Unit II: Sensors and Actuators

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6ME3A: Mechatronics

Introduction to Sensors and Actuators

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Unit-II

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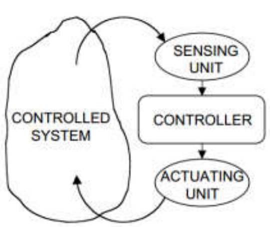
Introduction to Sensors: Linear and Rotational Sensors, Acceleration, Force, Torque, Power, Flow and Temperature Sensors, Light Detection, Image, and Vision Systems, Integrated Micro-sensors,

Introduction to Actuators: Electro-mechanical Actuators, Electrical Machines, Piezoelectric Actuators, Hydraulic and Pneumatic Actuation Systems, MEMS: Micro-transducers Analysis, Design and Fabrication.

Introduction

- Sensors and actuators are two critical components of every closed loop control system. Such a system is also called a mechatronics system.
- A sensing unit can be as simple as a single sensor or can consist of additional components such as filters, amplifiers, modulators, and other signal conditioners.
- The controller accepts the information from the sensing unit, makes decisions based on the control algorithm, and outputs commands to the actuating unit.
- The actuating unit consists of an actuator and optionally a power supply and a coupling mechanism.



Sensors

- Sensor is a device that when exposed to a physical phenomenon (temperature, displacement, force, etc.) produces a proportional output signal (electrical, mechanical, magnetic, etc.).
- The term transducer is often used synonymously with sensors.
- However, ideally, a sensor is a device that responds to a change in the physical phenomenon.
- On the other hand, a transducer is a device that converts one form of energy into another form of energy.
- Sensors are transducers when they sense one form of energy input and output in a different form of energy.
- For example, a thermocouple responds to a temperature change (thermal energy) and outputs a proportional change in electromotive force (electrical energy). Therefore, a thermocouple can be called a sensor and or transducer.

Sensor and Transducer

Sensors

According to the Instrument Society of America, sensor can be defined as

"A device which provides a usable output in response to a specified measurand."

Here, the output is usually an 'electrical quantity' and measurand is a 'physical quantity, property or condition which is to be measured'.

Transducer

It is defined **as an element when subjected to some physical change experiences a related change or an element which converts a specified measurand into a usable output** by using a transduction principle.

A wire of Constantan alloy (copper-nickel 55-45% alloy) can be called as a sensor because variation in mechanical displacement (tension or compression) can be sensed as change in electric resistance. This wire becomes a transducer with appropriate electrodes and input-output mechanism attached to it. Thus we can say that 'sensors are transducers'.

Sensor and Transducer Specifications

Various specifications of a sensor/transducer system are:

Range	Hysteresis
Span	Resolution
Error	Stability
Accuracy	Dead band/time
Sensitivity	Repeatability
Nonlinearity	Response time

Sensor and Transducer Specifications

Range

The range of a sensor indicates the limits between which the input can vary. For example, a thermocouple for the measurement of temperature might have a range of 25-225 °C.

Span

The span is difference between the maximum and minimum values of the input. Thus, the above-mentioned thermocouple will have a span of 200 °C.

Error

Error is the difference between the result of the measurement and the true value of the quantity being measured. A sensor might give a displacement reading of 29.8 mm, when the actual displacement had been 30 mm, then the error is –0.2 mm.

Sensitivity

Sensitivity of a sensor is defined as the ratio of change in output value of a sensor to the per unit change in input value that causes the output change. For example, a general purpose thermocouple may have a sensitivity of 41 μV/°C.

Sensor and Transducer Specifications

Accuracy

The accuracy defines the closeness of the agreement between the actual measurement result and a true value of the measurand.

It is often expressed as a percentage of the full range output or full–scale deflection.

Resolution

Resolution is the smallest detectable incremental change of input parameter that can be detected in the output signal. Resolution can be expressed either as a proportion of the full-scale reading or in absolute terms.

Example: if a LVDT sensor measures a displacement up to 20 mm and it provides an output as a number between 1 and 100 then the resolution of the sensor device is 0.2 mm.

Stability

Stability is the ability of a sensor device to give same output when used to measure a constant input over a period of time. The term 'drift' is used to indicate the change in output that occurs over a period of time. It is expressed as the percentage of full range output.

Sensor and Transducer Specifications

Dead band/time

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

Repeatability

It specifies the ability of a sensor to give same output for repeated applications of same input value. It is usually expressed as a percentage of the full range output:

$$\text{Repeatability} = \frac{(\text{Maximum} - \text{Minimum})}{\text{Full Range}} \times 100$$

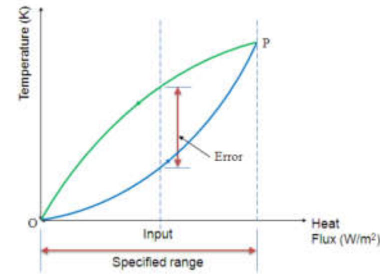
Response time

Response time describes the speed of change in the output on a step-wise change of the measurand. It is always specified with an indication of input step and the output range for which the response time is defined.

Sensor and Transducer Specifications

Hysteresis

The hysteresis is an error of a sensor, which is defined as the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and then with decreasing the input parameter.



Sensor and Transducer Specifications

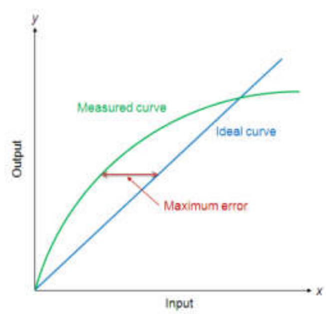
Nonlinearity

The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve.

Linearity is often specified in terms of *percentage of nonlinearity*, which is defined as:

$$\text{Nonlinearity}\ (\%) = \frac{\text{Maximum deviation in input}}{\text{Maximum full scale input}}$$

The static nonlinearity is dependent upon environmental factors, including temperature, vibration, acoustic noise level, and humidity. Therefore it is important to know under what conditions the specification is valid.



Sensors - Classification

Sensors	Features
	Linear/Rotational sensors
Linear/Rotational variable differential transducer (LVDT/RVDT)	High resolution with wide range capability Very stable in static and quasi-static applications
Optical encoder	Simple, reliable, and low-cost solution Good for both absolute and incremental measurements
Electrical tachometer	Resolution depends on type such as generator or magnetic pickups
Hall effect sensor	High accuracy over a small to medium range
Capacitive transducer	Very high resolution with high sensitivity Low power requirements Good for high frequency dynamic measurements
Strain gauge elements	Very high accuracy in small ranges Provides high resolution at low noise levels

Sensors - Classification

Sensors	Features
Interferometer	Laser systems provide extremely high resolution in large ranges Very reliable and expensive
Magnetic pickup Gyroscope	Output is sinusoidal
Inductosyn	Very high resolution over small ranges
Acceleration sensors	
Seismic accelerometer	Good for measuring frequencies up to 40% of its natural frequency
Piezoelectric accelerometer	High sensitivity, compact, and rugged Very high natural frequency (100 kHz typical)

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Sensors - Classification

Sensors	Features
Force, torque, and pressure sensor	
Strain gauge	Good for both static and dynamic measurements
Dynamometers/load cells	They are also available as micro- and nano-sensors
Piezoelectric load cells	Good for high precision dynamic force measurements
Tactile sensor	Compact, has wide dynamic range, and high
Ultrasonic stress sensor	Good for small force measurements

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Sensors - Classification

Sensors	Features
Flow sensors	
Pitot tube	Widely used as a flow rate sensor to determine speed in aircrafts
Orifice plate	Least expensive with limited range
Flow nozzle, venturi tubes	Accurate on wide range of flow More complex and expensive
Rotameter	Good for upstream flow measurements Used in conjunction with variable inductance sensor
Ultrasonic type	Good for very high flow rates Can be used for both upstream and downstream flow measurements
Turbine flow meter	Not suited for fluids containing abrasive particles Relationship between flow rate and angular velocity is linear

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Sensors - Classification

Sensors	Features
Flow sensors continue..	
Electromagnetic flow meter	Least intrusive as it is noncontact type Can be used with fluids that are corrosive, contaminated, etc. The fluid has to be electrically conductive
Temperature sensors	
Thermocouples	This is the cheapest and the most versatile sensor Applicable over wide temperature ranges (-200°C to 1200°C typical)
Thermistors	Very high sensitivity in medium ranges (up to 100°C typical) Compact but nonlinear in nature
Thermodiodes, thermo transistors	Ideally suited for chip temperature measurements Minimized self heating
RTD—resistance temperature detector	More stable over a long period of time compared to thermocouple Linear over a wide range

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Sensors - Classification

Sensors	Features
Temperature sensors continue..	
Infrared type	Noncontact point sensor with resolution limited by wavelength
Infrared thermography	Measures whole-field temperature distribution
Proximity sensors	
Inductance, eddy current, hall effect, photoelectric, capacitance, etc.	Robust noncontact switching action The digital outputs are often directly fed to the digital controller

Sensors - Classification

Sensors	Features
Light sensors	
Photoresistors, photodiodes, photo	Measure light intensity with high sensitivity
transistors, photo conductors, etc.	Inexpensive, reliable, and noncontact sensor
Charge-coupled diode	Captures digital image of a field of vision
Smart material sensors	
Optical fiber As strain sensor	Alternate to strain gages with very high accuracy and bandwidth Sensitive to the reflecting surface's orientation and status
As level sensor	Reliable and accurate
As force sensor	High resolution in wide ranges
As temperature sensor	High resolution and range (up to 2000 ^oC)

Sensors - Classification

Sensors	Features
Smart material sensors continue…	
Piezoelectric As strain sensor	Distributed sensing with high resolution and bandwidth
As force sensor	Most suitable for dynamic applications
As accelerometer	Least hysteresis and good set point accuracy
Magnetostrictive As force sensors	Compact force sensor with high resolution and bandwidth Good for distributed and noncontact sensing applications
As torque sensor	Accurate, high bandwidth, and noncontact sensor

Sensors - Classification

Sensors	Features
Micro- and nano-sensors	
Micro CCD image sensor	Small size, full field image sensor
Fiberscope	Small (0.2 mm diameter) field vision scope using SMA coil actuators
Micro-ultrasonic sensor	Detects flaws in small pipes
Micro-tactile sensor	Detects proximity between the end of catheter and blood vessels

Sensors

- Sensors can also be classified as passive or active.
- In passive sensors, the power required to produce the output is provided by the sensed physical phenomenon itself (such as a thermometer) whereas
- The active sensors require external power source (such as a strain gauge)
- Sensors are classified as analog or digital based on the type of output signal.
- Analogue sensors produce continuous signals that are proportional to the sensed parameter and typically require analogue-to-digital conversion before feeding to the digital controller.
- Digital sensors on the other hand produce digital outputs that can be directly interfaced with the digital controller.
- Often, the digital outputs are produced by adding an analog-to-digital converter to the sensing unit. If many sensors are required, it is more economical to choose simple analog sensors and interface them to the digital controller equipped with a multi-channel analog-to-digital converter.

Key Issues in The Selection of Sensors

(a) the field of view and range;
(b) accuracy;
(c) repeatability and resolution;
(d) responsiveness in the target-domain;
(e) power consumption;
(f) hardware reliability;
(g) size; and
(h) interpretation reliability.

Principle of Operation of Sensors

Linear and Rotational Sensors

- Two of the most fundamental of all measurements used in a typical mechatronics system
- Known as position sensors
- Produce an electrical output that is proportional to the displacement they experience
- There are contact type sensors:
  - Strain Gauge,
  - LVDT (Linear Variable Differential Transformer),
  - RVDT (Rotary Variable Differential Transformer),
  - Tachometer
- There are non contact type sensors:
  - Encoders,
  - Hall effect,
  - Capacitance,
  - Inductance, and
  - Interferometer

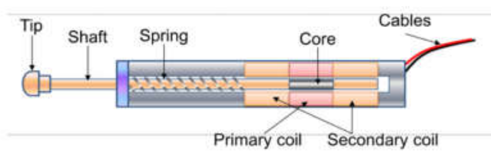
Linear and Rotational Sensors

- Also can be classified based on the range of measurement
  - High-resolution type (typically from 0.1 mm to 5 mm)
    - Hall Effect, Fibre optic Inductance, Capacitance and Strain Gauge
  - Large-resolution type (typically up to a meter)
    - Differential Transformer (LV or RV)
  - High and large resolution type
    - Interferometer (range: micron to meter): bulky, expensive, and requires large set up time

Linear variable differential transformer (LVDT)

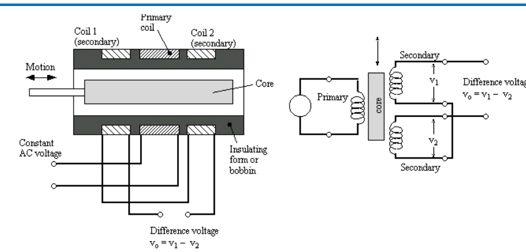
- A mechanical displacement transducer.
- Gives an A.C. voltage output proportional to the distance of the transformer core to the windings.
- The LVDT is a mutual-inductance device with three coils and a core

Linear variable differential transformer (LVDT)



- It has three coils symmetrically spaced along an insulated tube.
- The central coil is primary coil and the other two are secondary coils.
- Secondary coils are connected in series in such a way that their outputs oppose each other.
- A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube.

Linear variable differential transformer (LVDT)

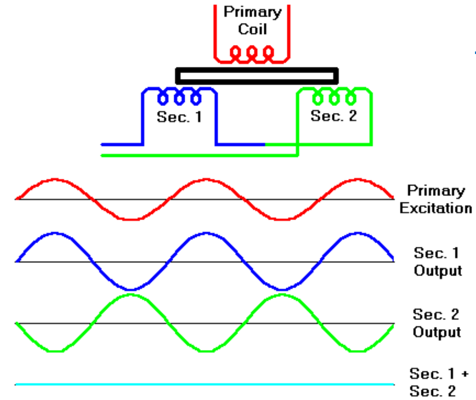


- Secondary coils are connected in series in such a way that their outputs oppose each other.
- A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube.

Linear variable differential transformer (LVDT)

- Linear variable differential transformer (LVDT) is a primary transducer used for measurement of linear displacement with an input range of about ± 2 to ± 400 mm in general.
- It has non-linearity error ± 0.25% of full range.
- Due to an alternating voltage input to the primary coil, alternating electromagnetic forces (emfs) are generated in secondary coils.
- When the magnetic core is centrally placed with its half portion in each of the secondary coil regions then the resultant voltage is zero.

LVDT



LVDT available in Lab.

- Range : +/- 10 mm
- Resolution : 0.1 mm
- Analoge o/p : 200 mV

Linear variable differential transformer (LVDT)

Advantages of LVDT:

- LVDT exhibits good repeatability and reproducibility.
- It is generally used as an absolute position sensor. Since there is no contact or sliding between the constituent elements of the sensor, it is highly reliable.
- These sensors are completely sealed and are widely used in Servomechanisms, automated measurement in machine tools.
- LVDT Provides Less friction, Low hysteresis, and Low power consumption device

Linear variable differential transformer (LVDT)

Disadvantages of LVDT:

- Very high displacement is required for generating high voltages.
- Shielding is required since it is sensitive to magnetic field.
- The performance of the transducer gets affected by vibrations.
- Its is greatly affected by temperature changes.

Linear variable differential transformer (LVDT)

Applications of LVDT sensors

- Measurement of spool position in a wide range of servo valve applications,
- To provide displacement feedback for hydraulic cylinders,
- To control weight and thickness of medicinal products viz. tablets or pills,
- For automatic inspection of final dimensions of products being packed for dispatch,
- To measure distance between the approaching metals during Friction welding process,
- To continuously monitor fluid level as part of leak detection system,
- To detect the number of currency bills dispensed by an ATM.

Example

- The output of a LVDT is connected to a 10A ammeter through an amplifier whose amplification factor is 200.
- An output of 3mA appears across the terminals of LVDT when the core moves trough a distance of 0.75mm
- Calculate the sensitivity of LVDT and that of the whole set-up.

- The millimeter scale has 100 division. The scale can be read to 1/10 of a division.
- Determine the resolution of the instrument in mm

Example

Sensitivity

$$Sensitivity\ of\ LVDT = \frac{Output\ current}{Displacement}$$

$$= \frac{3 \times 10^{-3}}{0.75} = 4 \times 10^{-3}\ A/mm$$

$$Sesitivity\ of\ instrument = Sensitivity\ of\ LVDT\ \times Amplification\ factor$$
$$= 4 \times 10^{-3} \times 200$$
$$= 0.8\ A/mm$$

Resolution

$$1\ Scale\ division = \frac{10A}{100} = 0.1A$$

$$Least\ current\ can\ be\ measured = \frac{0.1}{10} = 0.01A$$

$$Resolution = \frac{0.01}{0.8} = 0.0125\ mm$$

Strain Gauges

- The strain in an element is a ratio of change in length in the direction of applied load to the original length of an element.
- Resistance strain gauge is a transducer that exhibits the change in electric resistance when it is stretched or strained.
- The resistance of metal sample is:

$$R_0 = \rho \frac{l_0}{A_0} \qquad (1)$$

where ρ, l_0 and A_0 are density, length and cross-sectional area, respectively.

- When this metal sample is stressed by the application of a Force F,

The material elongates by some amount Δl and change in resistance is:

$$\Delta R = 2R_0 \frac{\Delta l}{l_0} \qquad (2)$$

Strain Gauges

- The strain changes the resistance R of the element.

$$\frac{\Delta R}{R} \alpha\ \varepsilon \qquad (3)$$

$$\frac{\Delta R}{R} = G\ \varepsilon \qquad (4a)$$

or

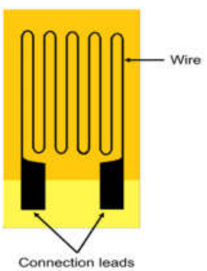
$$\Delta R = \frac{G \cdot \varepsilon}{R} \qquad (4b)$$

where G is the constant of proportionality and is called as Gauge Factor.

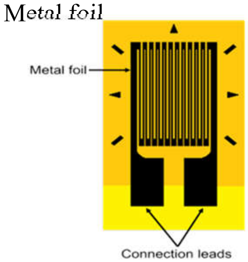
In general, the value of G is considered in between 2 to 4 and the resistances are taken of the order of 100 Ω.

Strain Gauge

- Wire



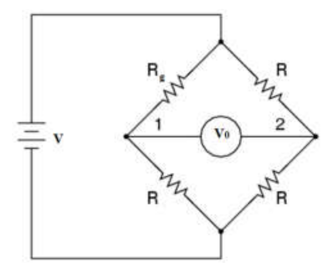
- Metal foil



These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and are bonded to a backing material plastic (ployimide), epoxy or glass fiber reinforced epoxy.

Strain Gauge

- Resistance strain gauge follows the principle of change in resistance as per the equation (4): ΔR/R=G ε
- As the workpiece undergoes change in its shape due to external loading, the resistance of strain gauge element changes.
- This change in resistance can be detected by a using a Wheatstone's resistance bridge



Strain Gauge: Wheatstone's resistance bridge

- $R_2/R_1 = R_x/R_3$

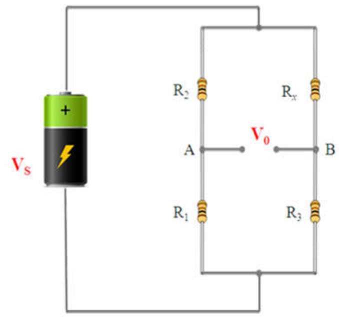
where

R_x is resistance of strain gauge element,

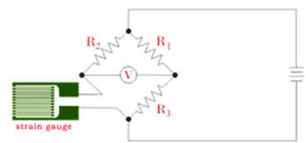
R_2 is balancing/adjustable resistor,

R_1 and R_3 are known constant value resistors.

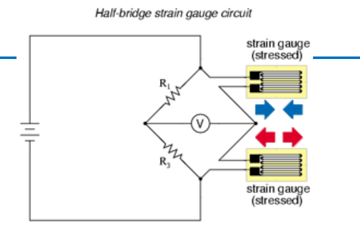
The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor R2 which makes the voltage across nodes A and B equal to zero.

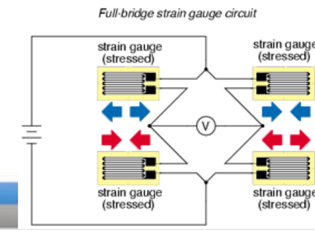


Strain Gauge: Type



Quarter-bridge strain gauge circuit





Strain Gauge: Applications

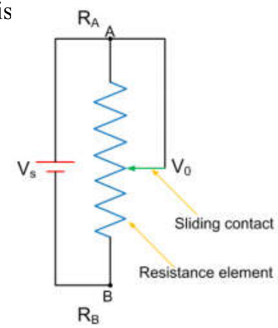
- Strain gauges are widely used in experimental stress analysis and diagnosis on machines and failure analysis.
- They are basically used for multi-axial stress fatigue testing, proof testing, residual stress and vibration measurement, torque measurement, bending and deflection measurement, compression and tension measurement and strain measurement.
- Strain gauges are primarily used as sensors for machine tools and safety in automotive.
- In particular, they are employed for force measurement in machine tools, hydraulic or pneumatic press and as impact sensors in aerospace vehicles.

Potentiometers

- The potentiometer is also called as 'pots'
- The potentiometer is the electrical type of transducer or sensor and it is of resistive type because it works on the principle of change of resistance of the wire with its length.
- The resistance of the wire is directly proportional to the length of the wire, thus as the length of the wire changes the resistance of the wire also changes.
-

Principle of Working of Linear Potentiometers

- During the sensing operation, a voltage V_s is applied across the resistive element.
- A voltage divider circuit is formed when slider comes into contact with the wire.
- The output voltage (V_A) is measured as shown in the figure.
- The output voltage is proportional to the displacement of the slider over the wire.
- The output parameter displacement is calibrated against the output voltage V_A.



Principle of Working of Linear Potentiometers

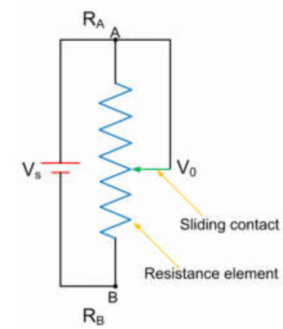
$V_A = I\,R_A$

But $I = V_S / (R_A + R_B)$

Therefore $V_A = V_S\,R_A / (R_A + R_B)$

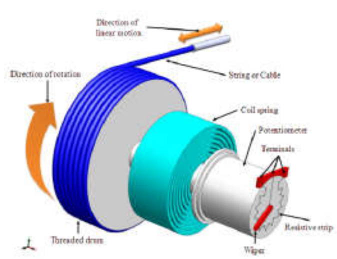
As we already know that $R = \rho\,L/A$, where ρ is electrical resistivity, L is length of resistor and A is area of cross section

$$V_A = V_S\,L_A / (L_A + L_B)$$



Potentiometer Sensors: Rotary

- A rotary type potentiometer sensor employed to measure the linear displacement.
- It works on the principle of conversion of mechanical displacement into an electrical signal.
- The sensor has a resistive element and a sliding contact (wiper).
- The slider moves along this conductive body, acting as a movable electric contact.



Principle of Working of Rotary Potentiometer (String)

- A Cable-Extension Transducer, sometimes also known as a string pot, a draw wire sensor, a string encoder or yo-yo sensor, is a device used to detect and measure linear position and velocity using a flexible cable and spring-loaded spool.
- Simply mount the transducer's body to a fixed surface and attach the stainless steel cable to the movable object. As the object moves, the transducer produces an electrical signal proportional to the cable's linear extension or velocity. This signal can then be sent to a PC via a suitable interface.

Principle of Working of Rotary Potentiometer (String)

- A Cable-Extension Transducer, sometimes also known as a string pot, a draw ... , is a device used to detec... using a flexible cable an...
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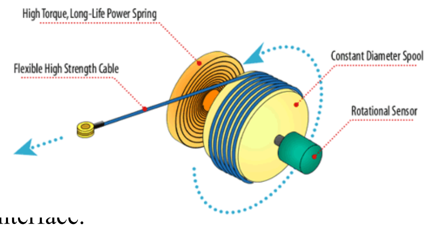


Applications

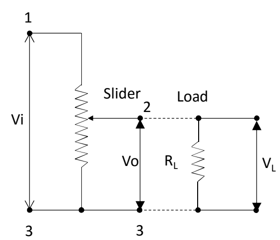
- The object of whose displacement is to be measured is connected to the slider by using
  - a rotating shaft (for angular displacement),
  - a moving rod (for linear displacement),
  - a cable that is kept stretched during operation.
- Commonly used in circuits for various purposes like to control volume in audio circuits, to regulate the speed of the motor in a fan, as light dimmer, etc.
- These are typically used on machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls. In manufacturing, these are used in control of injection molding machines, woodworking machinery, printing, spraying, robotics, etc. These are also used in computer-controlled monitoring of sports equipment.

Linear Potentiometer

- The resistance wire produce a uniform drop in the applied voltage, V_i along its length.
- For a constant input voltage V_i between terminals 1 and 3, the output voltage (V_o) between terminals 2 and 3 is a fraction of the output voltage.
- The fraction is

$$\frac{V_o}{V_i} = \frac{R_{23}}{R_{13}}$$

- The slider moves from one turn to other changing output voltage in steps.

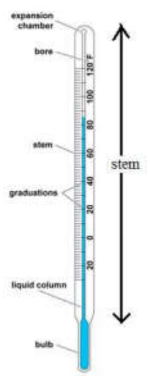


Temperature Sensors

➢ Common devices used for measuring temperature are:
- liquid-in-gas thermometer, bimetallic strip, Resistance, temperature device, thermistor, and thermocouple.

➢ The temperature scales used to express temperature are:
- Celsius (°C): Common SI unit of relative temperature.
- Kelvin (K): Standard SI unit of absolute thermodynamic temperature.
- Fahrenheit (°F): English system unit of relative temperature.
- Rankine (°R): English system unit of absolute thermodynamic temperature.

Temperature Sensors: Liquid-in-Glass Thermometer



- A simple nonelectrical temperature-measuring device
- It typically uses alcohol or mercury as the working fluid, which expands and contracts relative to the glass container.
- The upper range is usually on the order of 600^{O}F.
- When making measurements in a liquid, the depth of immersion is important, as it can result in different measurements.
- Because readings are made visually and there can be a meniscus at the top of the working fluid, measurements must be made carefully and consistently.

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Temperature Sensors: Bimetallic Strip

- Another nonelectrical temperature-measuring device.
- it is composed of two or more metal layers having different coefficients of thermal expansion.
- Because these layers are permanently bonded together, the structure will deform when the temperature changes. This is due to the difference in the thermal expansions of the two metal layers.
- The deflection δ can be related to the temperature of the strip.
- Bimetallic strips are used in household and industrial thermostats where the mechanical motion of the strip makes or breaks an electrical contact to turn a heating or cooling system on or off.

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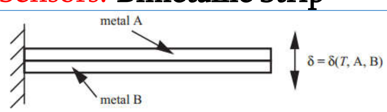
Temperature Sensors: Bimetallic Strip

- Another nonelec
- it is composed of ... efficients of thermal expansic



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Electrical Resistance Thermometer

- A **resistance temperature device (RTD)** is constructed of metallic wire wound around a ceramic or glass core and hermetically sealed.
- The resistance of the metallic wire increases with temperature.
- The resistance-temperature relationship is usually approximated by the following linear expression:

$$R = R_0 [1 + \alpha (T - T_0)]$$

- where T_0 is a reference temperature, R_0 is the resistance at the reference temperature, and α is a calibration constant.
- The sensitivity (dR/dT) is $R_0\alpha$
- The reference temperature is usually the melting ice point of water (0^{O}C).
- The most common metal used in RTDs is platinum because of its high melting point, resistance to oxidation, predictable temperature characteristics, and stable calibration values.
- The operating range for a typical platinum RTD is -220 ^{O}C to 750^{O}C.
- Lower cost nickel and copper types are also available, but they have narrower operating ranges.

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Thermistor

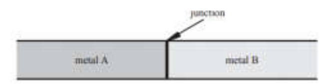
- A **thermistor** is a semiconductor device, available in probes of different shapes and sizes, whose resistance changes exponentially with temperature. Its resistance temperature relationship is usually expressed in the form

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

- where T_0 is a reference temperature, R_0 is the resistance at the reference temperature, and β is a calibration constant called the **characteristic temperature** of the material.
- A well-calibrated thermistor can be accurate to within 0.01^{O}C or better, which is better than typical RTD accuracies.
- However, thermistors have much narrower operating ranges than RTDs.

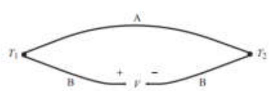
Thermocouple

- Two dissimilar metals in contact form a thermoelectric junction that produces a voltage proportional to the temperature of the junction. This is known as the Seebeck effect.



- Because an electrical circuit must form a closed loop, thermoelectric junctions occur in pairs, resulting in what is called a **thermocouple.**

Thermocouple



- The thermocouple voltage V depends on the metal properties of A and B and the difference between the junction temperatures $T1$ and $T2$.
- The thermocouple voltage is directly proportional to the junction temperature difference:

$$V = \alpha(T_1 - T_2)$$

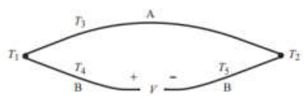
where α is called the **Seebeck coefficient.**

Thermocouple: Law

- The five basic laws of thermocouple behavior:
  1. Law of leadwire temperatures,
  2. Law of intermediate leadwire metals,
  3. Law of intermediate junction metals,
  4. Law of intermediate temperatures,
  5. Law of intermediate metals.

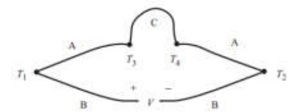
Thermocouple: 1. Law of leadwire temperatures

- The thermoelectric voltage due to two junctions in a circuit consisting of two different conducting metals depends only on the junction temperatures *T*1 and *T*2.
- The temperature environment of the leads away from the junctions (*T*3, *T*4, *T*5) does not influence the measured voltage.
- Therefore, we need not be concerned about shielding the leadwires from environmental conditions.



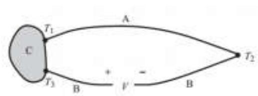
Thermocouple: 2. Law of *intermediate leadwire metals*

- A third metal C introduced in the circuit constituting the thermocouple has no influence on the resulting voltage as long as the temperatures of the two new junctions (A-C and C-A) are the same (T3 =T4).
- As a consequence of this law, a voltage measurement device that creates two new junctions can be inserted into the thermocouple circuit without altering the resulting voltage.



Thermocouple: 3. Law of intermediate junction metals

- If a third metal is introduced within a junction creating two new junctions (A-C and C-B), the measured voltage will not be affected as long as the two new junctions are at the same temperature (T1 = T3).
- Therefore, although soldered or brazed joints introduce thermojunctions, they have no resulting effect on the measured voltage.
- If T1 ≠ T3, the effective temperature at C is the average of the two temperatures ((T1 + T3)/2).

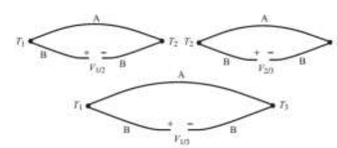


Thermocouple: 4. Law of intermediate temperatures

- Junction pairs at *T*1 and *T*3 produce the same voltage as two sets of junction pairs spanning the same temperature range (*T*1 to *T*2 and *T*2 to *T*3);

$$V_{1/3} = V_{1/2} + V_{2/3}$$

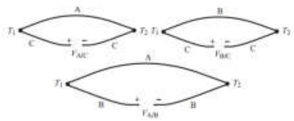
- The voltage resulting from measuring temperature *T*1 relative to *T*3 is the same as the sum of the voltages resulting from *T*1 relative to *T*2 and *T*2 relative to *T*3. This result supports the use of a reference junction to allow accurate measurement of an unknown temperature based on a fixed reference temperature.



Thermocouple: 5. Law of intermediate metals.

- the voltage produced by two metals A and B is the same as the sum of the voltages produced by each metal (A and B) relative to a third metal C:

$$V_{A/B} = V_{A/C} + V_{B/C}$$



- This result supports the use of a standard reference metal (e.g., platinum) to be used as a basis to calibrate all other metals.

THERMO-COUPLE TYPE	U.S. & CANADIAN (ANSI/MC96.1, ANSI/ASTM E230)				International	International	Czech British	Netherlands German	Japanese	French
	ALLOY COMBINATION	THERMOCOUPLE GRADE	EXTENSION GRADE	PLUG & JACK	IEC 584-3	IEC 584-3 Intrinsically Safe	BS 1843	DIN 43710	JIS C 1610	NFC 42-324
T	Copper / Constantan (Copper-Nickel)	Brown; Blue +; Red −	Blue +; Red −; Blue	Blue	Brown; Brown +; White −	Blue; Brown +; White −	Blue; White +; Blue −	Brown; Red +; Brown −	Brown; Red +; White −	Blue; Yellow +; Blue −
J	Iron (magnetic) / Constantan (Copper-Nickel)	Brown; White +; Red −	White +; Red −; Black	Black	Black; Black +; White −	Blue; Black +; White −	Black; Yellow +; Blue −	Blue; Red +; Blue −	Yellow; Red +; White −	Black; Yellow +; Black −
E	Nickel - Chromium / Constantan (Copper- Nickel)	Brown; Purple +; Red −	Purple +; Red −; Purple	Purple	Purple; Purple +; White −	Blue; Purple +; White −	Brown; Brown +; Blue −	Black; Red +; Black −	Purple; Red +; White −	Purple; Yellow +; Purple −
K	Nickel - Chromium / Nickel - Aluminium (magnetic)	Brown; Yellow +; Red −	Yellow +; Red −; Yellow	Yellow	Green; Green +; White −	Blue; Green +; White −	Red; Brown +; Blue −	Green; Red +; Green −	Blue; Red +; White −	Yellow; Yellow +; Purple −
N	Nicrosil (Nickel-Chromium- Silicon) / Nisil (Nickel-Silicon-Magnesium)	Brown; Orange +; Red −	Orange +; Red −; Orange	Orange	Pink; Pink +; White −	Blue; Pink +; White −	Orange; Orange +; Blue −	No Standard (Use American Color Codes)	No Standard (Use American Color Codes)	No Standard (Use American Color Codes)
S	Platinum Rhodium -10% / Platinum	None Established	Black +; Red −; Green	Green	Orange; Orange +; White −	Blue; Orange +; White −	Green; White +; Blue −	White; Red +; White −	Black; Red +; White −	Green; Yellow +; Green −
R	Platinum Rhodium -13% / Platinum	None Established	Black +; Red −; Green	Green	Orange; Orange +; White −	Blue; Orange +; White −	Green; White +; Blue −	White; Red +; White −	Black; Red +; White −	Green; Yellow +; Green −
B	Platinum Rhodium - 30% / Platinum Rhodium - 6%	None Established	Gray +; Red −; Gray (Compensated Cable)	White (Uncompensated)	Gray; Gray +; White −		No Standard (Use Copper Wire)	Gray; Red +; Gray − (Compensated Cable)	Gray; Red +; Gray − (Compensated Cable)	No Standard (Use Copper Wire)
C	Tungsten Rhenium - 5% / Tungsten Rhenium - 26%	None Established	Green +; Red −; Red	Red				No Standard (Use American Color Codes)	No Standard (Use American Color Codes)	No Standard (Use American Color Codes)

Thermocouple: Most common

- The six most commonly used thermocouple metal pairs are denoted by the letters E, J, K, R, S, and T.
- The 0^oC reference junction calibration for each of the types is nonlinear and can be approximated with a polynomial.

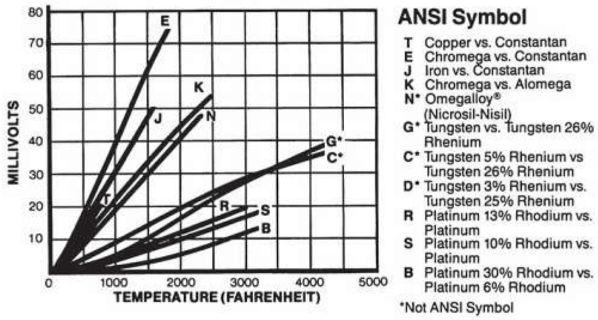
$$T = \sum_{i=0}^{9} c_i V^i = c_0 + c_1 V + c_2 V^2 + c_3 V^3 + c_4 V^4 + c_5 V^5 + c_6 V^6 + c_7 V^7 + c_8 V^8 + c_9 V^9$$

- The metals in the junction pair, the thermoelectric polarity, the commonly used color code, the operating range, the accuracy, and the polynomial order and coefficients are shown for each type in Table.

	Type E	Type J	Type K	Type R	Type S	Type T
Metal pair	Chromel (+) and constantan (−)	Iron (+) and constantan (−)	Chromel (+) and alumel (−)	87% platinum, 13% rhodium (+) and platinum (−)	90% platinum, 10% rhodium (+) and platinum (−)	Copper (+) and constantan (−)
Color code	Purple	Black	Yellow	Green	Green	Blue
Operating range	−100°C to 1000°C	0°C to 760°C	0°C to 1370°C	0°C to 1000°C	0°C to 1750°C	−160°C to 400°C
Accuracy	±0.5°C	±0.1°C	±0.7°C	±0.5°C	±0.1°C	±0.5°C
Approximate sensitivity (mV/°C)	0.079	0.054	0.042	0.012	0.011	0.049
Polynomial order	9	5	8	8	9	7
c_0	0.104967	−0.0488683	0.226585	0.263633	0.927763	0.100861
c_1	17,189.5	19,873.1	24,152.1	179,075.	169,527.	25,727.9
c_2	−282,639.	−218,615.	67,233.4	-4.88403×10^7	-3.15684×10^7	−767,346.
c_3	1.26953×10^7	1.15692×10^7	2.21034×10^6	1.90002×10^{10}	8.99073×10^9	7.80256×10^7
c_4	-4.48703×10^8	-2.64918×10^8	-8.60964×10^8	-4.82704×10^{12}	-1.63565×10^{12}	-9.24749×10^9
c_5	1.10866×10^{10}	2.01844×10^9	4.83506×10^{10}	7.62091×10^{14}	1.88027×10^{14}	6.97688×10^{11}
c_6	-1.76807×10^{11}	—	-1.18452×10^{12}	-7.20026×10^{16}	-1.37241×10^{16}	-2.66192×10^{13}
c_7	1.71842×10^{12}	—	1.38690×10^{13}	3.71496×10^{18}	6.17501×10^{17}	3.94078×10^{14}
c_8	-9.19278×10^{12}	—	-6.33708×10^{13}	-8.03104×10^{19}	-1.56105×10^{19}	—
c_9	2.06132×10^{13}	—	—	—	1.69535×10^{20}	—

Source: G. Burns, M. Scroger, and G. Strouse, "Temperature-Electromotive Force Reference Functions and Tables for the Letter-Designated Thermocouple Types Based on the ITS-90," NIST Monograph 175, April 1993.

Thermocouple

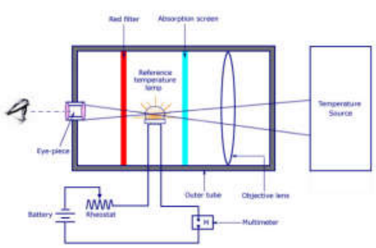


Radiation Pyrometers: Temperature Measurement

- Radiant energy emitted from a body increases with temperature, is used in measuring temperatures particularly in the higher ranges.
- Situation:
  - Relatively higher temperatures (700 – 3000^{O}C)
  - Not possible to contact the hot material
- Types of Pyrometers:
  - Total radiation pyrometer: Total radiant energy from a heated body is measured.
  - Selective (or partial) radiation pyrometer: Specular radiant intensity of the radiant energy from heated body at a given wavelength is measured.

Optical Pyrometers: Temperature Measurement

- Measure when matter glow above 500-700^{O}C and the color of visible radiation is proportional to the temperature of glowing matter.
- The device compares the brightness produced by the radiation of the object whose temperature is to be measured, with that of a reference temperature.



Optical Pyrometers: Advantages

- Simple assembling of the device enables easy use of it.
- Provides a very high accuracy with +/-5 degree Celsius.
- There is no need of any direct body contact between the optical pyrometer and the object. Thus, it can be used in a wide variety of applications.
- As long as the size of the object, whose temperature is to measured fits with the size of the optical pyrometer, the distance between both of them is not at all a problem. Thus, the device can be used for remote sensing.
- This device can not only be used to measure the temperature, but can also be used to see the heat produced by the object/source. Thus, optical pyrometers can be used to measure and view wavelengths less than or equal to 0.65 microns. But, a Radiation Pyrometer can be used for high heat applications and can measure wavelengths between 0.70 microns to 20 microns.

Optical Pyrometers: Disadvantages & Applications

Disadvantages

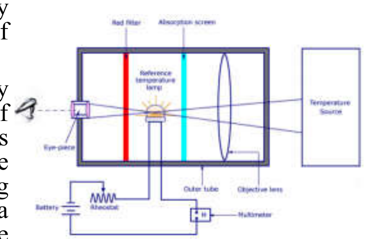
- As the measurement is based on the light intensity, the device can be used only in applications with a minimum temperature of 500-700^{o}C.
- The device is not useful for obtaining continuous values of temperatures at small intervals.

Applications

- Used to measure temperatures of liquid metals or highly heated materials like molten metals
- Can be used to measure furnace temperatures of the order of 1500 – 2500^{o}C.

Optical Pyrometers: Temperature Measurement

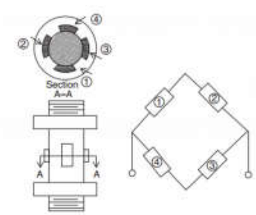
- The reference temperature is produced by a lamp whose brightness can be adjusted till its intensity becomes equal to the brightness of the source object.
- For an object, its light intensity always depends on the temperature of the object, whatever may be its wavelength. After adjusting the temperature, the current passing through it is measured using a multimeter, as its value will be proportional to the temperature of the source when calibrated.



Force Measurement with Load Cells

- A load cell is a sensor used to measure force.
- It contains an internal flexural element, usually with several strain gauges mounted on its surface.
- A **load cell** is a transducer that is used to create an electrical signal whose magnitude is directly proportional to the **force** being **measured**. The various types of **load cells** include hydraulic **load cells**, pneumatic **load cells** and strain gauge **load cells**.
- The flexural element's shape is designed so that the strain gauge outputs can be easily related to the applied force.
- The load cell is usually connected to a bridge circuit to yield a voltage proportional to the load.

Load Cell



Applications of load cell

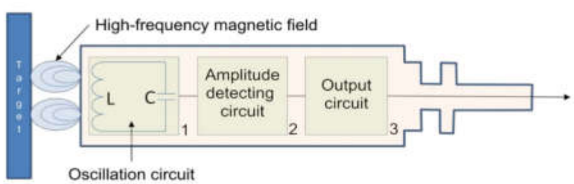
- In laboratory materials testing machines for measuring forces applied to a test specimen.
- Load cells are also used in weight scales, and they are sometimes included as integral parts of mechanical structures to monitor forces in the structures.

Acceleration Sensors

- ➢ Measurement of acceleration is important for systems subject to shock and vibration.
- ➢ Although acceleration can be derived from the time history data obtainable from linear or rotary sensors, the accelerometers whose output is directly proportional to the acceleration is preferred.
- ➢ Two common types include the seismic mass type and the piezoelectric accelerometer.
- ➢ The seismic mass type accelerometer is based on the relative motion between a mass and the supporting structure.
- ➢ The natural frequency of the seismic mass limits its use to low to medium frequency applications.
- ➢ The piezoelectric accelerometer, however, is compact and more suitable for high frequency applications.

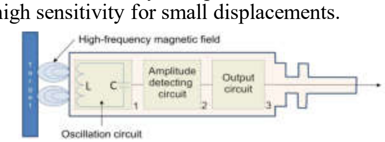
Eddy current proximity sensors

- Eddy current proximity sensors are used to detect non-magnetic but conductive materials.
- They comprise of a coil, an oscillator, a detector and a triggering circuit.



Eddy current proximity sensors

- When an alternating current is passed thru this coil, an alternative magnetic field is generated.
- If a metal object comes in the close proximity of the coil, then eddy currents are induced in the object due to the magnetic field.
- These eddy currents create their own magnetic field which distorts the magnetic field responsible for their generation.
- As a result, impedance of the coil changes and so the amplitude of alternating current.
- This can be used to trigger a switch at some pre-determined level of change in current.
- Eddy current sensors are relatively inexpensive, available in small in size, highly reliable and have high sensitivity for small displacements.

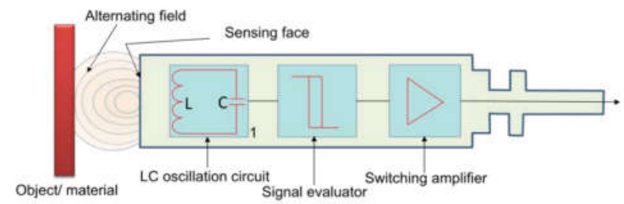


Applications of Eddy current proximity sensors

- Automation requiring precise location
- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Measuring the dynamics of a continuously moving target, such as a vibrating element,
- Drive shaft monitoring
- Vibration measurements

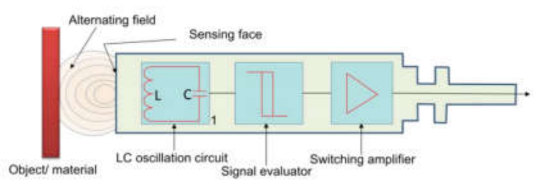
Inductive proximity switch

- Inductive proximity switches are basically used for detection of metallic objects.

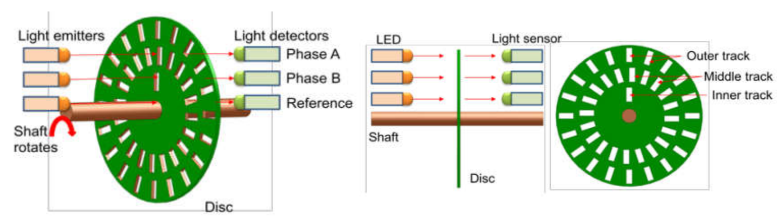


Inductive proximity switch

- An inductive proximity sensor has four components; the coil, oscillator, detection circuit and output circuit.
- An alternating current is supplied to the coil which generates a magnetic field. When, a metal object comes closer to the end of the coil, inductance of the coil changes. This is continuously monitored by a circuit which triggers a switch when a preset value of inductance change is occurred.



Optical encoders

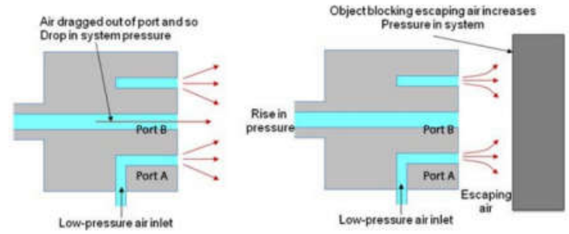


Optical encoders

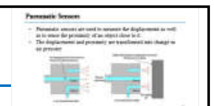
- Optical encoders provide digital output as a result of linear / angular displacement.
- These are widely used in the Servo motors to measure the rotation of shafts.
- It comprises of a disc with three concentric tracks of equally spaced holes.
- Three light sensors are employed to detect the light passing thru the holes.
- These sensors produce electric pulses which give the angular displacement of the mechanical element e.g. shaft on which the Optical encoder is mounted.
- The inner track has just one hole which is used locate the 'home' position of the disc.
- The holes on the middle track offset from the holes of the outer track by one-half of the width of the hole.
- This arrangement provides the direction of rotation to be determined.
- When the disc rotates in clockwise direction, the pulses in the outer track lead those in the inner; in counter clockwise direction they lag behind.
- The resolution can be determined by the number of holes on disc. With 100 holes in one revolution, the resolution would be 360/100 = 3.6 degree

Pneumatic Sensors

- Pneumatic sensors are used to measure the displacement as well as to sense the proximity of an object close to it.
- The displacement and proximity are transformed into change in air pressure.



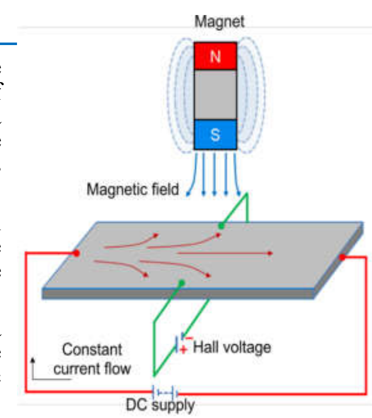
Pneumatic Sensors



- Low pressure air is allowed to escape through port A.
- In the absence of any obstacle / object, this low pressure air escapes and in doing so, reduces the pressure in the port B.
- However when an object obstructs the low pressure air (Port A), there is rise in pressure in output port B.
- This rise in pressure is calibrated to measure the displacement or to trigger a switch.
- These sensors are used in robotics, pneumatics and for tooling in CNC machine tools.

Hall effect sensor

- Hall effect sensors work on the principle that when a beam of charge particles passes through a magnetic field, forces act on the particles and the current beam is deflected from its straight line path.
- Thus one side of the disc will become negatively charged and the other side will be of positive charge.
- This charge separation generates a potential difference which is the measure of distance of magnetic field from the disc carrying current.



Applications of Hall effect sensor

- The typical application of Hall effect sensor is the measurement of fluid level in a container.
- The container comprises of a float with a permanent magnet attached at its top.
- An electric circuit with a current carrying disc is mounted in the casing.
- When the fluid level increases, the magnet will come close to the disc and a potential difference generates.
- This voltage triggers a switch to stop the fluid to come inside the container.

Applications of Hall effect sensor

- These sensors are used for the measurement of displacement and the detection of position of an object.
- Hall effect sensors need necessary signal conditioning circuitry.
- They can be operated at 100 kHz.
- Their non-contact nature of operation, good immunity to environment contaminants and ability to sustain in severe conditions make them quite popular in industrial automation.

Actuators

Unit-II: Actuators

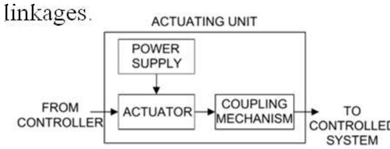
Contents
Introduction to Actuators: Electro-mechanical Actuators, Electrical Machines, Piezoelectric Actuators, Hydraulic and Pneumatic Actuation Systems, MEMS: Micro-transducers Analysis, Design and Fabrication.

Introduction

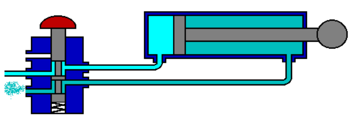
- Actuators are basically the muscle behind a mechatronics system that accepts a control command (mostly in the form of an electrical signal) and produces a change in the physical system by generating force, motion, heat, flow, etc.
- An **actuator** is a component of a machine that is responsible for moving or controlling a mechanism or system.
- Normally, the actuators are used in conjunction with the power supply and a coupling mechanism.

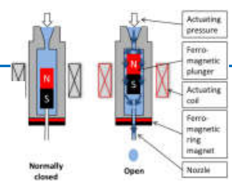
Introduction

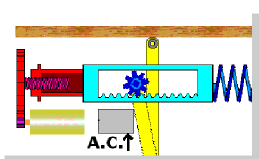
- An actuator requires a control signal and a source of energy.
- The control signal is relatively low energy: Electrical (voltage/current), Pneumatic Pressure, Hydraulic Pressure, Human power, etc.
- When the control signal is received, the actuator responds by converting the energy into mechanical motion.
- Typical mechanisms include rack and pinion, gear drive, belt drive, lead screw and nut, piston, and linkages.

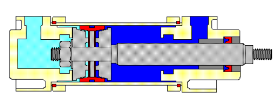


Examples









Classification

- Electrical,
- Electromechanical,
- Electromagnetic,
- Hydraulic,
- Pneumatic,
- Smart Material Actuators,
- Microactuators, and
- Nanoactuators.

Classification

- Actuators can also be classified as binary and continuous based on the number of stable-state outputs.
- A relay with two stable states is a good example of a binary actuator.
- Similarly, a stepper motor is a good example of continuous actuator.
- For a position control, the stepper motor can provide stable outputs with very small incremental motion.

Classification

Actuator			Feature
Electrical			
Diodes, thyristor, bipolar transistor, triacs, diacs, power MOSFET, solid state relay, etc.			Electronic type Very high frequency response Low power consumption
Electromechanical			
DC motor	Wound field	Separately excited	Speed can be controlled either by the voltage across the armature winding or by varying the field current
		Shunt Series	Constant-speed application High starting torque, high acceleration torque, high speed with light load
		Compound	Low starting torque, good speed regulation Instability at heavy loads

Classification cont…

Actuator			Feature
Electromechanical			
DC motor	Permanent magnet	Conventional PM motor	High efficiency, high peak power, and fast response
		Moving-coil PM motor	Higher efficiency and lower inductance than conventional DC motor
		Torque motor	Designed to run for a long periods in a stalled or a low rpm condition
	Electronic commutation (brushless motor)		Fast response High efficiency, often exceeding 75% Long life, high reliability, no maintenance needed Low radio frequency interference and noise production

Classification cont…

Actuator		Feature
Electromechanical		
AC motor	AC induction motor	The most commonly used motor in industry Simple, rugged, and inexpensive
	AC synchronous motor	Rotor rotates at synchronous speed Very high efficiency over a wide range of speeds and loads Need an additional system to start
	Universal motor	Can operate in DC or AC Very high horsepower per pound ratio Relatively short operating life
Stepper motor	Hybrid	Change electrical pulses into mechanical movement Provide accurate positioning without feedbac
	Variable reluctance	Low maintenance

Classification cont…

Actuator		Feature
Electromagnetic		
Solenoid type devices Electromagnets, relay		Large force, short duration On/off control
Hydraulic and Pneumatic		
Cylinder		Suitable for liner movement
Hydraulic motor	Gear type Vane type Piston type	Wide speed range High horsepower output High degree of reliability
Air motor	Rotary type Reciprocating	No electric shock hazard Low maintenance
Valves	Directional control valves Pressure control valves Process control valves	

Classification cont…

Actuator	Feature
Smart Material actuators	
Piezoelectric & Electrostrictive	High frequency with small motion High voltage with low current excitation High resolution
Magnetostrictive	High frequency with small motion Low voltage with high current excitation
Shape Memory Alloy	Low voltage with high current excitation Low frequency with large motion
Electrorheological fluids	Very high voltage excitation Good resistance to mechanical shock and vibration Low frequency with large force

Classification cont…

Actuator	Feature
Micro- and Nanoactuators	
Micromotors	Suitable for micromechanical system
Microvalves	Can use available silicon processing technology, such as electrostatic motor
Micropumps	Can use any smart material

Electrical Actuators

- Electrical switches are the choice of actuators for most of the on-off type control action.
- Switching devices such as diodes, transistors, triacs, MOSFET, and relays accept a low energy level command signal from the controller and switch on or off electrical devices such as motors, valves, and heating elements.

Electromechanical Actuators: DC motors

- The most common electromechanical actuator is a motor that converts electrical energy to mechanical motion.
- Motors are the principal means of converting electrical energy into mechanical energy in industry.
- Motors: DC motors, AC motors, and stepper motors.
- DC motors operate on DC voltage and varying the voltage can easily control their speed.
- Applications: starter motors, fan motors, windshield wiper motors, etc.
- Disadvantages: More costlier, require more maintenance compared to AC motors.

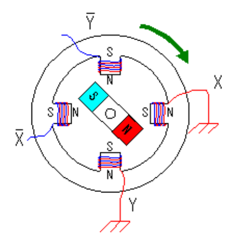
Electromechanical Actuators: AC Motors

- *AC motors* are the most popular since they use standard AC power, do not require brushes and commutator, and are therefore less expensive.
- Types: induction motors, synchronous motors, and universal motors.
- The induction motor is simple, rugged, and maintenance free.
- They are available in many sizes and shapes based on number of phases used.
- Application: Large-horsepower requirement (3ϕ), such as pump drives, steel mill drives, hoist drives, and vehicle drives.
- The two-phase servomotor is used extensively in position control systems.
- Single-phase induction motors are widely used in many household appliances.

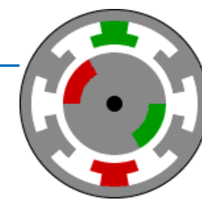
Electromechanical Actuators: Various Motors

- The synchronous motor is one of the most efficient electrical motors in industry, so it is used in industry to reduce the cost of electrical power.
- In addition, synchronous motors rotate at synchronous speed, so they are also used in applications that require synchronous operations.
- The universal motors operate with either AC or DC power supply.
- They are normally used in fractional horsepower application.
- The DC universal motor has the highest horsepower-per-pound ratio, but has a relatively short operating life.
- The *stepper motor* is a discrete (incremental) positioning device that moves one step at a time for each pulse command input.
- With the rapid progress in low cost and high frequency solid-state drives, they are finding increased applications.

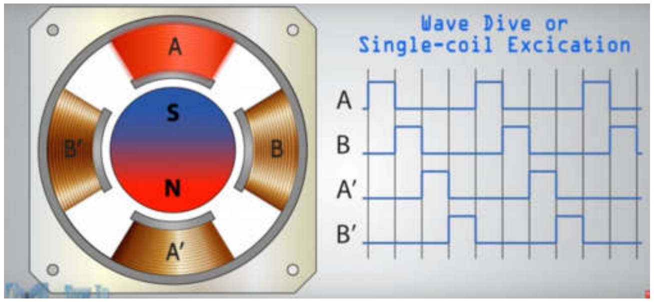
Steeper Motor



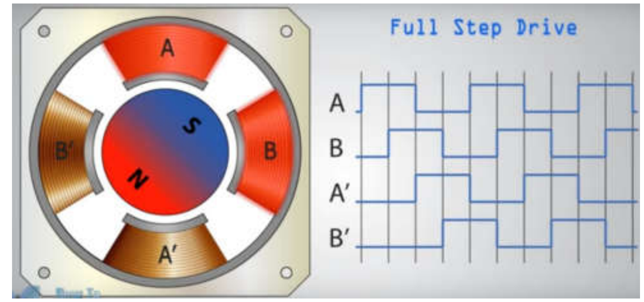
X	$\bar{X}$	Y	$\bar{Y}$
0	1	0	1
1	0	0	1
1	0	1	0
0	1	1	0



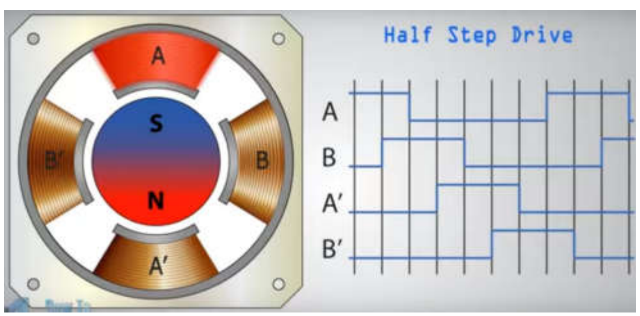
Stepper Motor: Single-coil Excitation



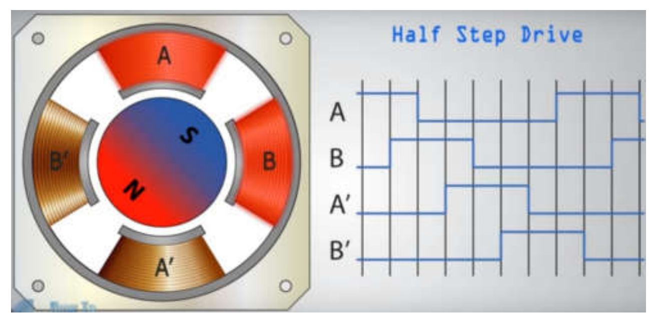
Stepper Motor: Full Step Drive



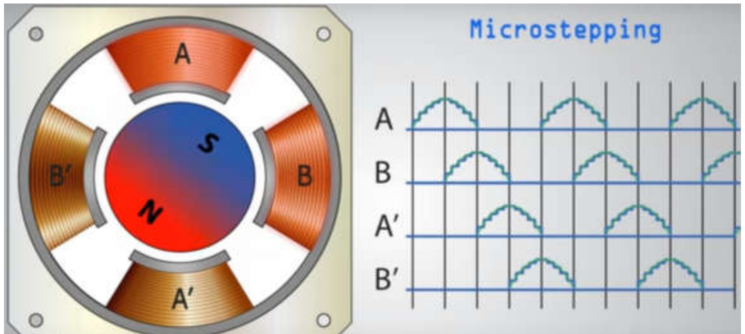
Stepper Motor: Half Step Drive



Stepper Motor: Half Step Drive



Stepper Motor: Micro-stepping



Hydraulic and Pneumatic Actuators

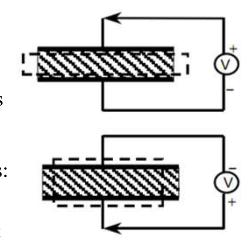
- Hydraulic and pneumatic actuators are normally either rotary motors or linear piston/cylinder or control valves.
- Ideally suited for generating very large forces coupled with large motion.
- Pneumatic actuators use air under pressure that is most suitable for low to medium force, short stroke, and highspeed applications.
- Hydraulic actuators use pressurized oil that is incompressible.
- They can produce very large forces coupled with large motion in a cost-effective manner.
- The disadvantage with the hydraulic actuators is that they are more complex and need more maintenance.

Smart Material Actuators

- Unlike the conventional actuators, the smart material actuators typically become part of the load bearing structures.
- This is achieved by embedding the actuators in a distributed manner and integrating into the load bearing structure that could be used to suppress vibration, cancel the noise, and change shape.
- Of the many smart material actuators, shape memory alloys, piezoelectric (PZT), magnetostrictive, Electrorheological fluids, and ion exchange polymers are most common.
- Shape Memory Alloys (SMA) are alloys of nickel and titanium that undergo phase transformation when subjected to a thermal field.

Smart Material Actuators: PZT

- The PZT actuators are essentially piezocrystals with top and bottom conducting films
- When an electric voltage is applied across the two conducting films, the crystal expands in the transverse direction as shown by the dotted lines.
- When the voltage polarity is reversed, the crystal contracts thereby providing bidirectional actuation.
- The interaction between the mechanical and electrical behavior of the piezoelectric materials can be expressed as:



$$T = c^E S - eE$$

where T is the stress, c^E is the elastic coefficients at constant electric field, S is the strain, e is the dielectric permitivity, and E is the electric field.

Micro- and Nanoactuators

- Micro-actuators, also called micromachines, microelectromechanical system (MEMS), and microsystems are

“ the tiny mobile devices being developed utilizing the standard microelectronics processes with the integration of semiconductors and machined micromechanical elements”.

OR

Any device produced by assembling extremely small functional parts of around 1–15 mm is called a micromachine.

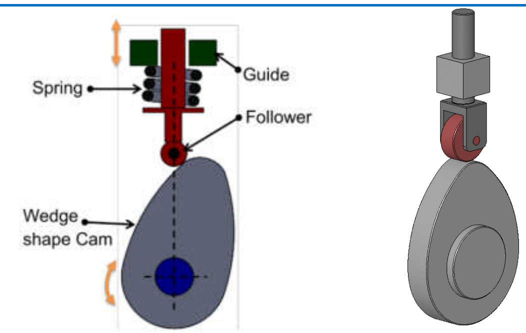
Actuator Selection Criteria

- Continuous power output: The maximum force/torque attainable continuously without exceeding the temperature limits
- Range of motion: The range of linear/rotary motion
- Resolution: The minimum increment of force/torque attainable
- Accuracy: Linearity of the relationship between the input and output
- Peak force/torque: The force/torque at which the actuator stalls
- Heat dissipation: Maximum wattage of heat dissipation in continuous operation
- Speed characteristics: Force/torque versus speed relationship
- No load speed—Typical operating speed/velocity with no external load
- Frequency response: The range of frequency over which the output follows the input faithfully, applicable to linear actuators
- Power requirement: Type of power (AC or DC), number of phases, voltage level, and current capacity

Drives and Mechanisms: Cams

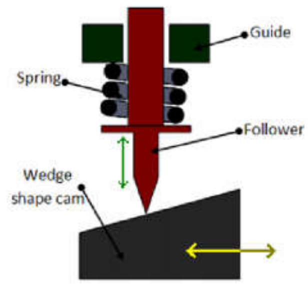
- Used to generate curvilinear or irregular motion.
- Used to convert rotary motion into oscillatory motion or oscillatory motion into rotary motion.
- There are two links: CAM and FOLLOWER
- The cam transmits the motion to the follower by direct contact.
- In a cam-follower pair, the cam usually rotates while the follower translates or oscillates.
- Cams are widely used in internal combustion engines, machine tools, printing control mechanisms, textile weaving industries, automated machines etc.

Drives and Mechanisms: Cams



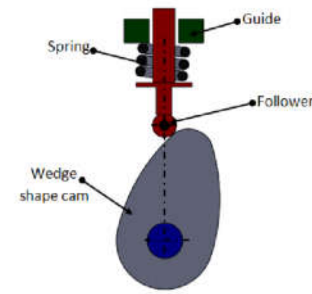
Classification of cams

- Wedge and Flat Cams:
  - A wedge cam has a wedge of specified contour and has translational motion.
  - The follower can either translate or oscillate.
  - A spring is used to maintain the contact between the cam and the follower.



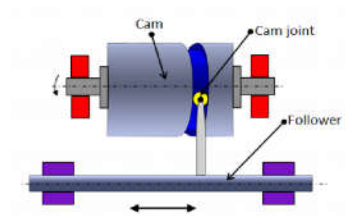
Classification of cams

- Plate cam
  - The follower moves in a radial direction from the center of rotation of the cam
  - They are also known as radial or disc cam.
  - The follower reciprocates or oscillates in a plane normal to the cam axis.



Classification of cams

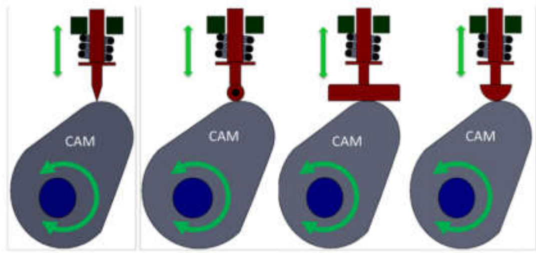
- Cylindrical cam
  - Cylinder has a circumferential contour cut in the surface and the cam rotates about its axis.
  - The follower motion is either oscillating or reciprocating type.
  - These cams are also called drum or barrel cams.



Classification of Followers

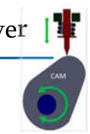
- Followers can be classified based on
  1. Type of Surface Contact Between Cam And Follower,
  2. Type of Follower Motion,
  3. Line of Motion of Followers.

Followers: Type of Surface Contact Between Cam and Follower



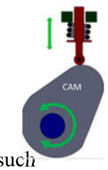
a) With knife edge follower
b) With roller follower
c) With plate type follower
d) With Spherical follower

Followers: Type of Surface Contact Between Cam and Follower



➢Knife edge follower

- The contacting end of the follower has a sharp knife edge.
- A sliding motion exists between the contacting cam and follower surfaces.
- It is rarely used in practice because the small area of contacting surface results in excessive wear.



➢Roller follower

- It consists of a cylindrical roller which rolls on cam surface.
- Because of the rolling motion between the contacting surfaces, the rate of wear is reduced in comparison with Knife edge follower.
- The roller followers are extensively used where more space is available such as gas and oil engines.

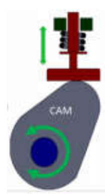
Followers: Type of Surface Contact Between Cam and Follower

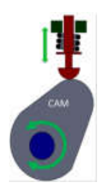
➢Flat face follower

- The follower face is perfectly flat.
- It experiences a side thrust due to the friction between contact surfaces of follower and cam.

➢Spherical face follower

- The contacting end of the follower is of spherical shape which overcomes the drawback of side thrust as experiences by flat face follower.





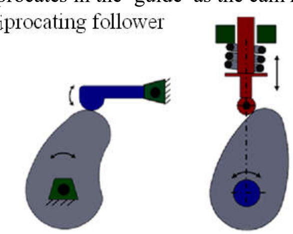
Followers: Type of followers' motion

➢Oscillating follower

- The rotary motion of the cam is converted into predetermined oscillatory motion of the follower.

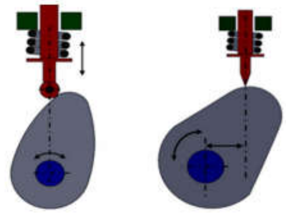
➢Translating follower

- The follower reciprocates in the 'guide' as the cam rotates uniformly.
- Also called as reciprocating follower



Followers: Line of Motion of Followers

- **Radial follower**
  - The line of movement of the follower passes through the center of the camshaft.
- **Offset follower**
  - The line of movement of the follower is offset from the center of the cam shaft



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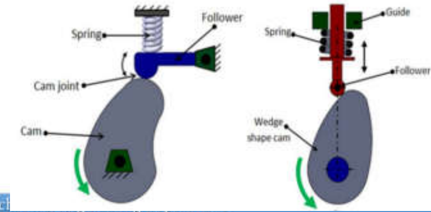
Force closed cam follower system

- In this type of cam-follwer system, an external force is needed to maintain the contact between cam and follower.
- Generally a spring maintains the contact between the two elements.
- The follower can be a oscillating type or of translational type.



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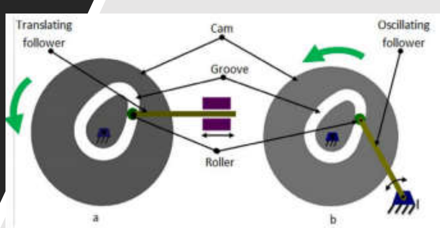
Form closed cam follower system

- In this system a slot or a groove profile is cut in the cam.
- The roller fits in the slot and follows the groove profile.
- These kind of systems do not require a spring.
- These are extensively used in machine tools and machinery.
- The follower can be a translating type and oscillating type.



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Three-dimensional cam or Camoid

- Camoid is a combination of radial and axial cams.
- It has three dimensional surface and two degrees-of-freedom.
- Two inputs are rotation of the cam about its axis and translation of the cam along its axis.
- Follower motion is based on both the inputs.

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Applications of cams

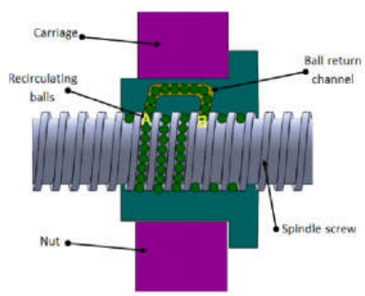
- Cams are widely used in automation of machinery, gear cutting machines, screw machines, printing press, textile industries, automobile engine valves, tool changers of machine centers, conveyors, pallet changers, sliding fork in wearhouses etc.
- Cams are also used in I.C engines to operate the inlet valves and exhaust valves.
- Cams in automatic lathes
- Automatic copying machine

Drives and Mechanisms: Linear motion drives

- Linear motion drives are mechanical transmission systems which are used to convert rotary motion into linear motion.
- A linear actuator is an actuator that produces motion in a straight line.

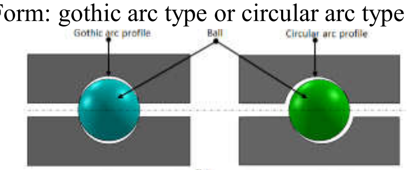
Ball-screw based linear drives

- Ball screw is also called as ball bearing screw or recirculating ball-screw.
- When debris or foreign matter enter the inside of the nut, it could affect smoothness in operation or cause premature wearing, either of which could adversely affect the ball screw's functions.

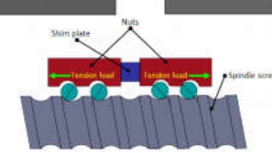


Characteristics of ball screws

- High mechanical efficiency
- Low in wear
- Thread Form: gothic arc type or circular arc type



- Preloading



Advantages of ball screws

- Highly efficient and reliable.
- Less starting torque.
- Lower co efficient of friction compared to sliding type screws and run at cooler temperatures
- Power transmission efficiency is very high and is of the order of 95 %.
- Could be easily preloaded to eliminate backlash.
- The friction force is virtually independent of the travel velocity and the friction at rest is very small; consequently, the stick-slip phenomenon is practically absent, ensuring uniformity of motion.
- Has longer thread life hence need to be replaced less frequently.
- Ball screws are well -suited to high through output, high speed applications or those with continuous or long cycle times.
- Smooth movement over full range of travel.

Disadvantages of ball screws

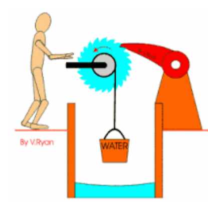
- Tend to vibrate.
- Require periodic overhauling to maintain their efficiency.
- Inclusion of dirt or foreign particles reduces the life of the screws.
- Not as stiff as other power screws, thus deflection and critical speed can cause difficulties.
- They are not self-locking screws hence cannot be used in holding devices such as vices.
- Require high levels of lubrication.

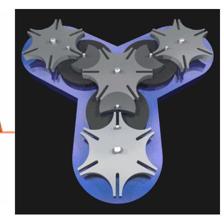
Applications of ball screws:

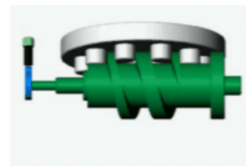
- Ball screws are employed in cutting machines, such as machining center and NC lathe where accurate positioning of the table is desired
- Used in the equipments such as lithographic equipment or inspection apparatus where precise positioning is vital
- High precision ball screws are used in steppers for semiconductor manufacturing industries for precision assembly of micro parts.
- Used in robotics application where precision positioning is needed.
- Used in medical examination equipments since they are highly accurate and provide smooth motion.

Drives and Mechanisms: Indexing Mechanisms

- Rigid elements arranged and connected to transmit motion in a predetermined fashion.
- Indexing mechanisms generally converts a rotating or oscillatory motion to a series of step movements of the output link or shaft.
- Examples: Tool turret, Milling machine indexing plate for gear cutting

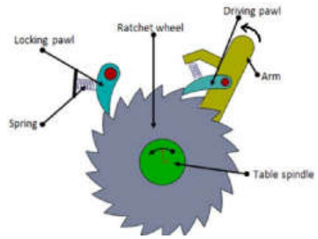






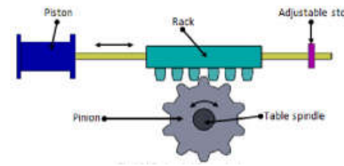
Ratchet and pawl mechanism

- A ratchet is a device that allows linear or rotary motion in only one direction.
- It is used in rotary machines to index air operated indexing tables.
- The ratchet and pawl are not mechanically interlocked hence easy to set up.

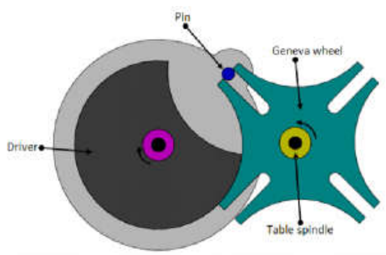


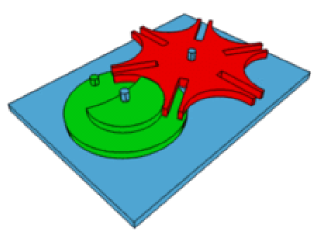
Rack and pinion mechanism

- A rack and pinion gear arrangement usually converts rotary motion from a pinion to linear motion of a rack.
- But in indexing mechanism the reverse case holds true.
- The device uses a piston to drive the rack, which causes the pinion gear and attached indexing table to rotate.
- A clutch is used to provide rotation in the desired direction.
- This mechanism is simple but is not considered suitable for high-speed operation.

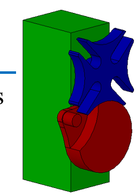


Geneva mechanism





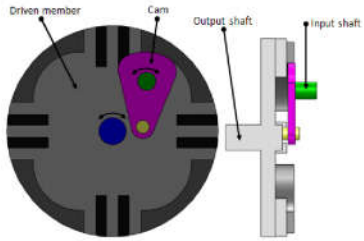
Geneva mechanism



- The Geneva drive is also commonly called a Maltese cross mechanism.
- The Geneva mechanism translates a continuous rotation into an intermittent rotary motion.
- The rotating drive wheel has a pin that reaches into a slot of the driven wheel.
- The drive wheel also has a raised circular blocking disc that locks the driven wheel in position between steps.
- If the driven wheel has n slots, it advances by 360°/n per full rotation of the drive wheel.
- Types: External, Internal and Spherical Geneva mechanism.

Internal Geneva drive

- In an internal Geneva drive the axis of the drive wheel of the internal drive is supported on only one side.
- The angle by which the drive wheel has to rotate to effect one step rotation of the driven wheel is always smaller than 180°.

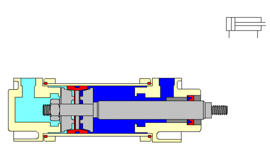


Applications of indexing mechanisms

- Automated work assembly transfer lines
- Gear Cutting in Milling machine
- Motion picture projectors
- CNC tool changers/turret
- Material inspection station

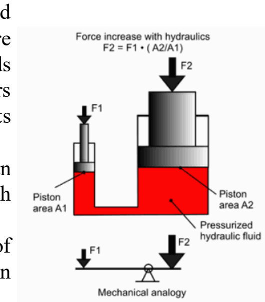
Hydraulic Systems

- Various controlled operations/actuations are performed mainly by using electrical machines or diesel, petrol and steam engines as a prime mover.
- The enclosed fluids (liquids and gases) can also be used as prime movers to provide controlled motion and force to the objects or substances.
- The well designed enclosed fluid systems can provide both linear as well as rotary motion with high magnitude controlled force.



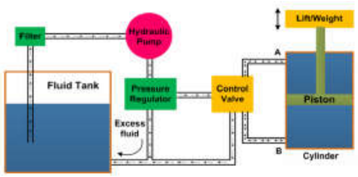
Hydraulic Systems

- The enclosed fluid based systems using pressurized incompressible liquids as transmission media are called as hydraulic systems. The enclosed fluids (liquids and gases) can also be used as prime movers to provide controlled motion and force to the objects or substances.
- The well designed enclosed fluid systems can provide both linear as well as rotary motion with high magnitude controlled force.
- The hydraulic system works on the principle of Pascal's law which says that the pressure in an enclosed fluid is uniform in all the directions.



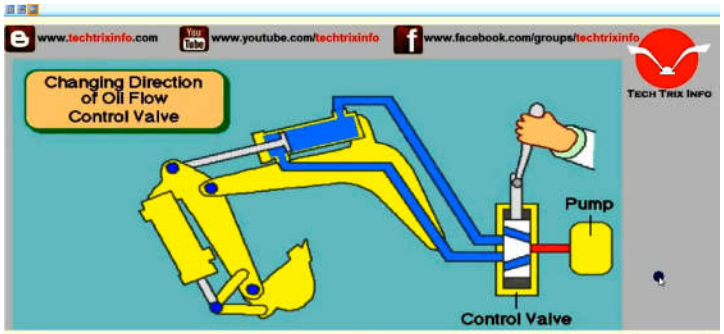
Hydraulic System

- Various Parts:
  - a movable piston connected to the output shaft in an enclosed cylinder
  - storage tank
  - filter
  - electric pump
  - pressure regulator
  - control valve
  - leak proof closed loop piping.



- The liquid used is generally high d
- Some accessories such as flow control system, travel limit control, electric motor starter and overload protection may also be used in the hydraulic systems.

Hydraulic system of JCB



Applications of hydraulic systems

The hydraulic systems are mainly used for precise control of larger forces. The main applications of hydraulic system can be classified in five categories:

1. **Industrial:** Plastic processing machineries, steel making and primary metal extraction applications, automated production lines, machine tool industries, paper industries, loaders, crushes, textile machineries, R & D equipment and robotic systems etc.
2. **Mobile hydraulics:** Tractors, irrigation system, earthmoving equipment, material handling equipment, commercial vehicles, tunnel boring equipment, rail equipment, building and construction machineries and drilling rigs etc.

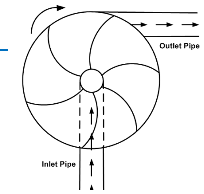
Applications of hydraulic systems

3. **Automobiles:** It is used in the systems like breaks, shock absorbers, steering system, wind shield, lift and cleaning etc.
4. **Marine applications:** It mostly covers ocean going vessels, fishing boats and navel equipment.
5. **Aerospace equipment:** There are equipment and systems used for rudder control, landing gear, breaks, flight control and transmission etc. which are used in airplanes, rockets and spaceships.

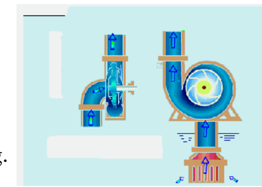
Hydraulic Pump

- The combined pumping and driving motor unit is known as hydraulic pump.
- The hydraulic pump takes hydraulic fluid (mostly some oil) from the storage tank and delivers it to the rest of the hydraulic circuit.
- The hydraulic pumps are characterized by its flow rate capacity, power consumption, drive speed, pressure delivered at the outlet and efficiency of the pump.
- The hydraulic pumps can be of two types:
  a) Centrifugal Pump
  b) Reciprocating Pump

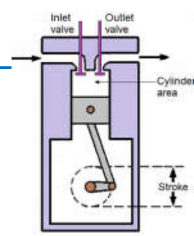
Centrifugal pump



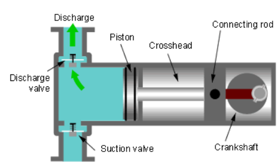
- Centrifugal pump uses rotational kinetic energy to deliver the fluid.
- The rotational energy typically comes from an engine or electric motor.
- In centrifugal pump the delivery of fluid is not constant and varies according to the outlet pressure.
- Not suitable for high pressure applications,
- The maximum pressure capacity is limited to 20-30 bars and the specific speed ranges from 500 to 10000.
- Most of the centrifugal pumps are not self-priming.



Reciprocating pump



- Also known as positive displacement pump or piston pump.
- Useful where relatively small quantity is to be handled and the delivery pressure is quite large.
- The crank is driven by some external rotating motor.
- Depending on the area of cylinder the pump delivers constant volume of fluid in each cycle independent to the pressure at the output port.



Advantages Hydraulic system

- The hydraulic system uses incompressible fluid which results in higher efficiency.
- It delivers consistent power output which is difficult in pneumatic or mechanical drive systems.
- Possibility of leakage is less in hydraulic system as compared to that in pneumatic system (due to use of high density fluid).
- The maintenance cost is less.
- These systems perform well in hot environment conditions.

Disadvantages of Hydraulic system

- The material of storage tank, piping, cylinder and piston can be corroded with the hydraulic fluid. Therefore one must be careful while selecting materials and hydraulic fluid.
- The structural weight and size of the system is large which makes it unsuitable for the smaller instruments.
- The small impurities in the hydraulic fluid can permanently damage the complete system, therefore one should be careful and suitable filter must be installed.
- The leakage of hydraulic fluid is also a critical issue and suitable prevention method and seals must be adopted.
- The hydraulic fluids, if not disposed properly, can be harmful to the environment.

Hydraulic Pumps

- These are mainly classified into two categories:

a) Non-positive displacement pumps
b) Positive displacement pumps.

Non-Positive Displacement Pumps

- These pumps are also known as hydro-dynamic pumps.
- In these pumps the fluid is pressurized by the rotation of the propeller and the fluid pressure is proportional to the rotor speed.
- The fluid pressure and flow generated due to inertia effect of the fluid.
- These pumps are not suitable for high pressures applications.
- These pumps provide a smooth and continuous flow but the flow output decreases with increase in system resistance (load).
- The flow output decreases because some of the fluid slip back at higher resistance.
- The fluid flow is completely stopped at very large system resistance and thus the volumetric efficiency will become zero.

Non-Positive Displacement Pumps

- Therefore, the flow rate not only depends on the rotational speed but also on the resistance provided by the system.
- The important advantages of non-positive displacement pumps are lower initial cost, less operating maintenance because of less moving parts, simplicity of operation, higher reliability and suitability with wide range of fluid etc.
- These pumps are primarily used for transporting fluids and find little use in the hydraulic or fluid power industries.
- Centrifugal pump is the common example of non-positive displacement pumps.

Positive displacement pump

- These pumps deliver a constant volume of fluid in a cycle.
- The discharge quantity per revolution is fixed in these pumps and they produce fluid flow proportional to their displacement and rotor speed.
- These pumps are used in most of the industrial fluid power applications.
- The output fluid flow is constant and is independent of the system pressure (load).
- The important advantage associated with these pumps is that the high-pressure and low-pressure areas (means input and output region) are separated and hence the fluid cannot leak back due to higher pressure at the outlets.
- These features make the positive displacement pump most suited and universally accepted for hydraulic systems.

Positive displacement pump

The important advantages of positive displacement pumps over non-positive displacement pumps include capability to generate high pressures, high volumetric efficiency, high power to weight ratio, change in efficiency throughout the pressure range is small and wider operating range pressure and speed.

Gear Pumps

- Gear pump is a robust and simple positive displacement pump.
- They are compact, relatively inexpensive and have few moving parts.
- The rigid design of the gears and houses allow for very high pressures and the ability to pump highly viscous fluids.
- They are suitable for a wide range of fluids and offer self-priming performance.

Gear Pumps

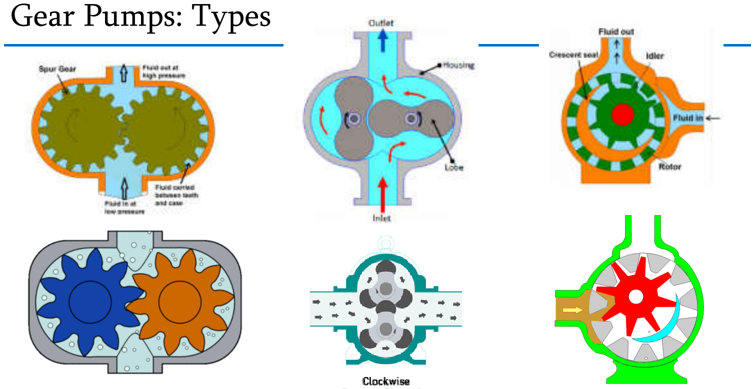
- These pump includes helical and herringbone gear sets (instead of spur gears), lobe shaped rotors similar to Roots blowers (commonly used as superchargers), and mechanical designs that allow the stacking of pumps.
- Based upon the design, the gear pumps are classified as:
  - External gear pumps
  - Lobe pumps
  - Internal gear pumps
  - Gerotor pumps

Gear Pumps: Applications

Generally gear pumps are used to pump:

- Petrochemicals: Pure or filled bitumen, pitch, diesel oil, crude oil, lube oil etc.
- Chemicals: Sodium silicate, acids, plastics, mixed chemicals, isocyanates etc.
- Paint and ink
- Resins and adhesives
- Pulp and paper: acid, soap, lye, black liquor, kaolin, lime, latex, sludge etc.
- Food: Chocolate, cacao butter, fillers, sugar, vegetable fats and oils, molasses, animal food etc.

Gear Pumps: Types



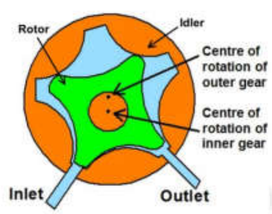
External gear pump

Lobe Pump

Internal Gear Pump

Gerotor Pump

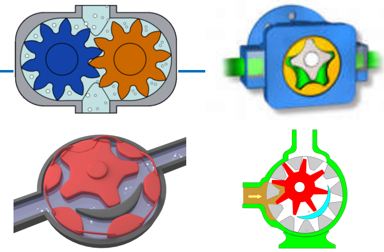
- Gerotor is a positive displacement pump.
- The name Gerotor is derived from "Generated Rotor".
- The inner rotor has N teeth, and the outer rotor has N+1 teeth.



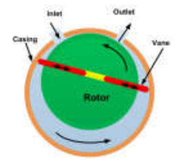
Gerotor Pump: Applications

- Gerotors are widely used in industries and are produced in variety of shapes and sizes by a number of different methods.
- These pumps are primarily suitable for low pressure applications such as lubrication systems or hot oil filtration systems, but can also be found in low to moderate pressure hydraulic applications.
- Light fuel oils
- Lube oil
- Cooking oils
- Hydraulic fluid

Vane Pumps



- The leakage is reduced by using spring or hydraulically loaded vanes placed in the slots of driven rotor.
- Capacity and pressure ratings of a vane pump are generally lower than the gear pumps, but reduced leakage gives an improved volumetric efficiency of around 95%.
- Vane pumps are available in a number of vane configurations including sliding vane, flexible vane, swinging vane, rolling vane, and external vane etc.



Vane Pumps

- External vane pumps can handle large solids.
- Flexible vane pumps can handle only the small solids but create good vacuum.
- Sliding vane pumps can run dry for short periods of time and can handle small amounts of vapor.

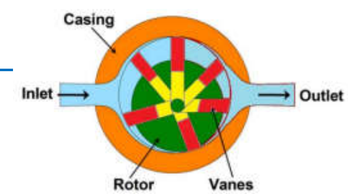
➢The vane pumps are known for their dry priming, ease of maintenance, and good suction characteristics. The operating range of these pumps varies from -32 °C to 260 °C.

Vane Pumps: Applications

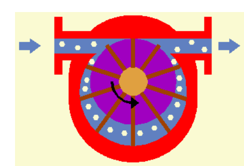
These pumps have various applications for the pumping of following fluids:

- Aerosol and Propellants
- Aviation Service - Fuel Transfer, Deicing
- Auto Industry - Fuels, Lubes, Refrigeration Coolants
- Bulk Transfer of LPG and NH_3
- LPG Cylinder Filling
- Alcohols
- Refrigeration - Freons, Ammonia
- Solvents
- Aqueous solutions

Unbalanced Vane pump

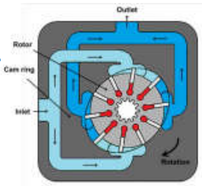


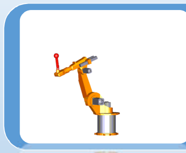
- Have more than one vane
- The rotor is offset within the housing, and the vanes are constrained by a cam ring as they cross inlet and outlet ports.
- The pressure difference between outlet and inlet ports creates a large amount of load on the vanes and a significant amount of side load on the rotor shaft which can lead to bearing failure.



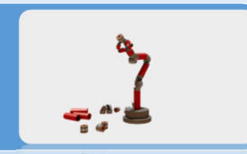
Balanced vane pump

- This pump has an elliptical cam ring with two inlet and two outlet ports.
- Pressure loading still occurs in the vanes but the two identical pump halves create equal but opposite forces on the rotor.
- It leads to the zero net force on the shaft and bearings.





Design and Fabrication of Actuators



Thank You
For
Your Attention