Advanced Measurement Systems & Sensors

(0640732)

Lecture (7)

Motion Detectors, Position, and Level Measurements

Prof. Kasim M. Al-Aubidy
Philadelphia University-Jordan

Introduction:

- The **occupancy sensors** detect the presence of people (and sometimes animals) in a monitored area.
- **Motion detectors** respond only to moving objects.
- The differences between the two is that the occupancy sensors produce signals whenever an object is stationary or not, while the motion detectors are selectively sensitive to moving objects.

- The following types of detectors are used for the occupancy and motion sensing:
  - **Air pressure sensors:** detect changes in air pressure resulted from opening doors and windows
  - **Capacitive detectors:** detectors of human body capacitance
  - **Acoustic detectors**: detectors of sound produced by people
  - **Photoelectric detectors** : interruption of light beams by moving objects
  - **Optoelectric detectors :** detection of variations in illumination or optical contrast in the protected area

Detectors are used for the occupancy and motion sensing:

- **Pressure mat switches:** pressure sensitive long strips used on floors beneath the carpets to detect weight of an intruder
- **Stress detectors:** strain gauges imbedded into floor beams, staircases, and other structural components
- **Switch sensors:** electrical contacts connected to doors and windows
- **Magnetic switches:** a noncontact version of switch sensors
- **Vibration detectors:** react to the vibration of walls or other building structures. Also, may be attached to doors or windows to detect movements
- **Glass breakage detectors:** sensors reacting to specific vibrations produced by shattered glass
- **Infrared motion detectors:** devices sensitive to heat waves emanated from warm or cold moving objects
- **Microwave detectors:** active sensors responsive to microwave electromagnetic signals reflected from objects

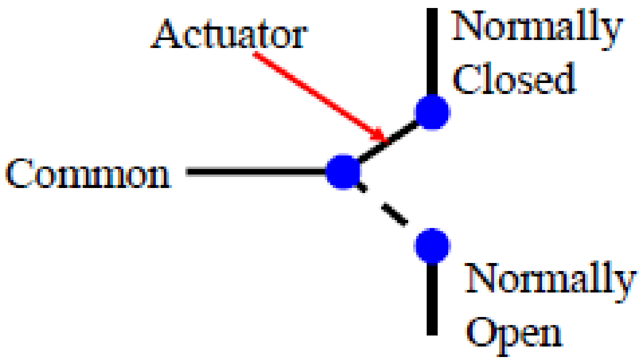
Detectors are used for the occupancy and motion sensing:

- **Ultrasonic detectors:** devices similar to microwave detectors except that instead of electromagnetic radiation, ultrasonic waves are used
- **Video motion detectors:** a video equipment that compares a stationary image stored in memory with the current image from a protected area
- **Video face recognition system:** image analyzers that compare facial features with database
- **Laser system detectors:** similar to photoelectric detectors, except that they use narrow light beams and combinations of reflectors
- **Tribo-electric detectors:** sensors capable of detecting static electric charges carried by moving objects

Proximity Sensors:

– Mechanical
– Optical
– Inductive/Capacitive

Mechanical Proximity Switches:



✓ Essentially a mechanical switch
✓ On/off operation only; Two general modes
  ➢ Normally Open (NO)
  ➢ Normally Closed (NC)
✓ Come in a wide variety of mechanical forms

When to Use Mechanical Proximity Switches:

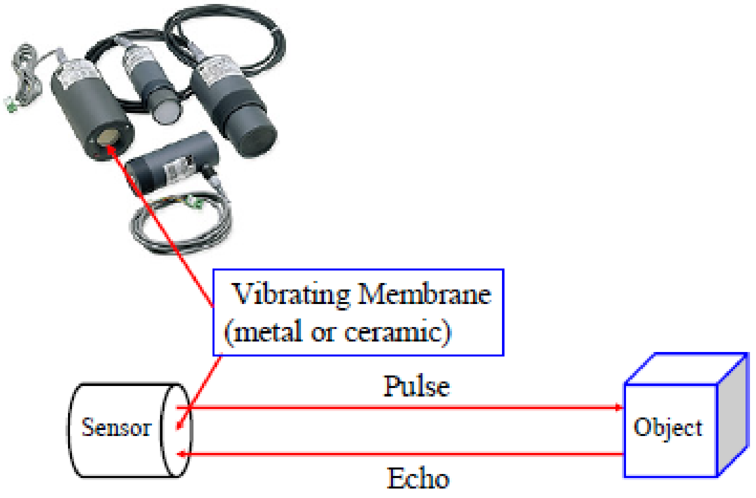
✓ Where physical contact is possible
✓ Where definitive position is required
✓ In operation-critical or safety-critical situations.
✓ Where environment conditions preclude the use of optical or inductive sensors.

Applications of Mechanical Proximity Switches:

- Easy to integrate into machinery of all types
- Requires contact
- Range of voltages: DC 0-1000V, AC, etc.
- Very robust (explosion proof if required)
- Usually used as:
  - ✓ Limit switch
  - ✓ Presence/absence indicator
  - ✓ Door closed/open

Ultrasonic Proximity Sensors:

- ❑ Use sound pulses
- ❑ Measures amplitude and time of flight
- ❑ Range provides more than on/off information
- ❑ Frequencies 40KHz-2MHz.



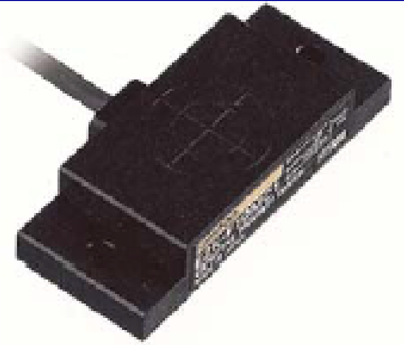
When to use Ultrasonic Sensors:

- ➢ Provide range data directly.
- ➢ Level monitoring of solid and liquids
- ➢ Approach warning (collisions)
- ➢ Can work in heavy dust and water
- ➢ Noise is potentially an issue

Ref: http://www.automationsensors.com/

Inductive and Capacitive Proximity Sensors:

- Inductive sensors use change in local magnetic field to detect presence of metal Target.
- Capacitive Sensors use change in local capacitance caused by non-metallic objects
- Generally short ranges only
- Very robust and reliable



Flat mounted Capacitive Sensor. Used for detecting panels of glass.
Range=10mm +/- 10%

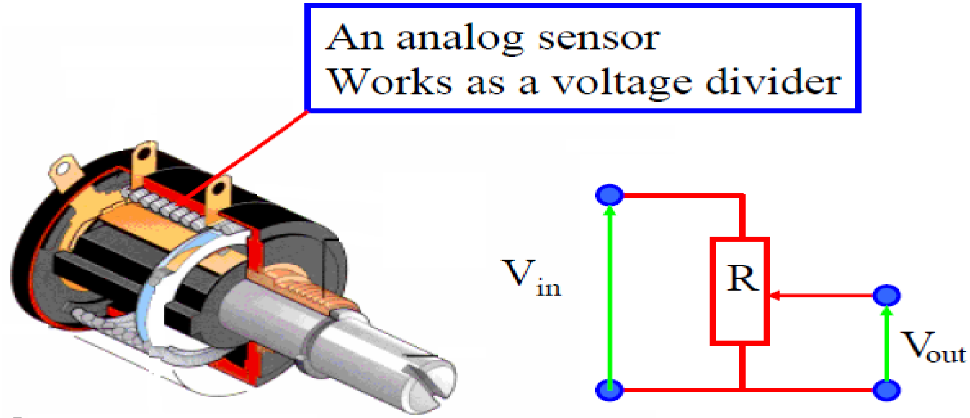
Panel Mounted Capacitive Sensor. Can detect wood, plastic and metal.
Range 3mm-25mm

Bulk mounted inductive sensors. Detect presence of object without contact.
Range 3mm +/- 10%

Position Sensors:

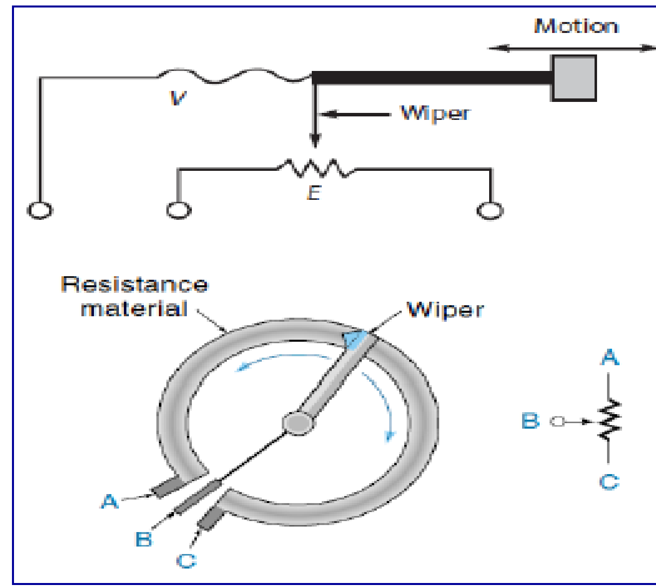
Position sensors are essential elements in the mechatronics systems for control purposes. There are three principle types:

1. Resistive sensors.
2. Capacitive sensors.
3. Inductive sensors.
4. Optical sensors.



1. Resistive Sensors: Potentiometers:

- ➢ A potentiometer is a variable electrical resistance. A length of resistance material has a voltage applied over its ends.
- ➢ A slider moves along it (either linear or rotary) and picks off the voltage at its position or angle.
- ➢ The tracks may be made from carbon , resistance wire or piezo resistive material.
- ➢ The wire wound type produces small step changes in the output depending on how fine the wire is and how closely it is coiled on the track.

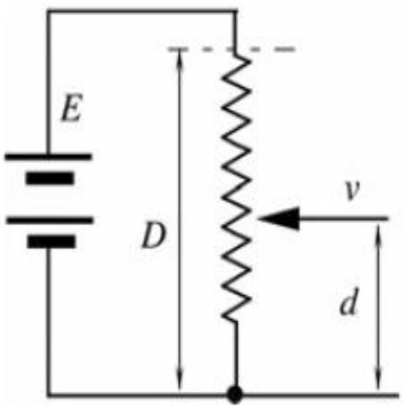


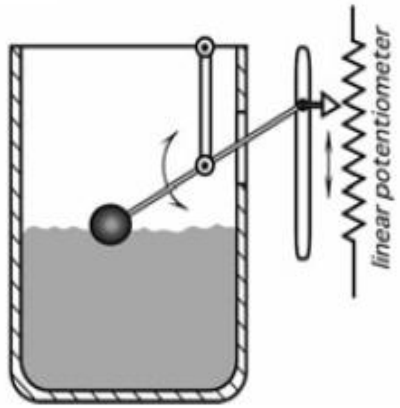
Potentiometers:

A position or displacement transducer may be built with a linear or rotary potentiometer.

The voltage across the wiper of a linear pot is proportional to the displacement (d);

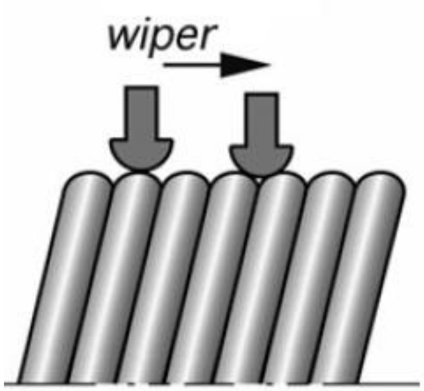
$$v = E\frac{d}{D}$$

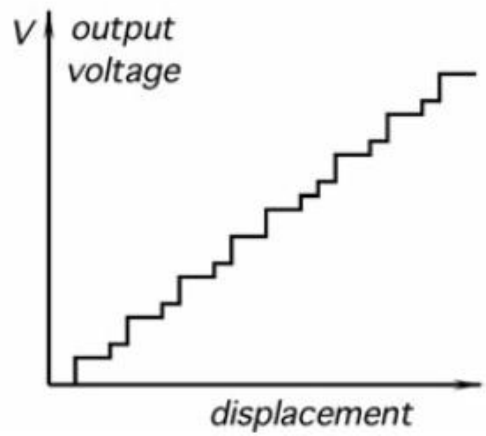




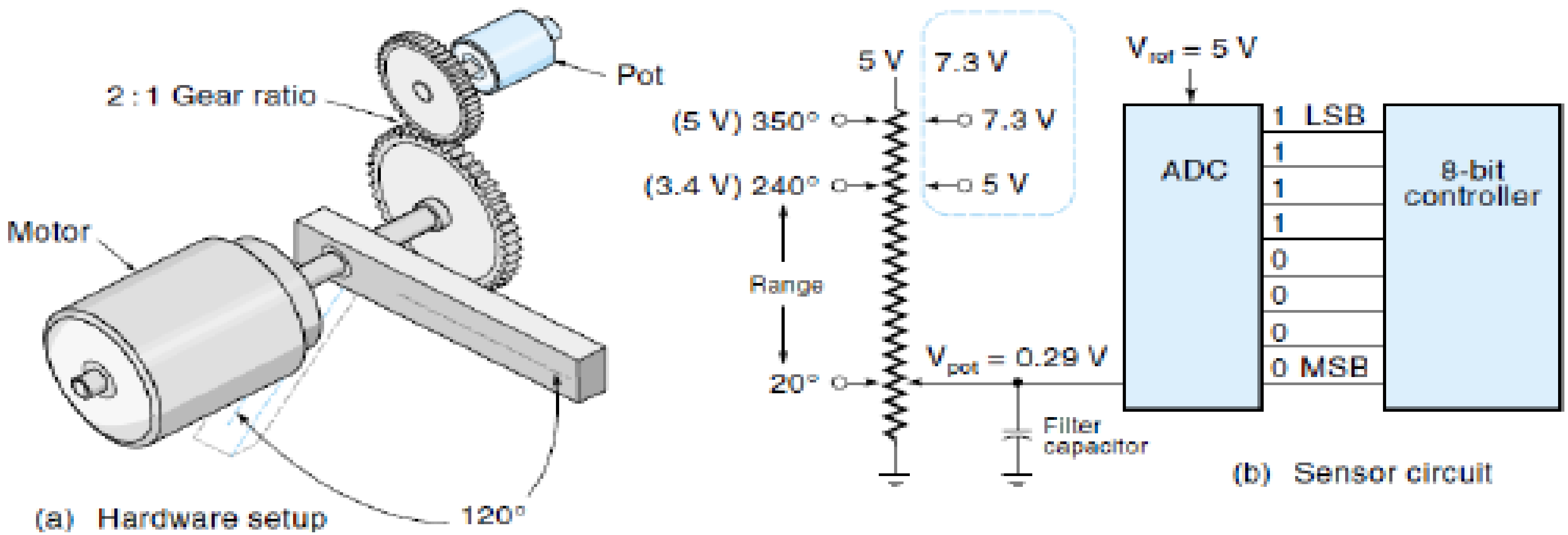
Problem: The wiper, when moving across the winding, may make contact with either one or two wires, thus resulting in uneven voltage steps (then variable resolution). Therefore, when a coil potentiometer with (N) turns is used, only the average resolution (n) should be considered:

$$n = 100/N\%$$





Example: Potentiometer sensor position system for Robot Arm

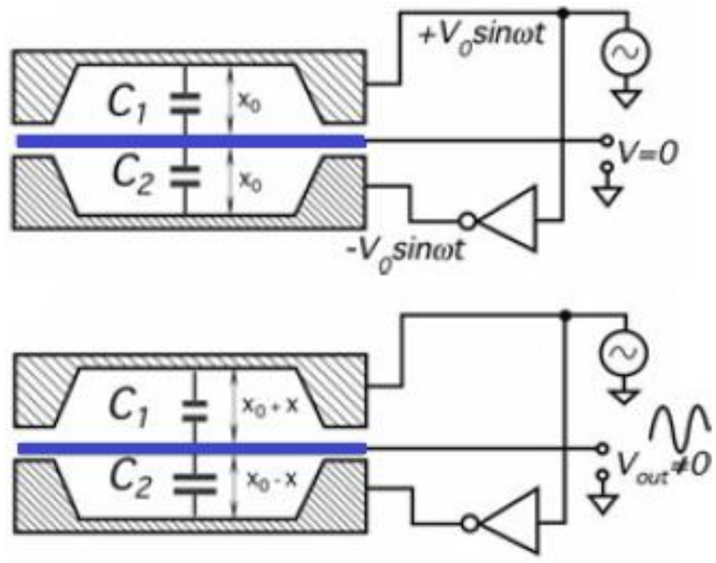


System Values for Various Angles of Robot Arm

Arm angle (degrees)	Pot angle (degrees)	Pot voltage (V)	ADC output (binary states)
0	0	0	00000000
10	20	0.29	00001111
120	240	3.43	10110000
175	350	5	11111111

2. Capacitive Sensors:

- The ability of capacitive detectors to sense virtually all materials makes them an attractive choice for many applications.
- They are employed directly to gauge displacement and position and also as building blocks in other sensors where displacements is produced by force, pressure, temperature, etc.
- The capacitance of a flat capacitor is inversely proportional to the distance between the plates. The operating principle of a capacitive gauge , proximity , and position sensors is based on either changing the geometry (i.e. a distance between the capacitor plates), or capacitance variations in the presence of conductive or dielectric materials.



Example: Assume that the central plate moves downward by distance (x). This causes changes in the respective capacitance values:

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

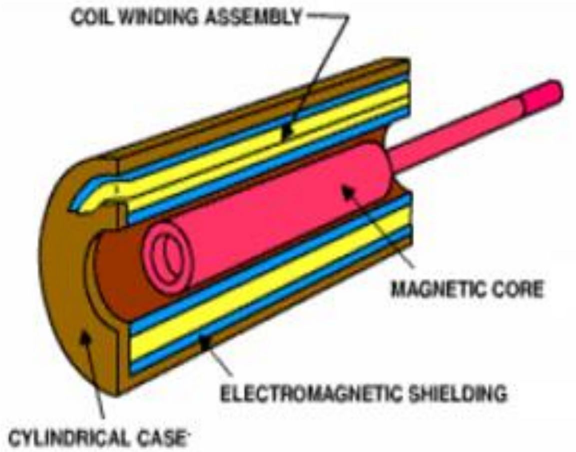
The amplitude of the output signals is

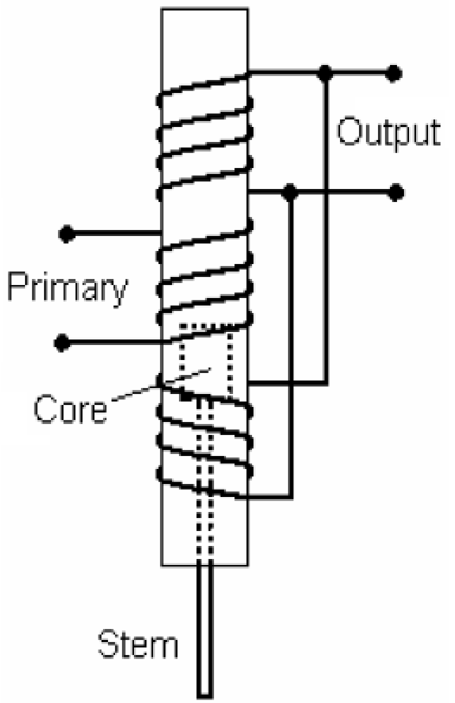
$$V_{out} = V_0\left(-\frac{x}{x_0 + x} + \frac{\Delta C_0}{C_0}\right)$$

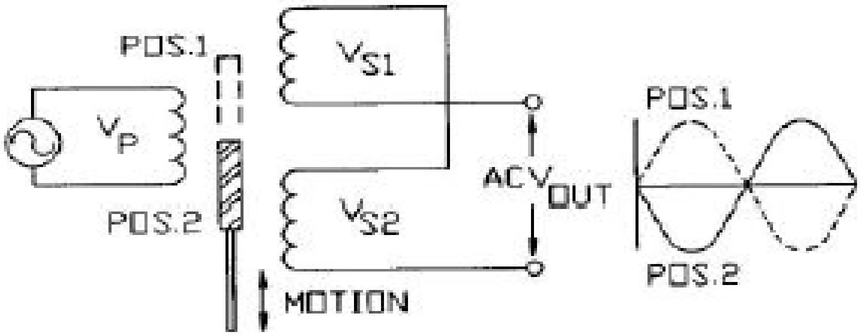
3. Linear Variable Differential transformer (LVDT):

It is made with one primary coil and two secondary coils. A magnetic core slides in the tube and is attached to the mechanism being monitored with a non magnetic stem (e.g. brass).

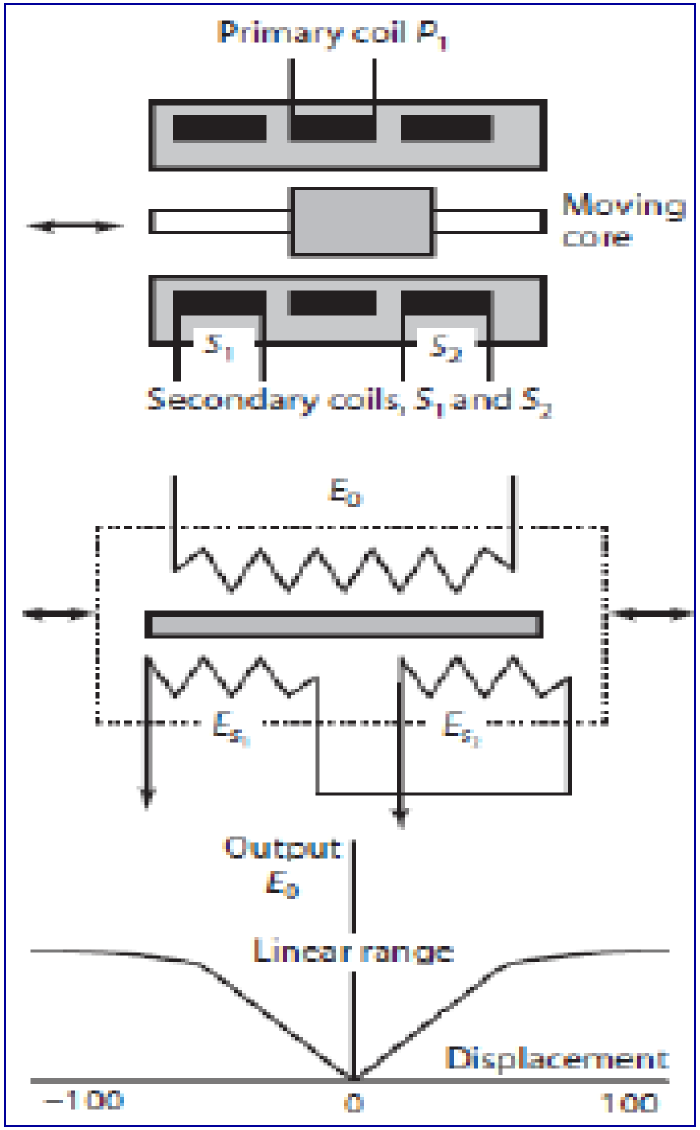
A constant AC voltage is applied to the primary coil. This induces a voltage in both secondary coils. When the core is exactly in the middle, equal voltages are induced and when connected as shown in the figure, they cancel each other out. When the core moves, the voltage in one secondary coil grows but reduces in the other. The result is an o/p voltage which represents the position of the core.

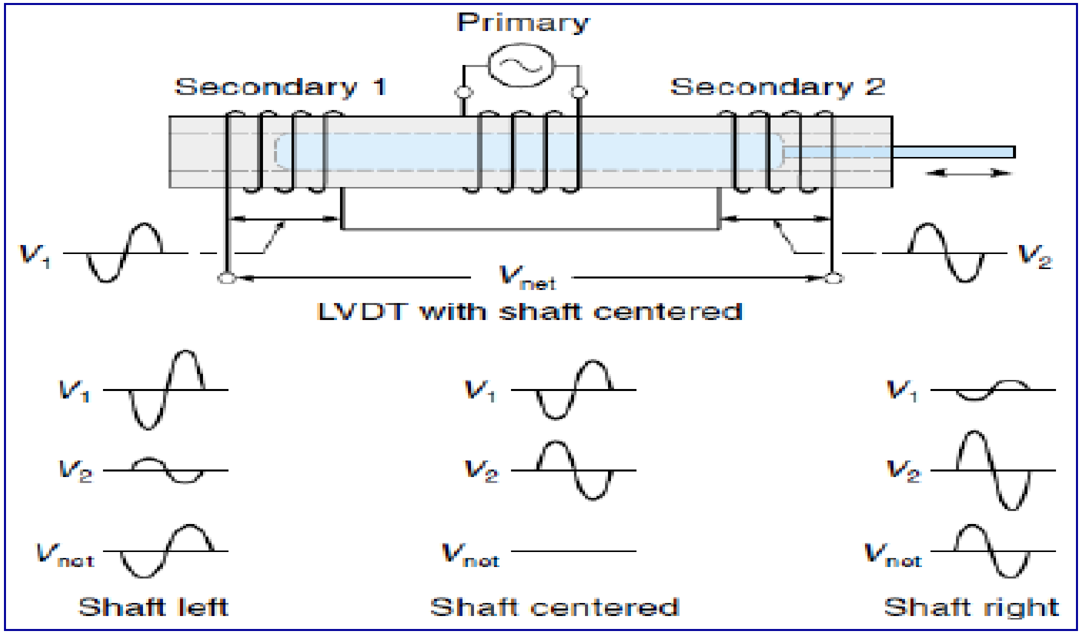


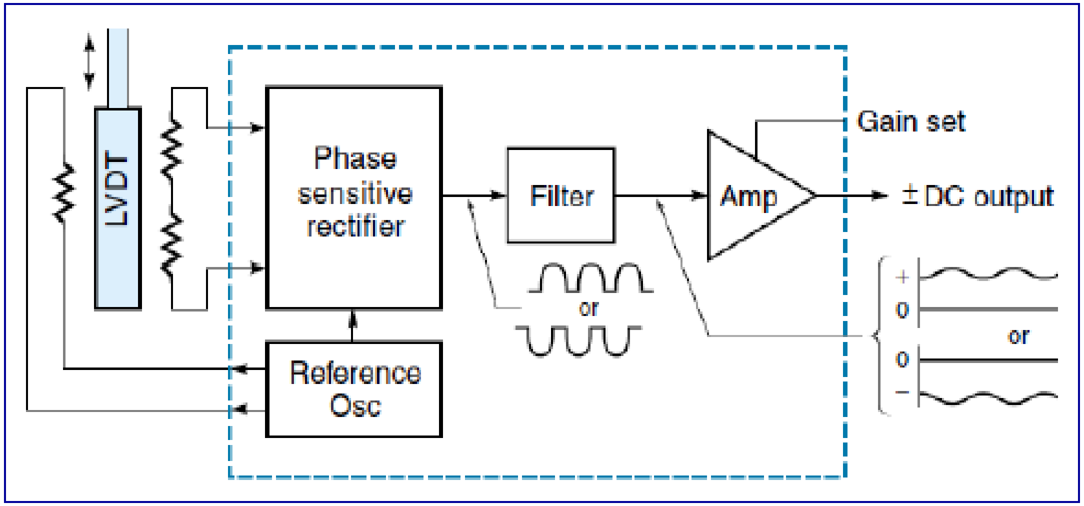




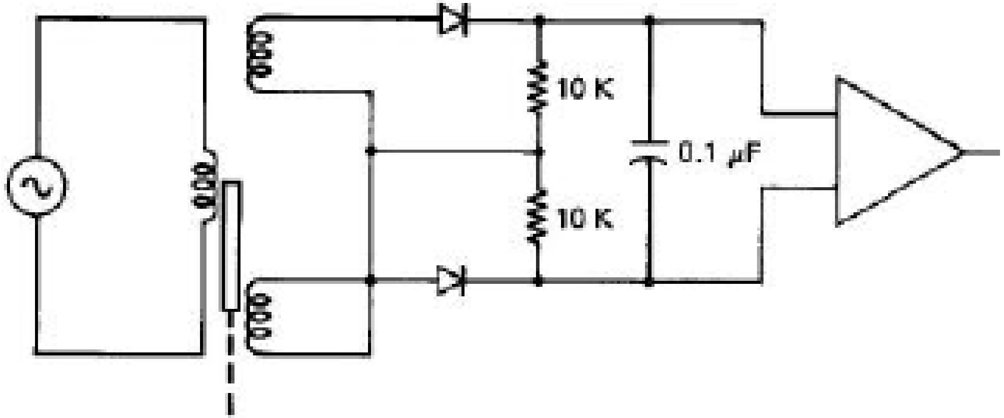
LVDT Principles:

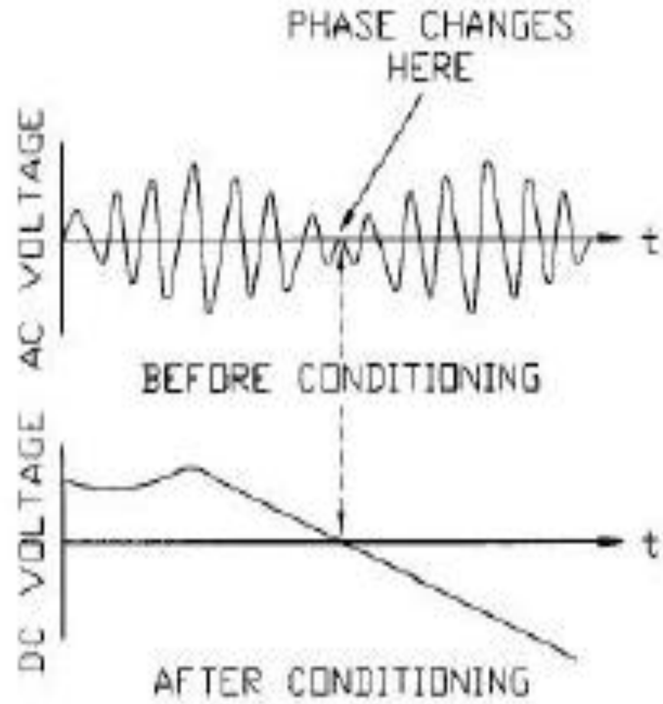




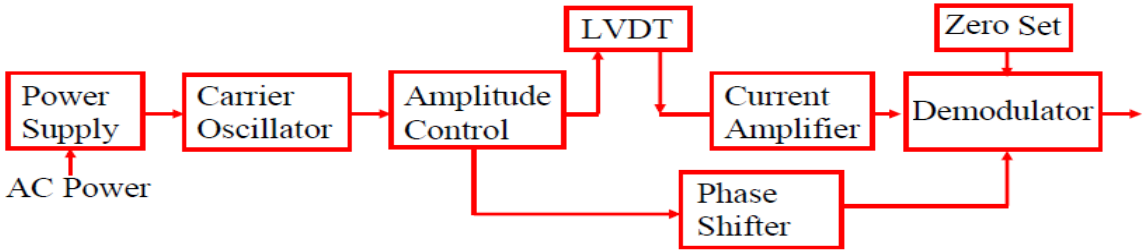


The o/p voltage is converted into DC with suitable electronic circuit for phase detection. It is possible to detect which direction the core moves and to switch the DC voltage from plus to minus as the core passes the centre position. These can be very accurate and are widely used for gauging the dimensions of machined components.





LVDT Signal Conditioning:

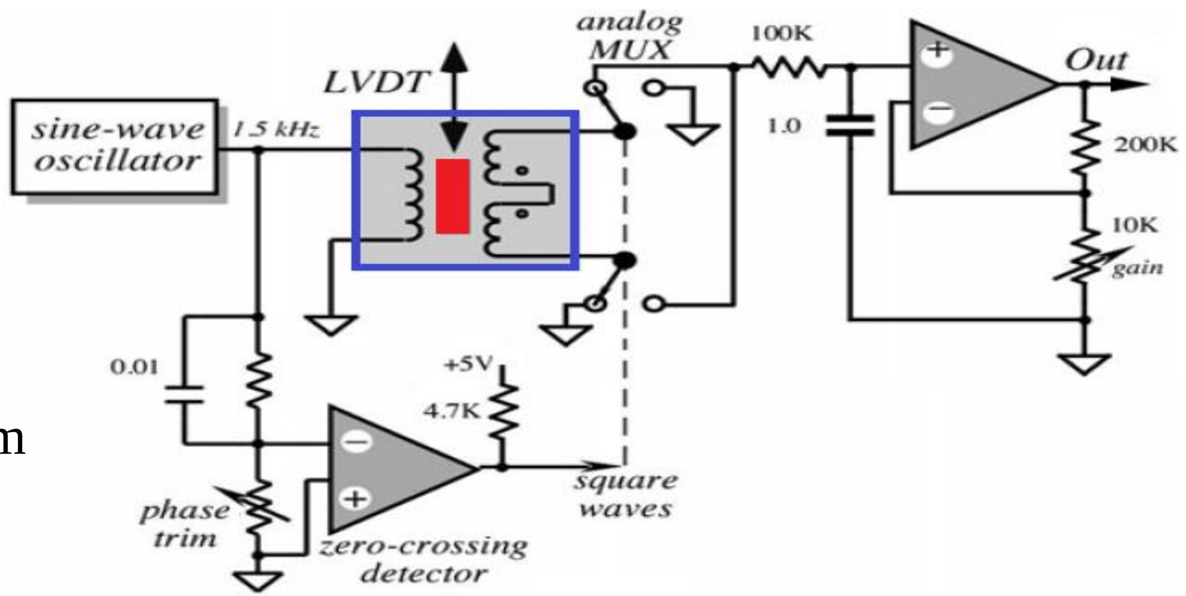


It is connected to a synchronous detector that rectifies the sine wave and presents it at the output as a DC signal.

The synchronous detector is comprised of;

- An analog multiplexer (MUX),
- Zero-crossing detector, and
- Output Amplifier.

The LVDT sensor output voltage represents how far the core is from the center and on which side.



- For accurate measurement , the frequency of the oscillator must be at least ten times higher than the highest significant frequency of the movement.
- For a slow-changing process, stable oscillator may be replaced by coupling to a power line frequency of 60 or 50 Hz.

Rotary Variable Differential Transformer (RVDT):

- The RVDT operates on the same principle as LVDT, except that a rotary ferromagnetic core is used.
- The prime use for the RVDT is the measurement of angular displacement.
- A typical linear range of measurement is about ±40 with a nonlinearity error of about 1%.

When to use an LVDT When to use an LVDT:

- ✓ High accuracy
- ✓ Linear operation (synchro resolver is equivalent RVDT)
- ✓ Harsh environment
- ✓ Analog position control
- ✓ Embedding (in cylinder for example)

Standard measurement Characteristics of LVDT:

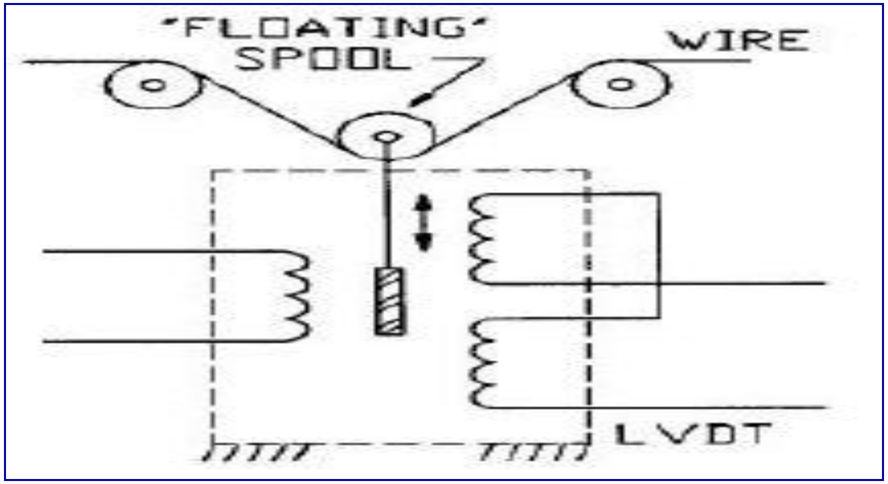
- ✓ Measurement range is from 200 μm to 50 cm.
- ✓ Practical resolution may be better than 0.1% or below 1 μm.
- ✓ The excitation frequency is usually between 50 Hz and 20 kHz.

The advantages of the LVDT and RVDT:

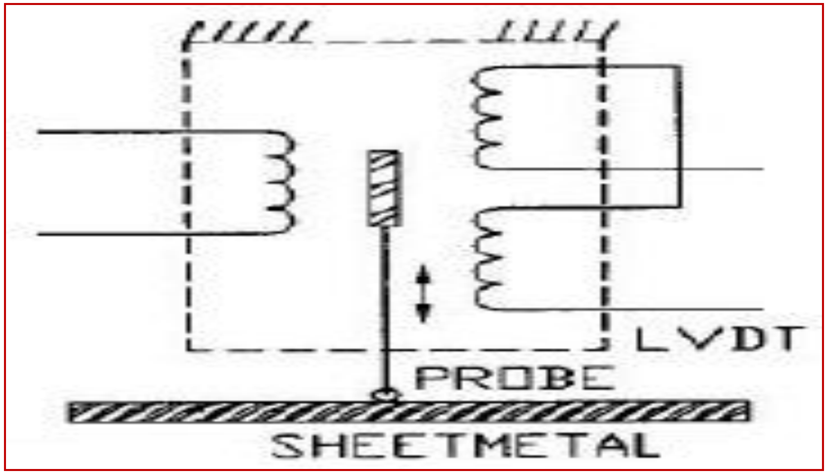
- It is a noncontact device with no or very little friction resistance.
- Hysteresis (magnetic and mechanical) are negligible.
- Output impedance is very low.
- Low ability to noise and interferences.
- Construction is solid and robust.
- High resolution is possible.

LVDT Applications:

LVDT used for maintaining proper wire spool tension

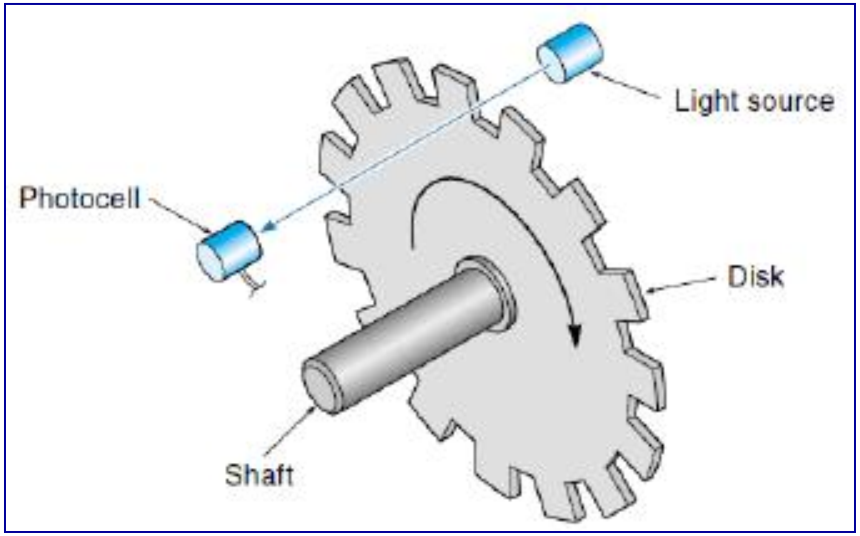


LVDT used for sheet metal thickness



4. Optical Sensors: Shaft Encoders:

- Encoders are electro-mechanical devices that convert the angular position or motion of a shaft or axle to an analog or digital code.
- There are two main types: absolute and incremental (relative).
- The output of absolute encoders indicates the current position of the shaft, making them angle transducers.
- It consists of a glass or plastic disc that rotates between a light source (LED) and a pair of photo-detectors
- Disk is encoded with alternate light and dark sectors so pulses are produced as disk rotates.
- When a disk with a pattern rotates, light passing through the slits is transmitted or blocked according to the pattern. The received light is converted to electrical currents in the detector elements, takes the form of waves, and becomes digital signals.

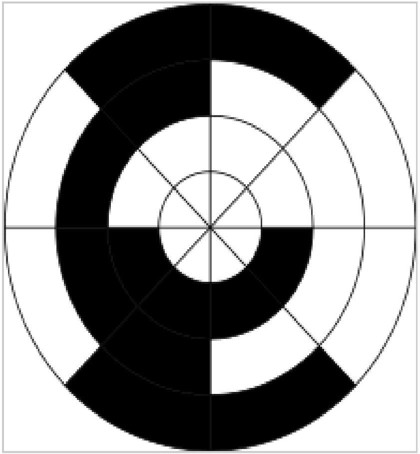


Absolute Encoders:

- Absolute encoders have a unique code that can be detected for every angular position.
- The optical absolute encoder's disc is made of glass or plastic with transparent and opaque areas. A light source and photo detector array reads the optical pattern that results from the disc's position at any one time.
- They are available in the form of a "grey code"; a binary code of minimal change.
- Absolute encoders are much more complex and expensive than incremental encoders.

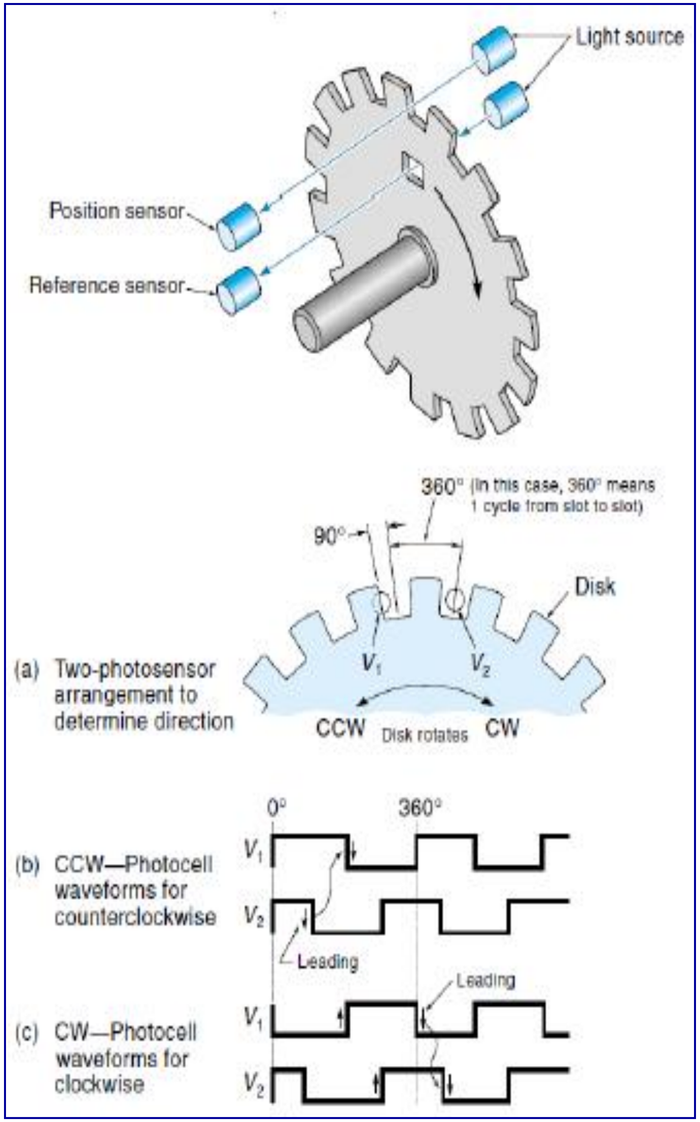
Sector	Contact 1	Contact 2	Contact 3	Angle
0	off	off	off	0° to 45°
1	off	off	ON	45° to 90°
2	off	ON	ON	90° to 135°
3	off	ON	off	135° to 180°
4	ON	ON	off	180° to 225°
5	ON	ON	ON	225° to 270°
6	ON	off	ON	270° to 315°
7	ON	off	off	315° to 360°

Gray Coding



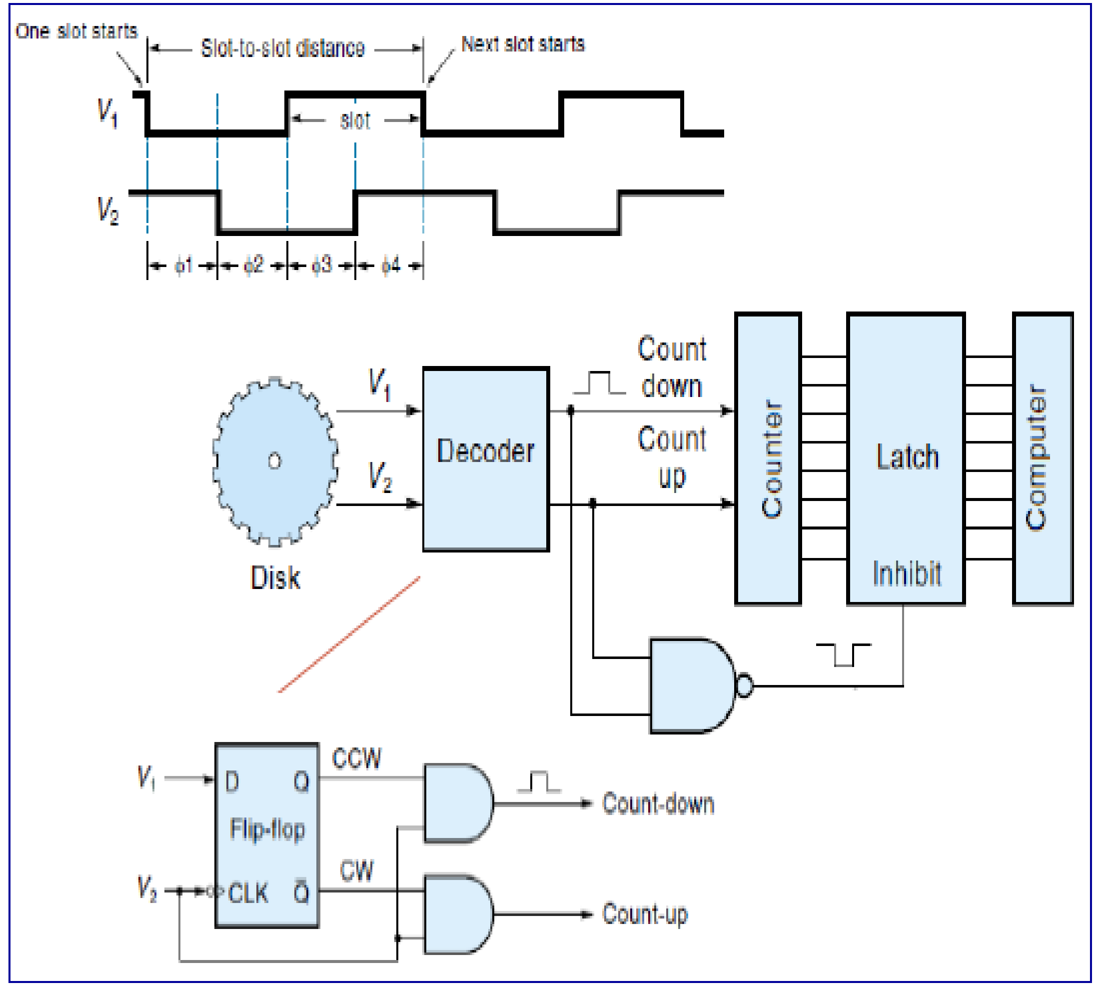
When to Use an Encoder:

- Require accurate position information:
  10,000 line incremental
  360 line absolute
- Digital feed-back loop.
- Compact and reasonably rugged.



Light source
Position sensor
Reference sensor
360° (In this case, 360° means 1 cycle from slot to slot)
90°
Disk
(a) Two-photosensor arrangement to determine direction
CCW
Disk rotates
CW
0°
360°
(b) CCW—Photocell waveforms for counterclockwise
Leading
(c) CW—Photocell waveforms for clockwise
Leading

Example:

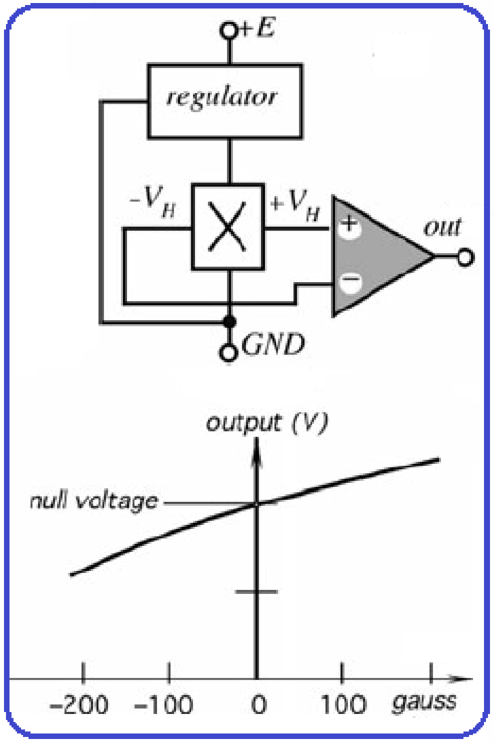


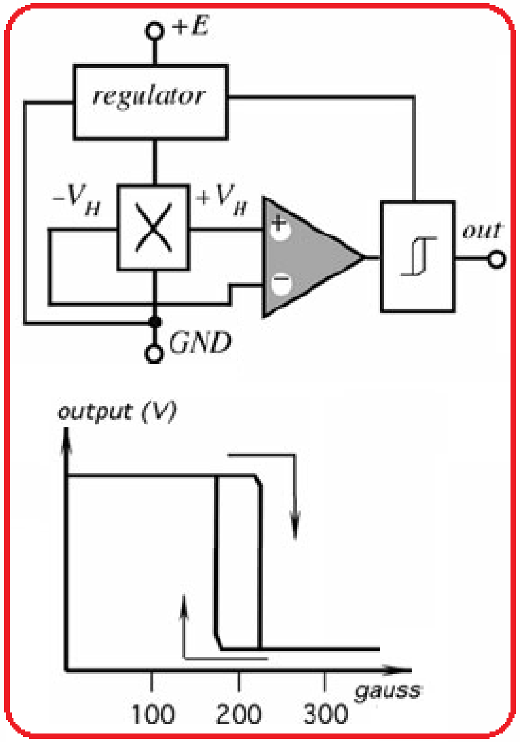
One slot starts
Slot-to-slot distance
Next slot starts
slot
ϕ1
ϕ2
ϕ3
ϕ4
Count down
Count up
Decoder
Disk
Counter
Latch
Inhibit
Computer
D
Q
CCW
Flip-flop
CLK
CW
Count-down
Count-up

4. Hall Effect Sensors:

There are two types of the Hall sensors:

- **Analog sensors:** operates over a broader voltage range and more stable in a noisy environment. These sensors are not quite linear wrt the magnetic field density.
- **A bi-level sensor:** in addition to the amplifier contains a Schmitt trigger with a built-in hysteresis of the threshold level.





For position and displacement measurements, the Hall effect sensors must be provided with a magnetic field source and interface electronic circuit. A magnetic field has two important for this application characteristics: flux density and polarity (or orientation).

Example: liquid level detector

A permanent magnet is imbedded inside a float having a hole in the center.

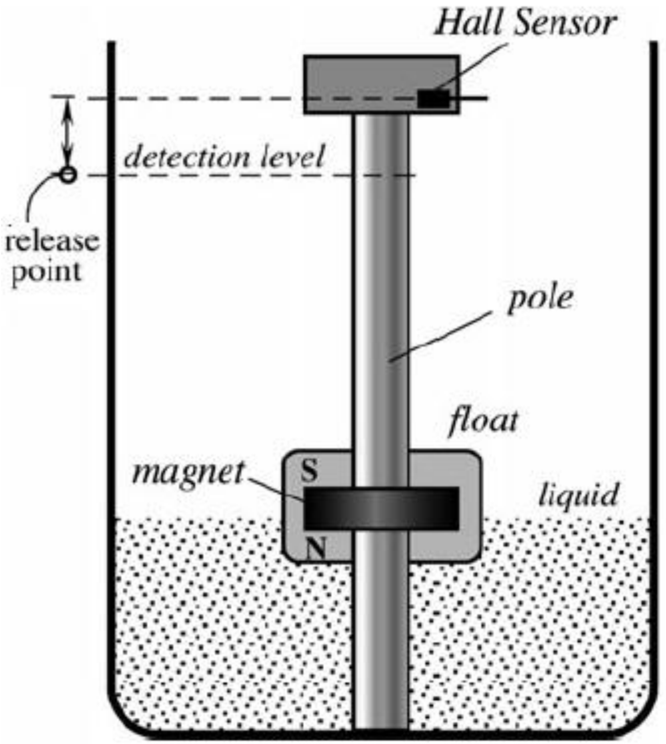
A bi-level Hall sensor is mounted at the top of the pole, which should be fabricated on a nonmagnetic material.

When the liquid level rises and reaches the detection level, the Hall switch triggers and sends signal to the monitoring device.

When the liquid level drops below the release point plus the threshold hysteresis, the Hall sensor output voltage changes, indicating that the liquid level dropped.

The detection point depends on these key factors:

1. the magnet strength and shape,
2. the Hall sensor's sensitivity,
3. the hysteresis, and
4. presence of ferromagnetic components in the vicinity of the Hall sensor.



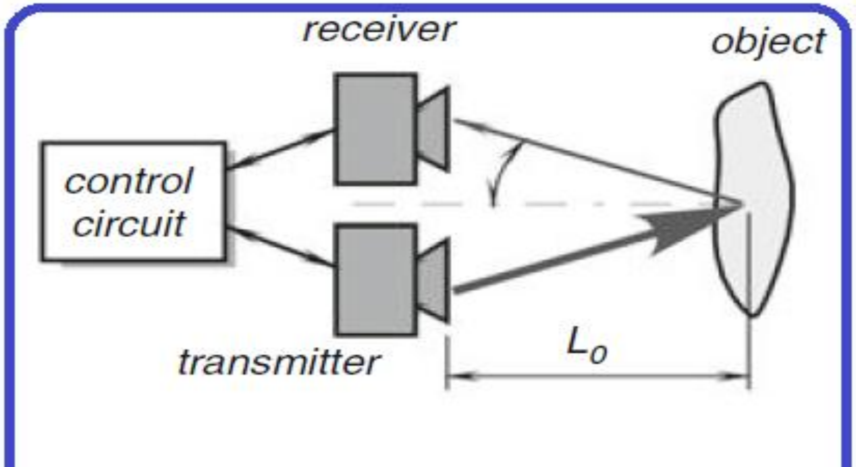
Ultrasonic Detectors:

- These detectors are based on transmission to the object and receiving the reflected acoustic waves.
- For motion detection, they require a longer operating range and a wider angle of coverage.

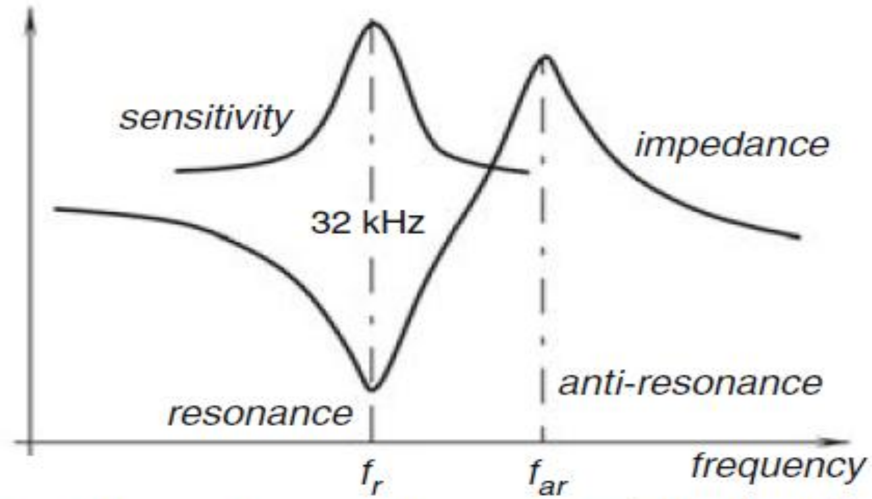
For noncontact distance measurements;

- An ultrasonic sensor transmits a signal and receives a reflected signal from the object.
- When the waves are incident on an object, part of their energy is reflected.
- Regardless of the direction where the energy comes from, it is reflected almost
- uniformly within a wide solid angle, which may approach 180°.
- If an object moves, the frequency of the reflected wavelength will differ from the transmitted waves, this is called the **Doppler effect**.

Noncontact Distance Measurements:



Ultrasonic distance measurement



impedance characteristic of a piezoelectric transducer

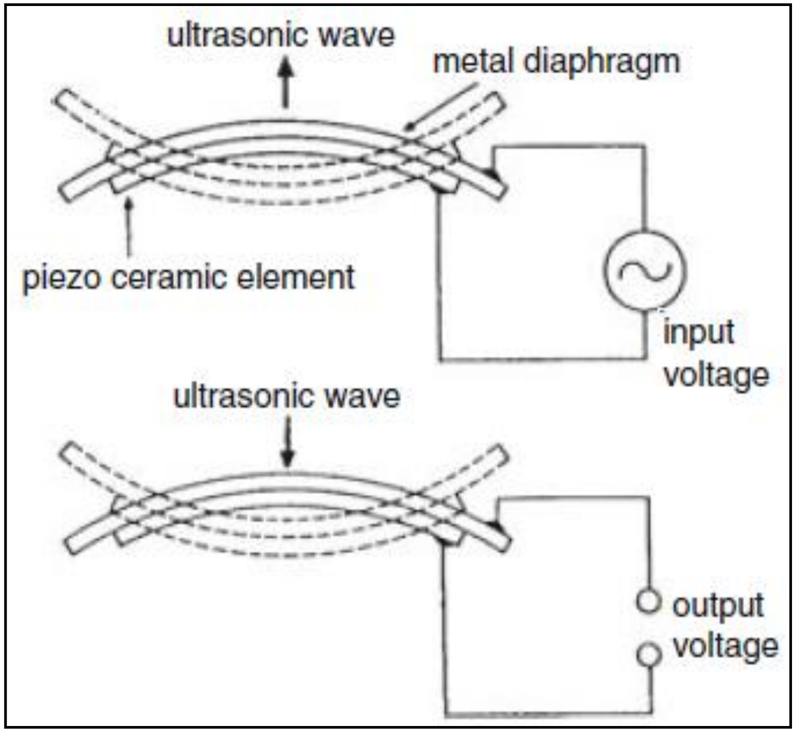
A distance (L_0)to the object can be calculated through the speed (v) of the ultrasonic waves in the media, and the angle (Θ);

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

where t is the time for the ultrasonic waves to travel to the object and back to the receiver (thus the denominator 2).

Noncontact Distance Measurements:

- If a transmitter and a receiver are positioned close to each other as compared with the distance to the object, then CosΘ = 1.
- Ultrasonic waves have an obvious advantage over the microwaves: they propagate with the speed of sound (which is much slower than the speed of light at what the microwaves propagate). Thus, time t is much longer and its measurement can be accomplished easier and cheaper.
- The input voltage applied to the ceramic element causes it to flex and transmit ultrasonic waves.
- Because piezoelectricity is a reversible phenomenon, the ceramic generates voltage when incoming ultrasonic waves flex it. In other words, the element may work as both the sonic transmitter and receiver (a microphone).



Microwave Motion Detectors

- They offer an attractive alternative to cover large areas and to operate over an extended temperature range under the influence of strong interferences.
- These detectors are active sensors (provide an excitation signal). Thus they can operate at day or night and do not rely on the external sources of energy.
- Its operating principle is based on radiation of electromagnetic radiofrequency (RF) waves toward a protected area. The electromagnetic waves reflected from objects are received, amplified, and analyzed.
- A time delay between the transmitted signal and received reflected signal is used to measure distance to the object, while the frequency shift is used to measure speed of motion of the object.

Frequency Range of Microwave Signals:

- The microwave detectors belong to the class of devices known as radars. Radar is an acronym for **RA**dio **D**etection **A**nd **R**anging.
- The name microwave is assigned to the wavelengths (λ< 4cm), i.e. ≈ 1GHz to ≈ 30 GHz. They are long enough to pass freely through most contaminants, such as clouds and airborne dust, and short enough for being reflected by larger objects.

Frequency Range	Abbreviation	Type of Signal and Characteristics
Very low, low, and medium frequency: 3 kHz to 3 MHz	VLF LF MF	Very long-range communication (ships at sea, and so forth), commercial AM radio. Ground waves circle the Earth.
High frequency: 3 to 30 MHz	HF	Over-the-horizon communication, Signals reflect from ionosphere.
Very high frequency: 30 to 300 MHz	VHF	Mobile communication, TV, and commercial FM radio. Line-of-sight required.
Ultra high frequency: 300 MHz to 1 GHz	UHF	Mobile communication and TV. Line-of-sight required.
Microwave: 1 to 30 GHz	Mw	TV and telephone links, satellite links. Line-of-sight required.
Millimeter wave: 30 to 100 GHz	MMW	Very short-range communication. Requires line-of-sight, high absorption in rain and fog.

Microwave Detector:

It consists of; a Gunn oscillator, an Antenna, and a Mixer diode.

1. The Gunn Oscillator:

- It is a diode mounted in a small precision cavity oscillates at microwave frequencies.
- It produces electromagnetic waves (frequency f_0), part of which is directed through an iris into a waveguide.
- It is sensitive to the stability of applied dc voltage and, therefore, must be powered by a good quality voltage regulator.
- It may run continuously, or pulsed, which reduces the power consumption from the power supply.

2. Focusing Antenna:

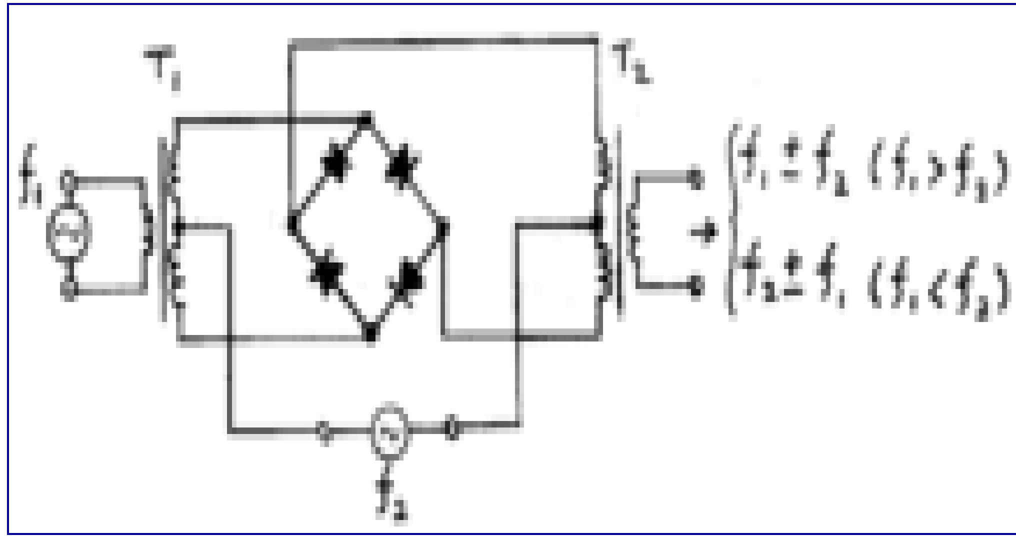
- It directs the radiation toward the object.
- Its focusing characteristics are determined by the application.
    - As a general rule, the narrower the directional diagram of the antenna, the more sensitive it is (the antenna has a higher gain).
    - Another general rule is that a narrow-beam antenna is much larger, whereas a wide-angle antenna can be quite small.

3. Mixer diode:

In electronic a **mixer** is a nonlinear circuit that creates new frequencies from two signals applied to it.

A diode can be used to create a simple mixer. This type of mixer produces the original frequencies as well as their sum and their difference.

Two signals (f_1 &f_2) are applied to a mixer, and it produces new signals;

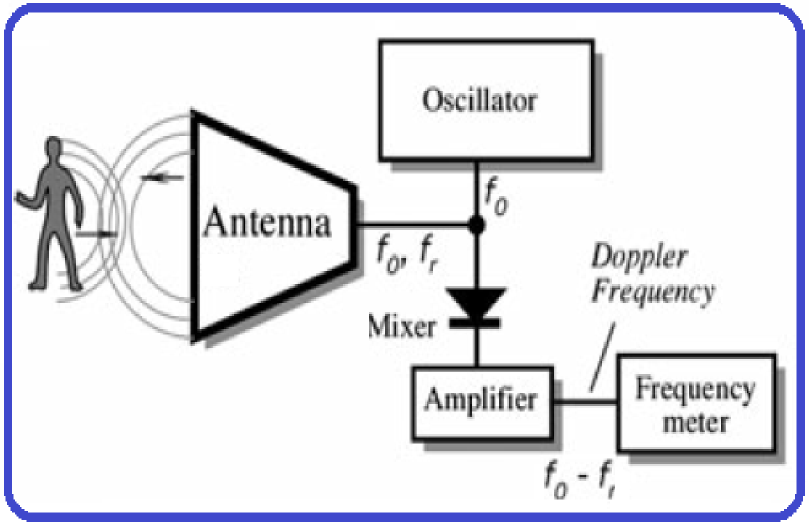


The sum ($f_1 + f_2$) and the difference ($f_1 - f_2$) of the original frequencies.

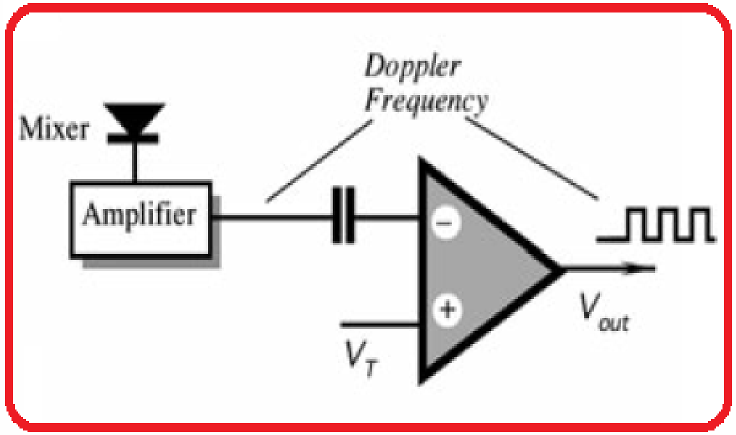
Note: There is no output unless both f_1 and f_2 inputs are present.

- The target reflects some waves back toward the antenna, which directs the received radiation toward the mixing diode whose current contains a harmonic with a phase differential between the transmitted and reflected waves.
- The phase difference is in a direct relationship to the distance to the target. The phase-sensitive detector is useful mostly for detecting the distance to an object.

Occupancy & Motion Detector:



circuit for measuring Doppler frequency



circuit with a threshold detector

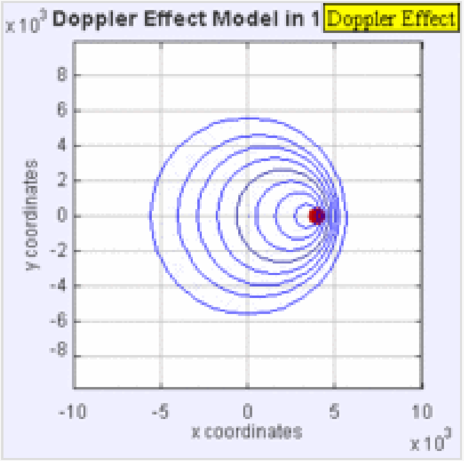
- The Doppler effect is the basis for the operation of microwave and ultrasonic detectors. The Doppler effect device is responsive only to moving targets.
- An antenna transmits the frequency (f_0), which is defined as the ratio between the speed of light in air (C_0) and the wavelength (λ_0);

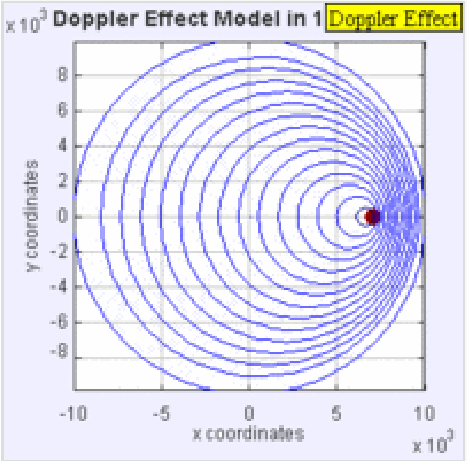
$$f_0 = \frac{c_0}{\lambda_0}$$

- When the target moves toward or away from the transmitting antenna, the frequency of the reflected radiation will change. Thus, if the target is moving away with velocity v, the reflected frequency will decrease and it will increase for the approaching targets. **This is called the Doppler effect**.

Doppler effect :

It is the change in frequency of a wave for an observer moving relative to its source. The frequency of reflected electromagnetic waves can be predicted by the Einstein's special theory of relativity as;





$$f_r = f_0 \frac{\sqrt{1 - \left(\frac{v}{c_0}\right)^2}}{1 + \frac{v}{c_0}} \qquad (v/c_0)^2 \ll 1$$

$$f_r = f_0 \frac{1}{1 + \frac{v}{c_0}}$$

$$\Delta f = f_0 - f_r = f_0 \frac{1}{1 + \frac{c_0}{v}} \qquad c_0/v \gg 1$$

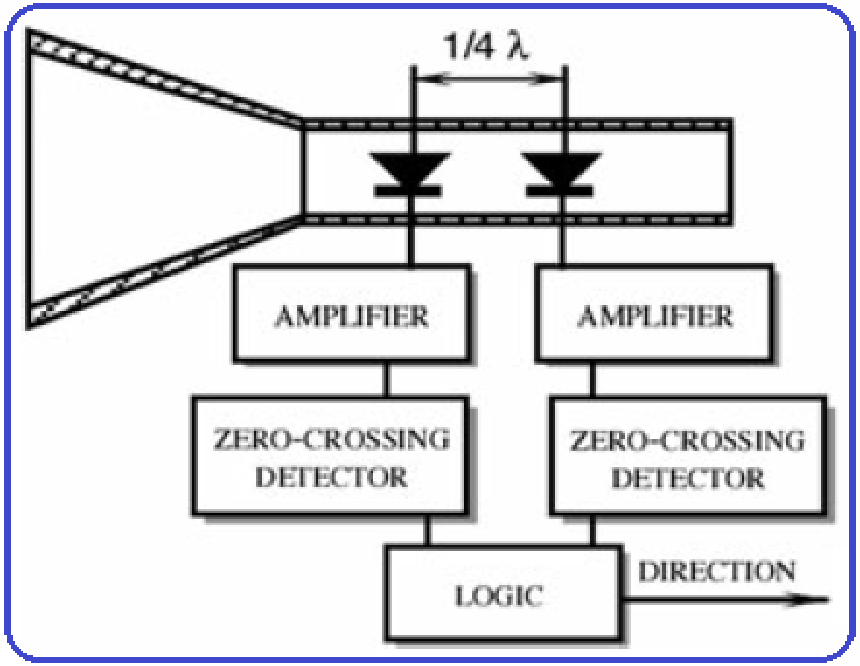
$$\Delta f \approx \frac{v}{\lambda_0}$$

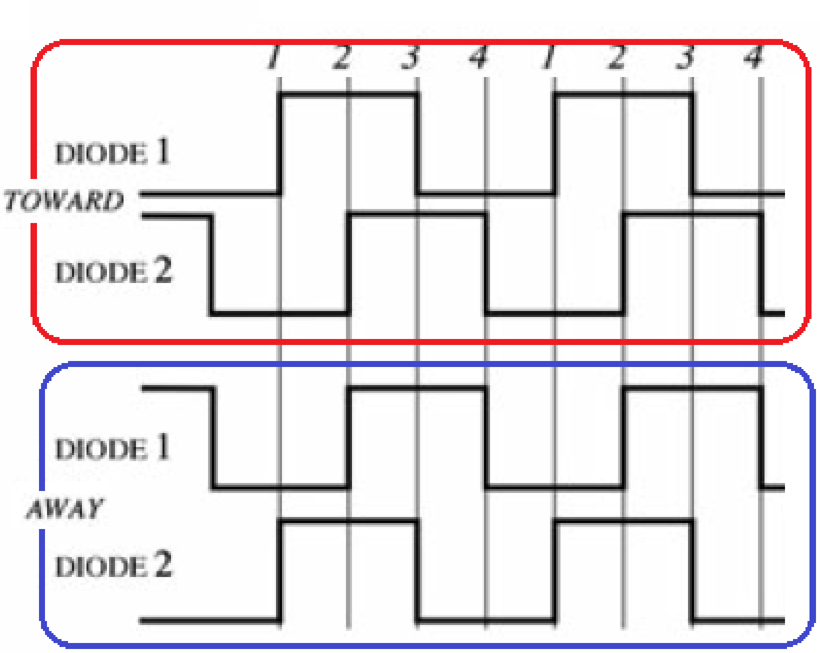
- The above relation is true only for movements in the normal direction.
- When the target moves at angles (Θ) with respect to the detector, then;

$$\Delta f \approx \frac{v}{\lambda_0} \cos \Theta$$

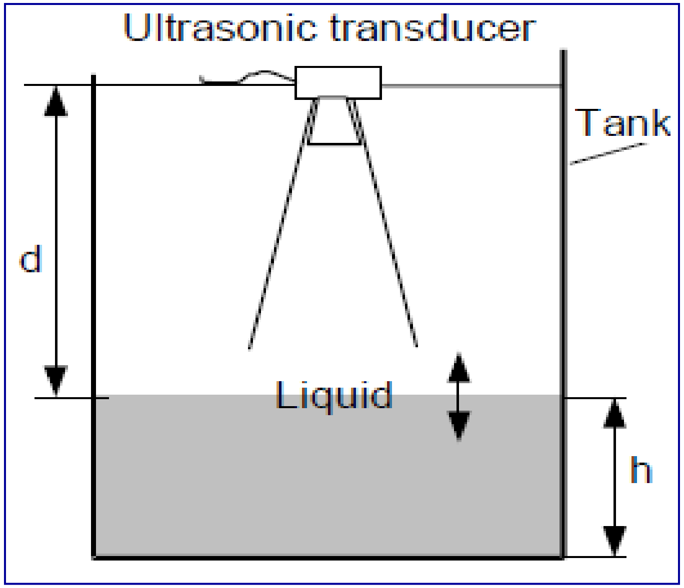
Direction Detection:

- To detect whether a target moves toward or away from the antenna, another mixing diode is added to the transceiver module.
- The second diode is located in the waveguide in such a manner that the Doppler
- signals from both diodes differ in phase by one-quarter of wavelength or by 90.
- These outputs are amplified separately and converted into square pulses, which can be analyzed by a logic circuit.





6. Ultrasonic Sensors:

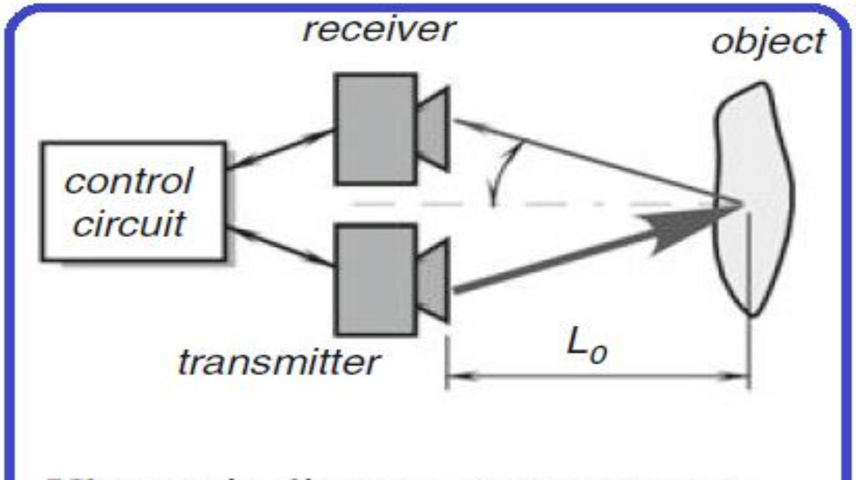


- These detectors are based on transmission to the object and receiving the reflected acoustic waves.
- For motion detection, they require a longer operating range and a wider angle of coverage.

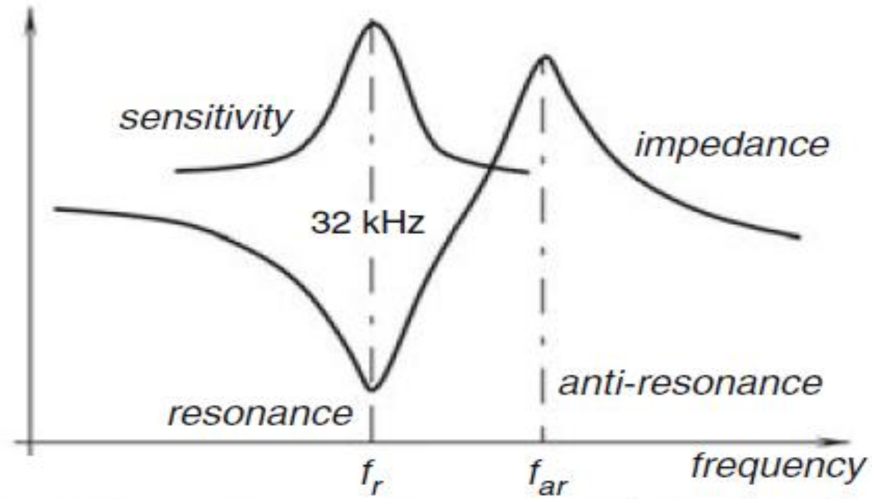
For noncontact distance measurements;

- An ultrasonic sensor transmits a signal and receives a reflected signal from the object.
- When the waves are incident on an object, part of their energy is reflected.
- Regardless of the direction where the energy comes from, it is reflected almost
- uniformly within a wide solid angle, which may approach 180°.
- If an object moves, the frequency of the reflected wavelength will differ from the transmitted waves, this is called the **Doppler effect**.

Noncontact Distance Measurements:



Ultrasonic distance measurement



impedance characteristic of a piezoelectric transducer

A distance (L_0)to the object can be calculated through the speed (v) of the ultrasonic waves in the media, and the angle (Θ);

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

where t is the time for the ultrasonic waves to travel to the object and back to the receiver (thus the denominator 2).

6. Microwave Sensors (Radar):

- The travel time of microwave signals is measured.
- Due to the high value of light velocity, the duration of the pulses is only 1 ns, otherwise the transmitted and received pulse would overlap.
- Short pulses require special requirements on time interval measurement.

Micropower Impulse Radar (MIR):

MIR is a low-cost noncontact ranging sensor. Its operating principle is the same as of a conventional pulse radar system.

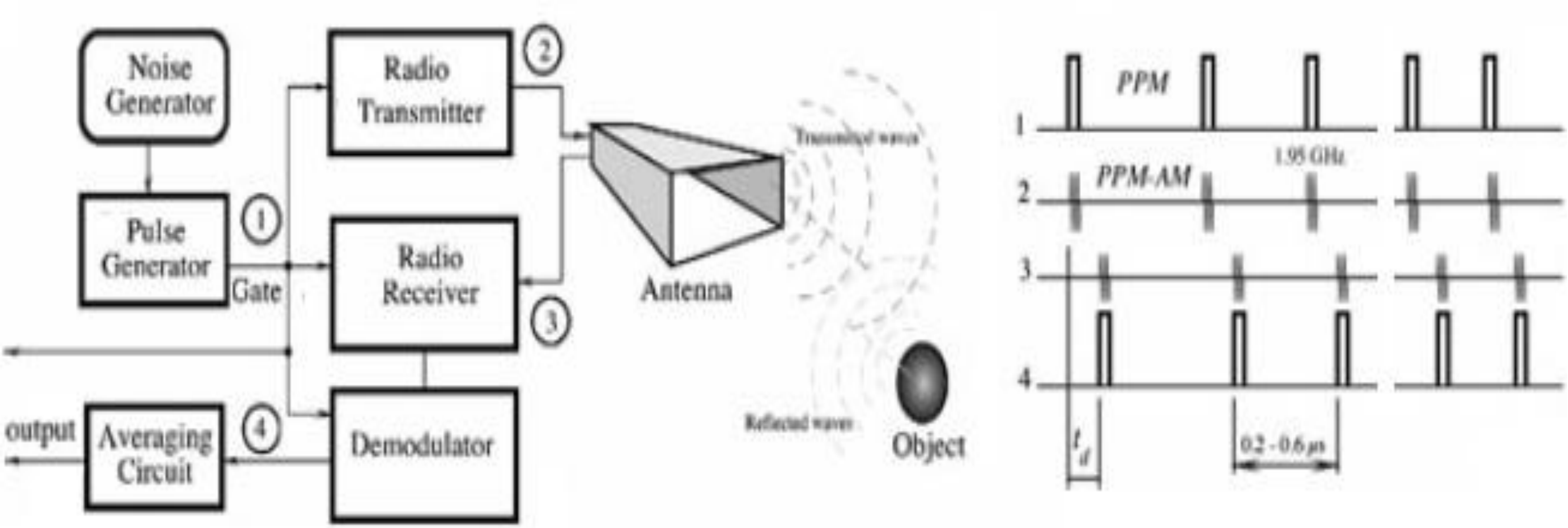
MIR is used for sensing and measuring distances to objects in proximity to each other.

Commercial applications include:

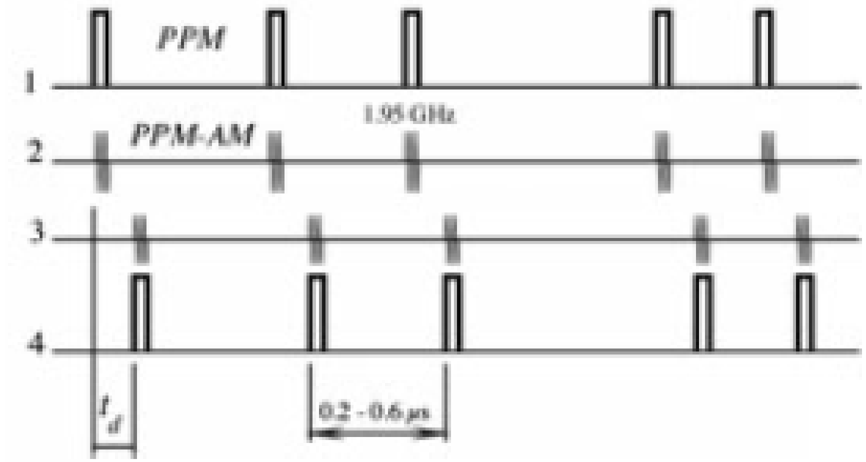
- **Vehicles:** parking assistance, backup warnings, pre-collision detection and smart cruise control (measures the distance to the vehicles in front of you and if they get too close, throttle is released and brakes are applied).
- **Appliances:** stud finders and laser tape measures.
- **Security:** home intrusion motion sensors and perimeter surveillance.
- **Search and rescue:** MIR can detect the beating of a human heart or respiration from long distances.

MIR Architecture:

- It consists of a white noise generator whose output signal triggers a pulse generator.
- The pulse generator produces very short pulses with the average rate of 2 MHz±20%. Each pulse has a fixed short duration (τ), while the repetition of these pulses is random, according to triggering by the noise generator.
- The distance between the pulses ranges from 200 to 625 ns. It can be said that the pulses have a pulse-position modulation (PPM) by white noise with the maximum index of 20%.



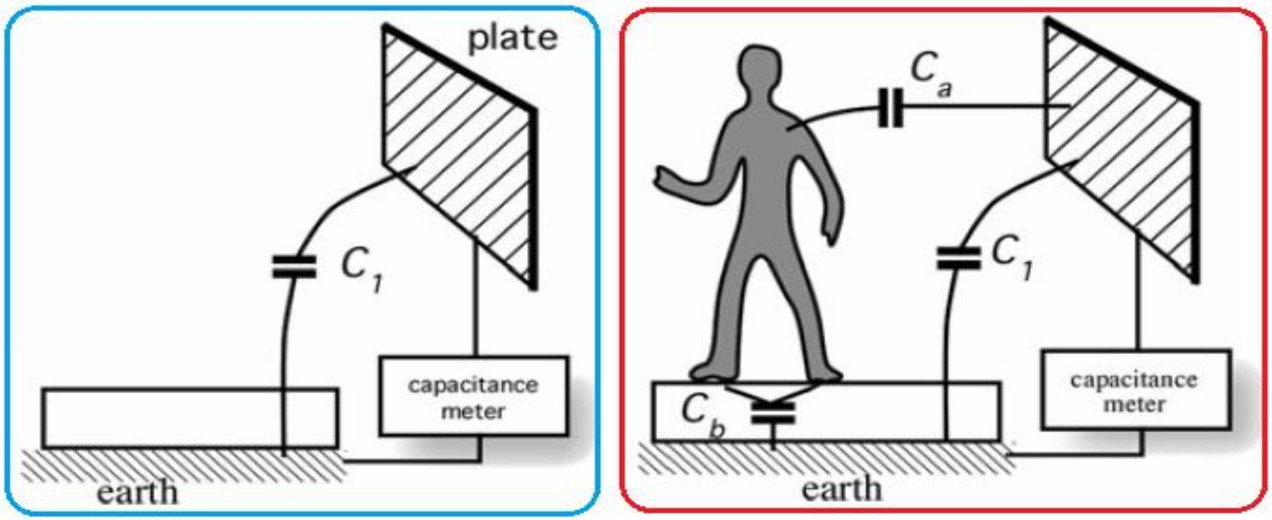
- The square wave pulses cause the AM of a radio transmitter.
- The modulation has a 100% depth, that is, the transmitter is turned on and off by the pulses. Such a double-step modulation is called PPM-AM.



- The radiotransmitter produces short bursts of high-frequency radio packest, which propagate from the transmitting antenna to the surrounding space.
- The electromagnetic waves reflect from the objects and propagate back to the radar.
- The same pulse generator, which modulates the transmitter, with a predetermined delay gates the radio receiver to enable reception by the MIR only during a specific time window when the reflected waves are expected to arrive.
- The reflected pulses are received, demodulated, and the time delay with respect to the transmitted pulses is measured.
- The time delay is proportional to distance D from the antenna to the object from which the radio waves are reflected: $t_d = 2D/c$, where c is the speed of light.

Capacitive Occupancy Detectors:

- A human body develops a coupling capacitance to its surroundings. Its value (from few pF to several nF) depends on; body size, clothing, materials, weather, type of surrounding objects, and so forth.
- When a person moves, the coupling capacitance changes, thus making it possible to discriminate static objects from moving objects.

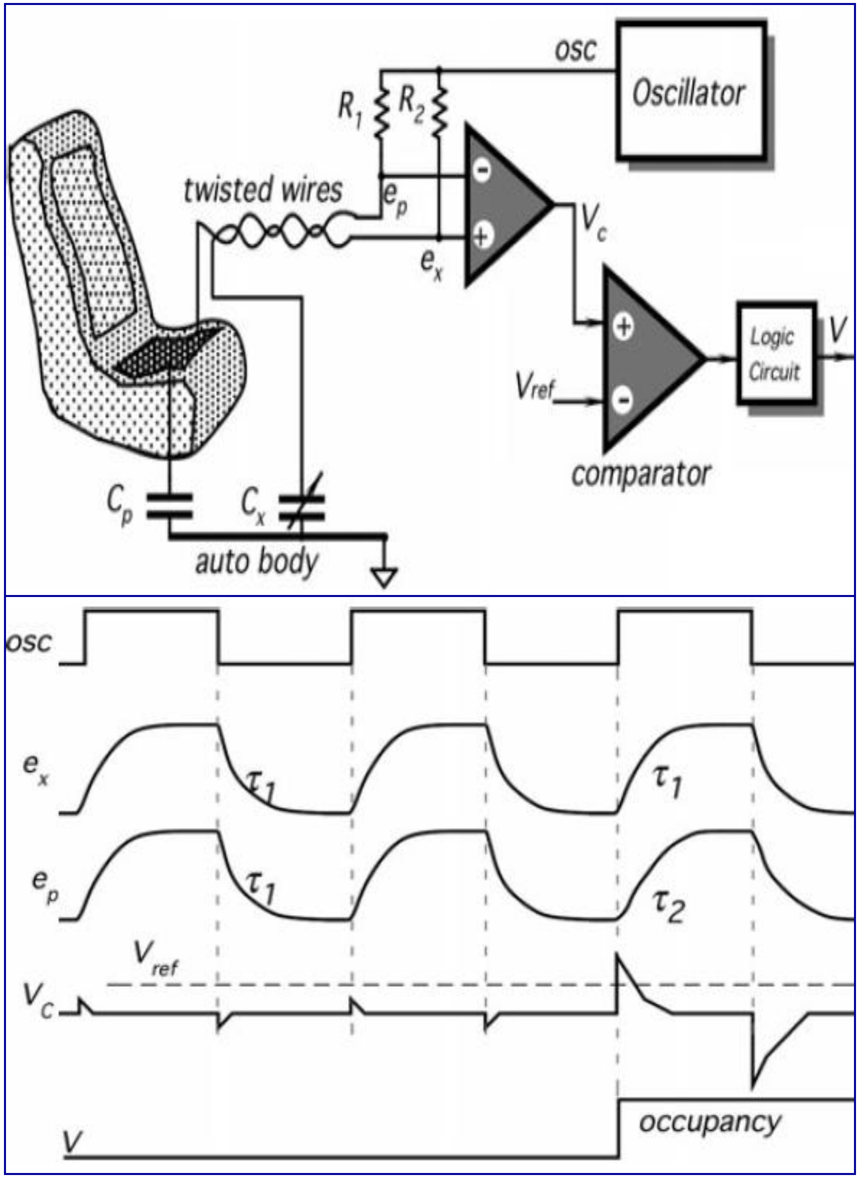


➢The resulting capacitance (C) between the test plate and the earth becomes;

$$\boxed{C = C_1 + \Delta C = C_1 + \frac{C_a C_b}{C_a + C_b}}$$

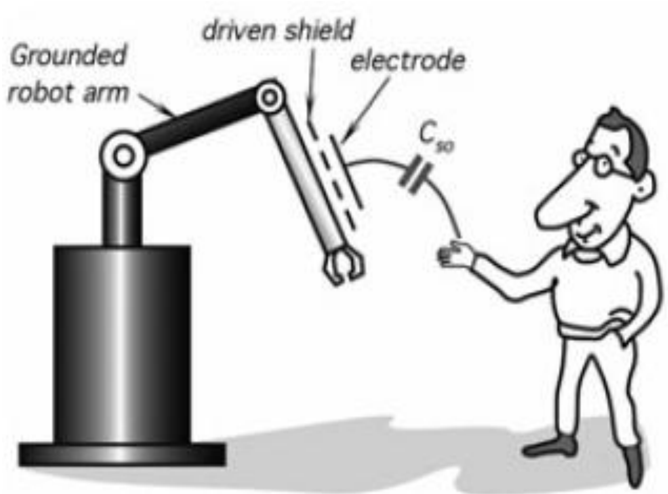
Example: Capacitive security system for an automobile

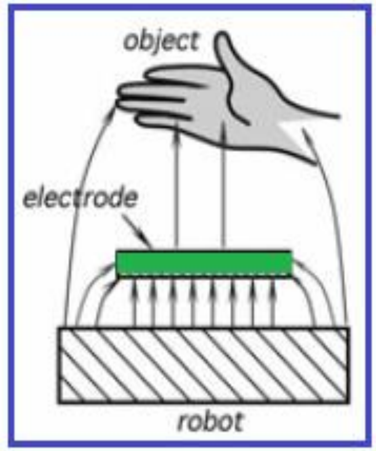
- A sensing probe is imbedded into a car seat to form one plate of a capacitor (Cp). The other plate of the capacitor is formed either by a body of an automobile, or by a separate plate positioned under a floor mat. A reference capacitor (Cx) is placed close to the seat probe.
- Both RC circuits have nearly equal time constants (τ_1).
- When a person is positioned on the seat, her body forms an additional capacitance in parallel with Cp, thus increasing a time constant of the R1Cp-network from (τ_1) to (τ_2).

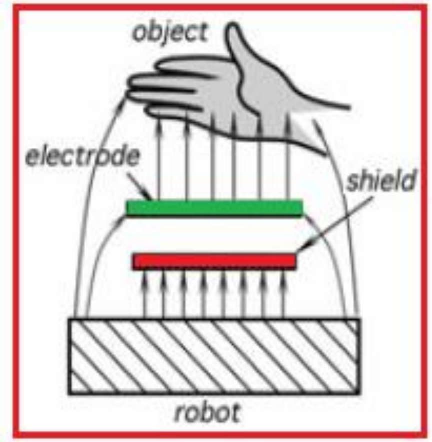


Example: Capacitive proximity sensor

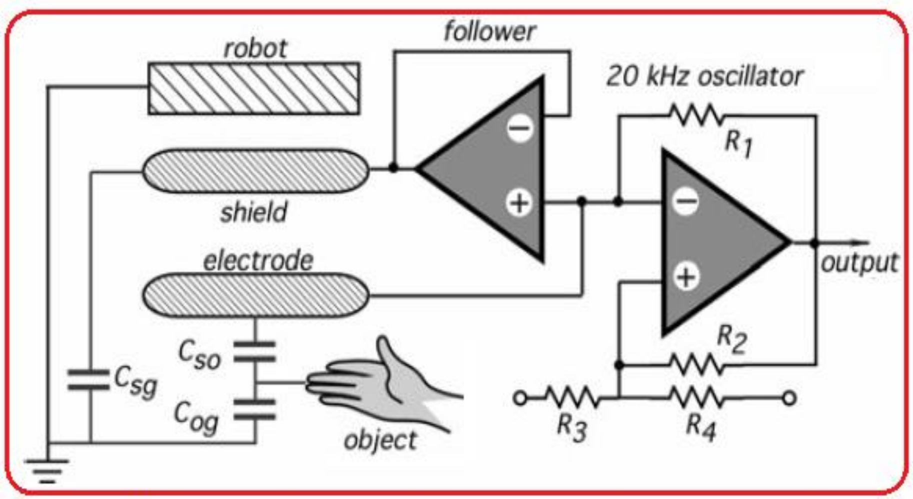
- Any object approaching the robot arm (an electrode) forms a capacitive coupling (C_{so}) with it. A coupling capacitance is used to detect the proximity.







- Without the shield, the electric field is distributed between the electrode and the robot, while a driven shield directs electric field toward the object.
- Oscillator frequency depends on the net input capacitance (Csg , Cso, and Cog).
- This circuit allows to detect proximity to conductive objects over the range of 30 cm.



Simplified circuit diagram of a frequency modulator controlled by the input capacitances

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