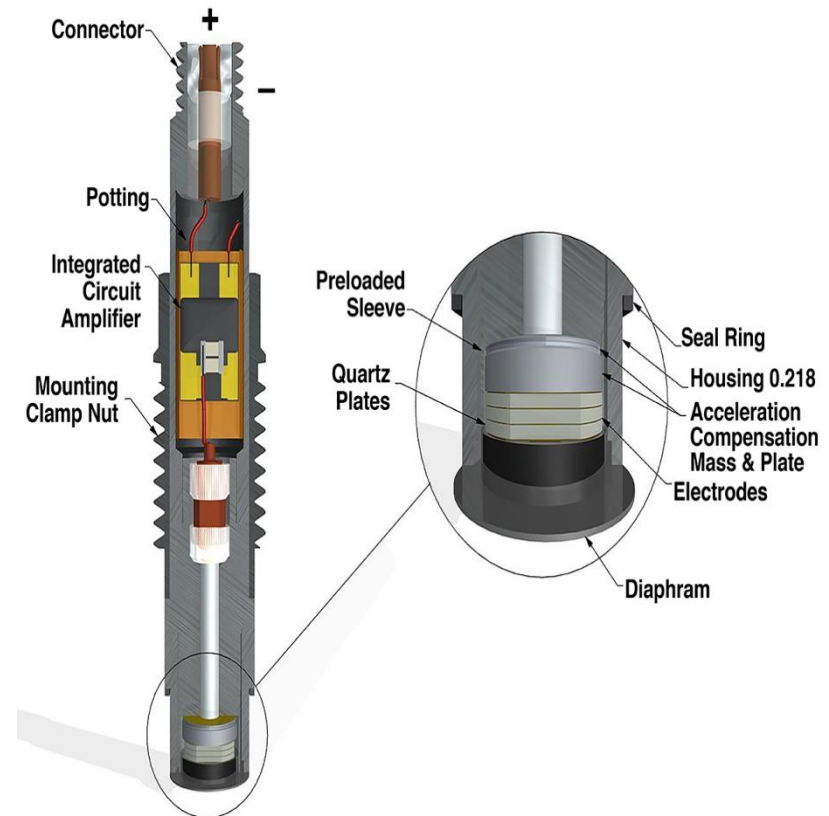


Dynamic pressure measurement

- PCB[®] manufactures two types of pressure sensors. Charge mode pressure sensors generate a high impedance charge output. ICP[®] (Integrated Circuit Piezoelectric) voltage mode sensors feature built-in microelectronic amplifiers that convert the high impedance charge signal into a low impedance voltage output.

Dynamic pressure measurement

- Piezoelectric pressure sensors are available in various shapes and thread configurations to allow suitable mounting for various types of pressure measurements. Quartz crystals are used in most sensors to ensure stable, repeatable operation. The quartz crystals are usually preloaded in the housings to ensure good linearity. Tourmaline, another stable naturally piezoelectric crystal, may be used in PCB sensors where volumetric sensitivity is required. Figure 1 is a general purpose pressure sensor with built-in electronics.





Polarity

- When a positive pressure is applied to an ICP pressure sensor, the sensor yields a positive voltage. The polarity of PCB charge mode pressure sensors is the opposite: when a positive pressure is applied, the sensor yields a negative output. Charge output sensors are usually used with external charge amplifiers that invert the signal. The resulting system output polarity of a charge output sensor used with a charge amplifier produces an output that is the same as an ICP sensor. Reverse polarity sensors are also available.

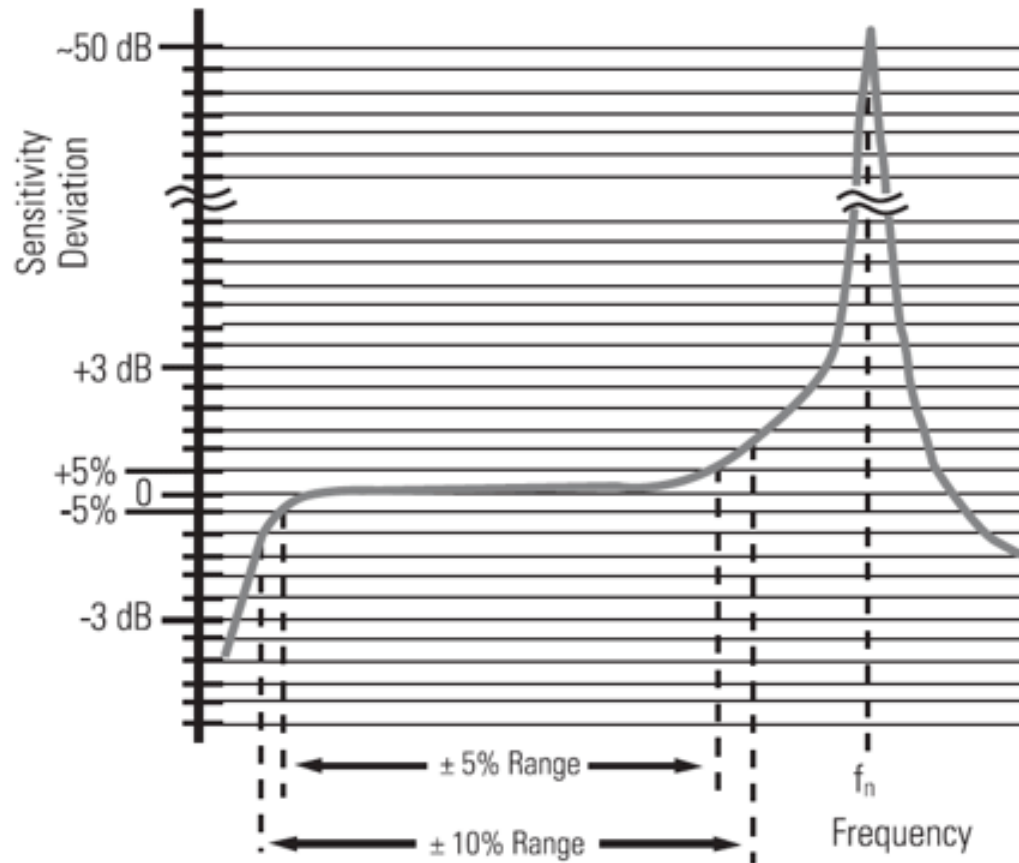


High Frequency response

- Most PCB piezoelectric pressure sensors are constructed with either compression mode quartz crystals preloaded in a rigid housing or unconstrained tourmaline crystals. These designs give the sensors microsecond response times and resonant frequencies in the hundreds of kilohertz, with minimal overshoot or ringing.
- The mechanical structure of the pressure sensor will impose a high frequency limit. The sensitivity begins to rise rapidly as the natural frequency of the sensor is approached. The increase in sensitivity is illustrated in Figure 2.
- It is generally acceptable to use sensors over a range where the sensitivity deviates by less than $\pm 5\%$. The upper frequency limit occurs at approximately 20% of the sensor resonant frequency.

The high frequency response can be limited by drive current, cable length and cable capacitance. For more detailed information on driving long cables refer to the PCB [Driving Long Cables webpage](#).

High Frequency response





Low Frequency response

- The low frequency response of a charge mode pressure sensor is determined by the charge amplifier. The discharge time constant (DTC) of the amplifier that sets the low frequency response can be very long or very short depending on the charge amplifier model used. A longer DTC allows for lower frequency measurements. A shorter DTC will limit the low frequency response.
- Internal resistance and capacitance values set the discharge time constant and the low frequency response of ICP[®] pressure sensors. The discharge time constant establishes the low frequency response analogous to the action of a first order R-C high pass filter. The DTC of the signal conditioner should also to be taken into consideration. It influences the low frequency response of the overall system. Refer to the Low Frequency Response of ICP[®] Sensors section in the PCB General Signal Conditioning guide for more detailed information.

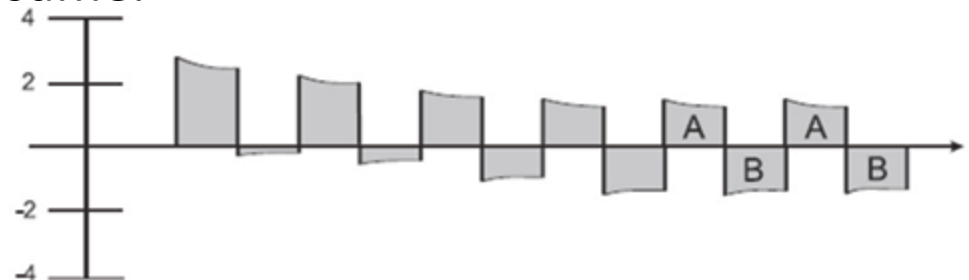


Piezo electric pressure sensor measures dynamic pressure

- The quartz crystals of a piezoelectric pressure sensor generate a charge when pressure is applied. Even though the electrical insulation resistance is quite large, the charge eventually leaks to zero. The rate at which the charge leaks back to zero is dependent on electrical insulation resistance.
- In a charge mode pressure sensor with a voltage amplifier, the leakage rate is fixed by capacitance and resistance values in the sensor, low noise cable, and the external source follower voltage amplifier. When a charge mode pressure sensor is used with a charge amplifier, the leakage rate is fixed by the electrical feedback resistor and capacitor in the charge amplifier.
- The resistance and capacitance of the crystal and the built-in electronics normally determine the leakage rate in an ICP[®] pressure sensor.

Typical piezo electric system output

- The output characteristic of piezoelectric pressure sensor systems is that of an AC coupled system. Repetitive signals decay until there is an equal area above and below the original base line. As magnitude levels of the monitored event fluctuate, the output remains stabilized around the base line with the positive and negative areas of the curve remaining equal. Figure 3 represents an AC signal following this curve.
- In this example, a 0 to 2 volt output signal is generated from an AC coupled pressure application with a one second steady state pulse rate and one second between pulses. The frequency remains constant, but the signal quickly decays negatively until the signal centers around the original base line (where area A = area B). Peak to peak output remains the same.





- http://www.pcb.com/Resources/Technical-Information/Tech_Pres



Piezoelectric and Piezoresistive

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Piezoelectric Sensing Element

- The stiffness k of the crystal is large, typically $2 \times 10^9 \text{ Nm}^{-1}$. The dynamic relation between x and F can be represented by the second-order transfer function:

$$x = \frac{1}{k} F$$

- The stiffness k of the crystal is large, typically $2 \times 10^9 \text{ Nm}^{-1}$. The dynamic relation between x and F can be represented by the second-order transfer function:

$$\frac{\Delta \bar{x}}{\Delta F}(s) = \frac{1/k}{\frac{1}{\omega_n^2} s^2 + \frac{2\xi}{\omega_n} s + 1}$$

where

$\omega_n = 2\pi f_n$ is large, typically $f_n = 10$ to 100 kHz , and ξ is small, typically $\xi \approx 0.01$.

- In a piezoelectric crystal, this deformation of the crystal lattice results in the crystal acquiring a net charge q , proportional to x , i.e.

- $q = Kx$

$$q = \frac{K}{k} F = dF \longrightarrow \text{Direct piezoelectric effect}$$

where $d = K/k \text{ C N}^{-1}$ is the charge sensitivity to force. Thus a piezoelectric crystal gives a direct electrical output, proportional to applied force, so that a secondary displacement sensor is not require

- Applied force produces an electric charge.
There is also an inverse effect where a voltage V applied to the crystal causes a mechanical displacement x .
- $x = dV$
- The inverse effect is important in ultrasonic transmitters

- In order to measure the charge q , metal electrodes are deposited on opposite faces of the crystal to give a capacitor. The capacitance of a parallel plate capacitor formed from a rectangular block of crystal of thickness t is given by:

$$C_N = \frac{\epsilon_0 \epsilon A}{t}$$

- The crystal can therefore be represented as a charge generator q in parallel with a capacitance C_N
- by a Norton equivalent circuit consisting of a current source i_N in parallel with C_N

$$i_N = \frac{dq}{dt} = K \frac{dx}{dt}$$

- in transfer function form

$$\frac{\Delta \bar{i}_N}{\Delta \bar{x}}(s) = Ks$$

- where d/dt is replaced by the Laplace operator s. We note that for a steady force F, F and x are constant with time, so that dx/dt and i_N are zero.
- If the piezoelectric sensor is connected directly to a recorder (assumed to be a pure resistive load R_L) by a cable (assumed to be a pure capacitance C_C) then the complete equivalent circuit is

$$\frac{\Delta \bar{V}_L(s)}{\Delta \bar{i}_N(s)} = \frac{R_L}{1 + R_L(C_N + C_C)s}$$

The overall system transfer function relating recorder voltage V_L to input force F is:

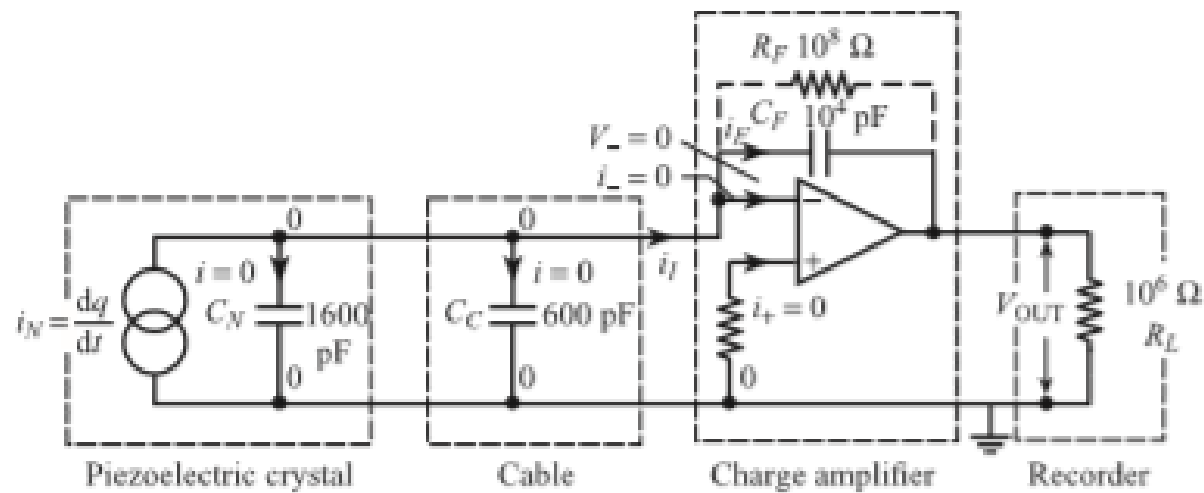
$$\frac{\Delta \bar{V}_L(s)}{\Delta \bar{F}} = \frac{\Delta \bar{V}_L}{\Delta \bar{i}_N} \frac{\Delta \bar{i}_N}{\Delta \bar{x}} \frac{\Delta \bar{x}}{\Delta \bar{F}}$$

$$\begin{aligned} \frac{\Delta \bar{V}_L(s)}{\Delta \bar{F}} &= \frac{R_L}{1 + R_L(C_N + C_C)s} Ks \frac{1/k}{\frac{1}{\omega_n^2}s^2 + \frac{2\xi}{\omega_n}s + 1} \\ &= \frac{K}{k} \frac{1}{(C_N + C_C)} \frac{R_L(C_N + C_C)s}{1 + R_L(C_N + C_C)s} \frac{1}{\frac{1}{\omega_n^2}s^2 + \frac{2\xi}{\omega_n}s + 1} \end{aligned}$$

*Transfer function for
basic piezoelectric
force measurement
system*

$$\frac{\Delta V_L(s)}{\Delta \bar{F}} = \frac{d}{(C_N + C_C)} \frac{\tau s}{(1 + \tau s)} \frac{1}{\left(\frac{1}{\omega_n^2}s^2 + \frac{2\xi}{\omega_n}s + 1 \right)}$$

where $\tau = R_L(C_N + C_C)$.



Transfer characteristics
of ideal charge
amplifier

$$\frac{dV_{OUT}}{dt} = -\frac{1}{C_F} \frac{dq}{dt} \quad \text{i.e.} \quad V_{OUT} = -\frac{q}{C_F}$$

Transfer function for
piezoelectric system
with ideal charge
amplifier

$$\frac{\Delta \bar{V}_{OUT}}{\Delta \bar{F}}(s) = \frac{d}{C_F} \frac{1}{\left(\frac{1}{\omega_n^2} s^2 + \frac{2\xi}{\omega_n} s + 1 \right)}$$

Properties of piezoelectric materials

Material	Charge sensitivity d pC N ⁻¹	Dielectric constant ϵ	Voltage sensitivity $g \times 10^{-3}$ V m N ⁻¹	Young's modulus $E \times 10^9$ N m ⁻²	Damping ratio ξ
Quartz	2.3	4.5	50	80	2×10^{-5}
PZT	110	1200	10	80	7×10^{-3}
BaTi ₂ O ₃	78	1700	5.2	80	1×10^{-3}
PVDF	23	12	230	2	5×10^{-2}

Piezoresistive sensing elements

- The piezoresistive effect was defined as the change in resistivity ρ of a material with applied mechanical strain e , and is represented by the term $(1/e)(\Delta \rho / \rho)$ in the equation for gauge factor of a strain gauge.

