Automation in Manufacturing

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Week – 04
Sensors
Lecture – 02
Displacement, position and proximity sensors – I

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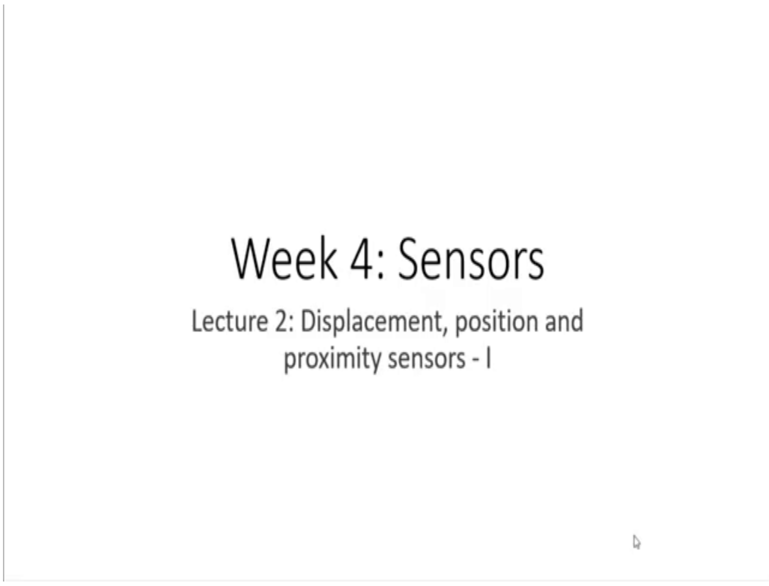

In this lecture we will be studying various Displacement, position and proximity sensors.

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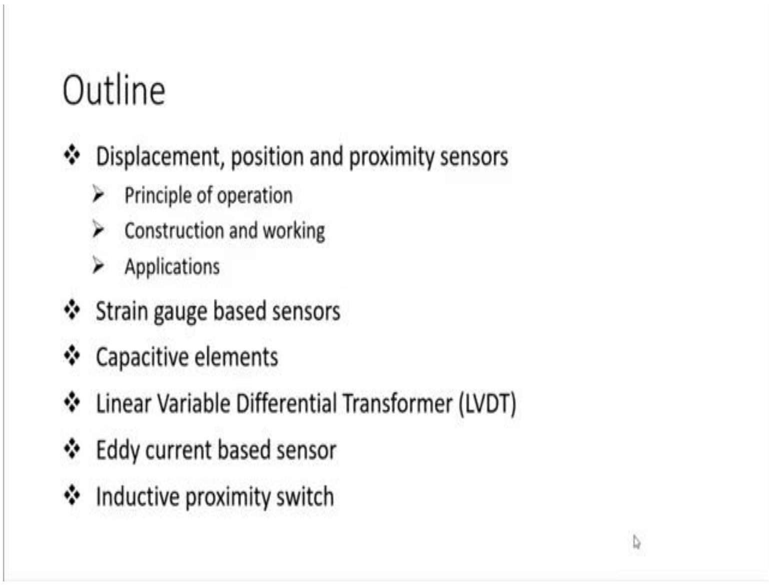

The outline of this lecture is as follows.We will be learning various sensors such as strain gauge based sensor, capacitive elements, LVDT that is linear variable differential transformer, eddy current based sensor and inductive proximity switch.

We will learn the principle of operation of the sensors, their construction details and we will study the applications of the sensors in the automation industry.

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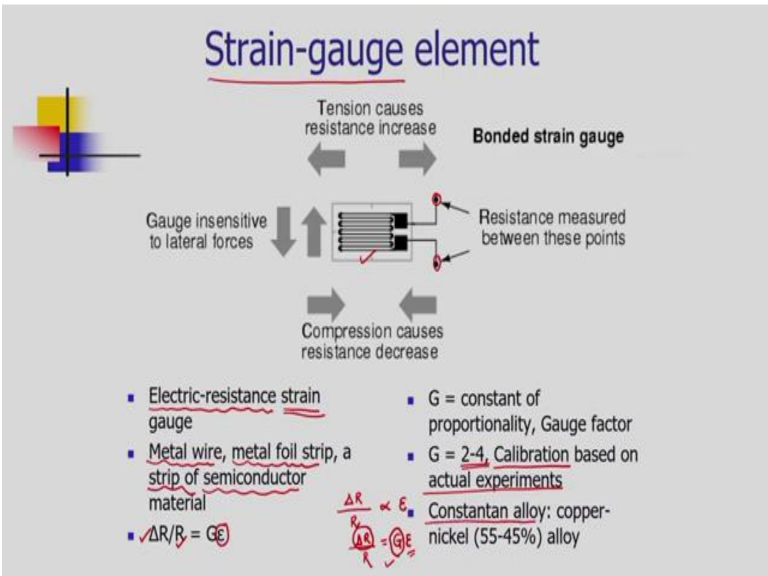

The next important displacement sensor is strain gauge element sensor; it works on the principle of change in resistance when we are giving tension or compression to a mechanical element.

We can see a simple arrangement of a strain gauge element. It has a foil which has two terminals and we are measuring resistance across these two terminals. This foil is attached to the mechanical element of which the strain is to be measured. When there is tension in the foil, then the resistance of that foil or the resistance of that mechanical element will increase; and when there is a compression, then the resistance will decrease.

It works based upon the principle of electrical resistance and is particularly measuring the mechanical strain inside the work parts or the body parts of automated system. Strain gauge sensors are available either in metal wire or metal foil strip form; the strain gauges are also made up of semiconductor material. The advantage of semiconductor material is that it has high gauge factor. The resistance is directly proportional to the strain. In strain gauge element, the ratio of change in resistance of the mechanical element to its original resistance is directly proportional to the strain that is developed in the mechanical element. The change in resistance due to the strain of the original resistance is directly proportional to the strain, and the constant of proportionality is called as the gauge factor.

In general the gauge factor is about 2 to 4 and it is decided by conducting the actual experiments in the laboratory, this is called the calibration process. In the calibration process, we are computing the gauge factor for known displacement and known strain inside the mechanical element. For a known strain, we are computing delta R that is change in resistance inside the coil or the foil and accordingly we are computing the G.

In general a gauge factor of 2 to 4 is noticed for the variety of mechanical elements. The most common material which is used as the strain gauge material is constantan alloy; it has copper and nickel in the proportion of 55 percentage of copper and 45 percentage of nickel.

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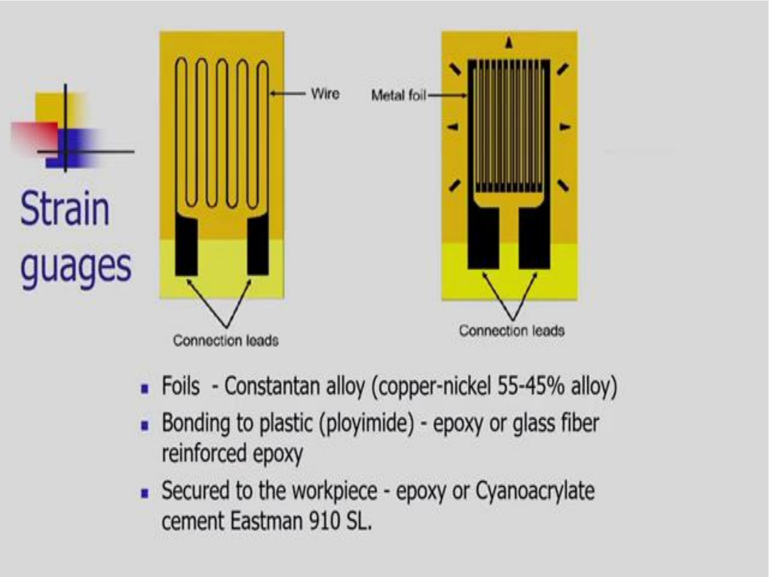

Two more pictures are there on the screen; in the first picture we can see a thin foil and on the thin foil, a wire is wound, which is attached.

In the second picture we are having metal foil. A foil is nothing, but a thin layer of the metal which is cut as per the required dimension. This foil is in continuous mode and it has the connection leads.

The foils are also made up of constantan alloy and the foils are of size of a postage stamp and we are pasting these posted stamp like strain gauges on the mechanical element of which we want to measure the strain.

The metal foils are attached to the plastic which is called the bonding to the plastic by using epoxy material or glass fiber reinforced epoxy material. And this entire strip which is having the metal foil or the metal wire and the plastic material is secured to the workpiece by using again an epoxy or a special material that is Cyanoacrylate cement Eastman of number 910 SL.

These are the materials which are helping us to paste the postage stamp size strain gauge elements on the machine tools or on the product of which we want to measure the strain or the displacement.

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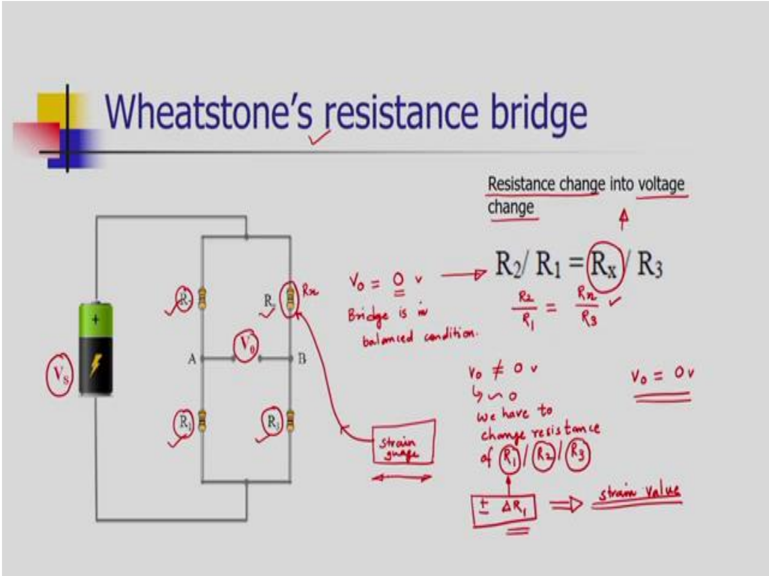

The strain gauge element is providing the passive output. Passive output as is producing the change in resistance; but for microprocessor processing, we need the active element, the voltage change in voltage; a pulse of voltage that is the digital signal that is useful for the microprocessor. For that purpose the resistance change have to be converted into voltage change.

To carry out these operations, Wheatstone's resistance bridge is used; a typical arrangement of the Wheatstone resistant bridge is shown on the screen. In this arrangement we are using four resistors R_1, R_2, R_3 and R_x. Supply voltage is applied across a bridge of these four resistors and an output voltage is measured across the two connections A and B. The values of these four resistors are chosen in such a way that, the V_0 that is output voltage should be 0.

When the output voltage is 0, then the bridge is in balanced condition. To have output voltage is equal to 0 volt; if you try to get the correlation between this resistor values, we get

$R_2 / R_1 = R_x / R_3$

To get 0 voltage, we are choosing R_2, R_1, R_3 and R_x. Now in the application of Wheatstone resistance bridge, we are attaching this R_x to our strain gauge leads. Let us attach our strain gauge at R_x. Whatever the output that is coming out from the strain gauge is the R_x value. For no load condition, the strain gauge is providing certain resistance that is R_x.

For R_x, we are choosing the value of R_1, R_2, R_3 such that this equation satisfies. But when this strain gauge is in action, when there is tension in the strain gauge; so the resistance of R_x is getting increased, there is change in R_x value due to the mechanical movement which is occurring that is strain. Thus, as R_x is increasing or it is changing; we are getting certain output at the V_o.

The output at V_o will not be 0 volts, it would be a nonzero output at this. To make it 0, we have to change the resistance of one of the other resistors which are R_1, R_2 or R_3. We have to change resistance of either of R_1 or R_2 or R_3. We can choose any resistor here. Let us consider if we have chosen; how much should be the change in R_1, so that we can achieve our condition that, V output is 0 volts.

This means we have to carry out the resistance change, it may be plus or minus; we have to add a resistance of plus or minus delta R into R_1, so that we are getting this condition. The change in resistance in R_1 resistor is the indicator of the strain. The change in resistance at R_1 to get output voltage equal to 0 is indicating the strain value inside the strain gauge .

In laboratory for known value of strain values, we can easily get the delta R_1 and in this way we can calibrate the strain gauges. When the Wheatstone resistant bridge is attached, a simple strain gage element sensor will be converted into a transducer.

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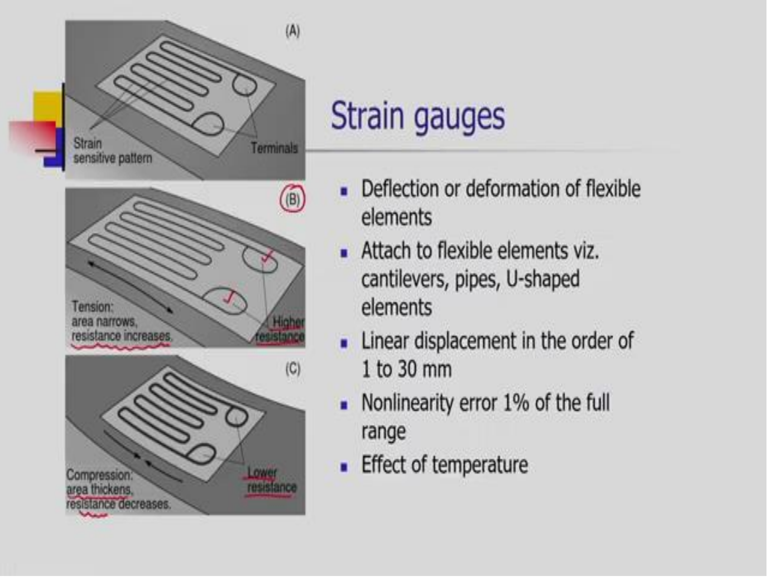

Some more pictures are there, which will clear the idea of the strain gauge. We can see the strain sensitive pattern and the terminals of a typical strain gauge.

Now, the figure B shows, when the tension is there, the cross section area is getting narrowed and the resistant is increasing. The higher resistance are indicated here. When compression is occurring along the length, then we are getting thickening of the area; the cross section area is thickening and the resistance will decrease.

Thus, we are getting lower resistance. The strain gauges are effective when there is a longitudinal strength along the length when the strain is occurring; then the strain gauges are working for the lateral application of the strain and are ineffective. The strain gauges are useful for measurement of displacement from 1 to 30 mm. However, they do have a nonlinearity error of 1 percentage and it is basically due to the temperature; because when the temperature is high, and the conditions are harsh, then the temperature will affect the material properties of the metal foil or the metal and that may lead to errors in the measurement of the strains.

These type of strips are attached to cantilevers, pipes, U shaped elements, and accordingly the strains are measured.

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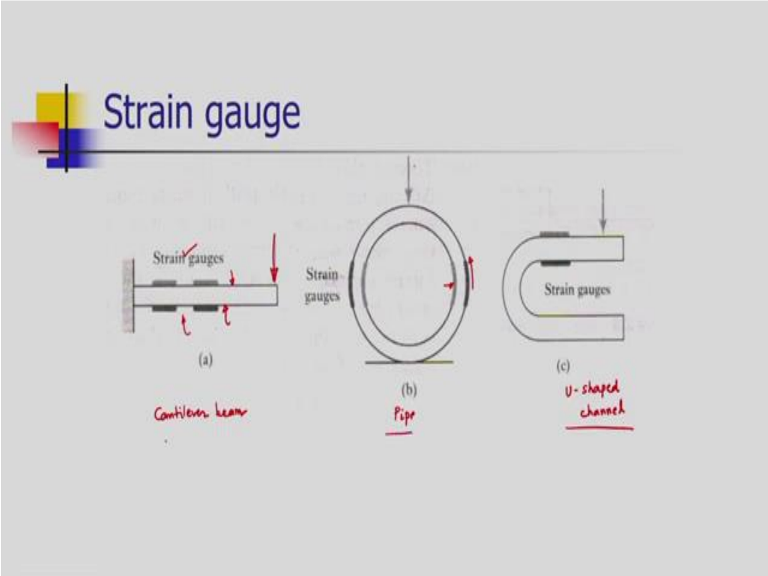

Now, on the screen we can see, how the vibrations are measured. If suppose we are applying a repetitive load at the cantilever beam here, the load is applied intermittently; then the strain gauges which are pasted on the top surface are experiencing tension due to the tension in the fiber of the top surface.

While the fibers which are there on the bottom surface of the cantilever are experiencing compression. The resistance value of the top strain gauges increases and the resistance values of the bottom strain gauges decrease. By monitoring the periodicity or by measuring the periodicity of the signals from the strain gauges for its increase and decrease, the vibrations value can be easily monitored or recorded.

Second is a pipe, a thick pipe. When we apply a load over a thick pipe; again we can find out the deformation in the thick pipe on its outer surface, and we can notice the tension. Increase in resistance and the inside strain gauges are measuring the compression. The third is U shaped channel which may be part of your mechanical system.

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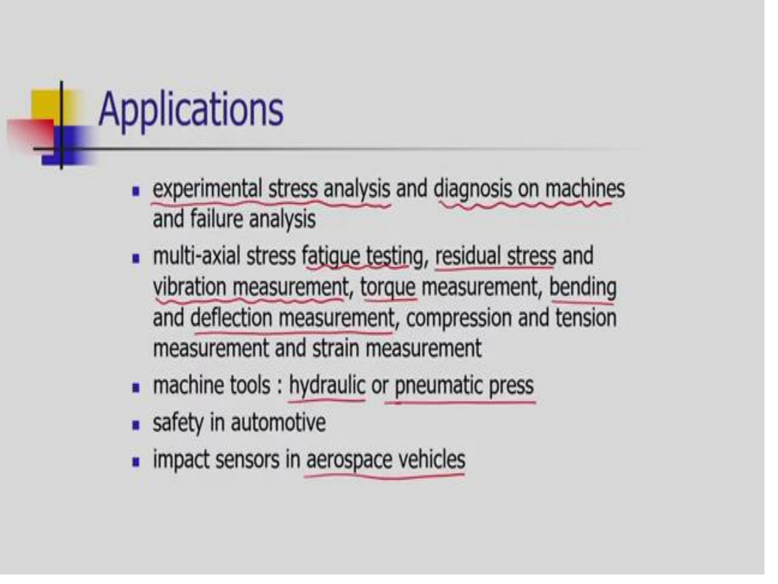

Basically strain gauges are widely used in experimental stress analysis. For stress analysis and for diagnosis of machine tools, strain gauges are widely used, particularly to measure the forces. Moreover for fatigue analysis, fatigue testing, stress analysis, vibration measurement, torque measurement, bending and deflection measurement the strain gauges are used.

In machine tools, particularly in hydraulic and pneumatic presses; since we are applying more pressure, more hydraulic pressure or more pneumatic pressure on the pipes or the elements of the systems, there may be strain and deformation in these mechanical elements. To monitor the deformation of these elements, it is very essential to paste certain strain gauges and get the output from them.

Safety in automotives, the very important feature of today's automotive is the airbags which are protecting during the collision. These bags are operated based upon the strain gauges. Impact sensors in aerospace vehicles are also an important application.

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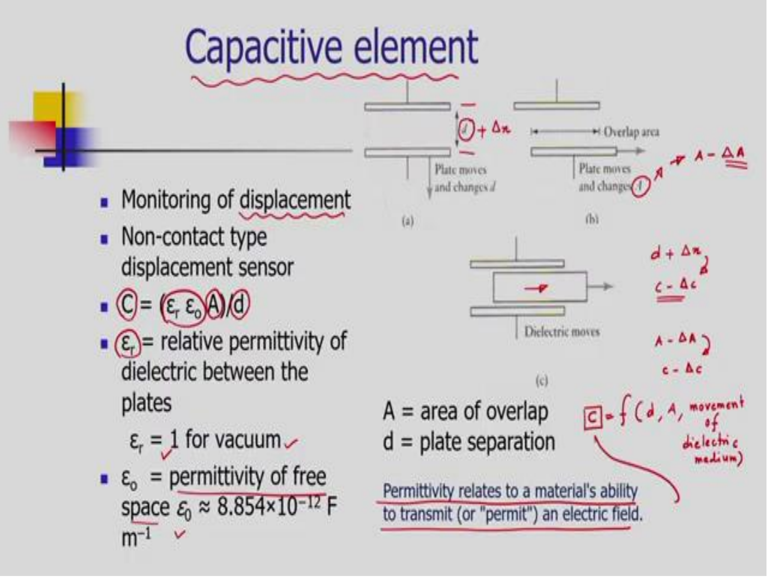

The next sensor is capacitive elements sensor; its advantage is that it is a non-contact type of sensor and used to monitor the displacement.

When two charged plates are in the vicinity or when two charged plates are closer to each other; then the capacitance developed in between these two charge plates is directly proportional to their area of overlap, and it is inversely proportional to the distance between these two plates. The constant of proportionalities are called as the relative permittivity of dielectric between the plates and the permittivity of free space.

Permittivity basically relates to the materials ability to transmit an electrical field. We are having two charge plates and there is a material or a medium in between these two charge plates. The ability of this medium to permit an electrical field is nothing, but the permittivity.

Here we are considering ε_r is the relative permittivity of the dielectric medium between the plates and it is considered as 1 for vacuum; whereas ε_o is the permittivity of the free space.

These useful principles can be utilized for measurement of the displacement in our domain that is manufacturing automation. On the screen we can see configuration, there is a top plate and there is a bottom plate and these two plates are separated by a distance

d. There is overlap of A between these two plates. When this separation is increased by Δx i.e. d+Δx, then the capacitance is changing.

Thus we get c-Δc. If we are increasing the overlap area or decreasing the overlap area that is also affecting on the capacitance. The area in this case is reduced. The area is reduced by an amount ΔA, thus A - Δ A will also reduce the capacitance.

Let us consider one of these plates is attached to the mechanical element in our domain; then by changing the separation or the overlap area, we can easily measure the change in capacitance. Change in capacitance is the passive output; we have to convert the change in capacitance into the change in voltage value. The third case in capacitive element may be the moment of the dielectric medium itself.

As we are moving the dielectric medium, we are getting the change in capacitance value. The capacitance is a function of separation distance, area of overlap and movement of dielectric medium. This change in capacitance is further utilized to get the displacement.

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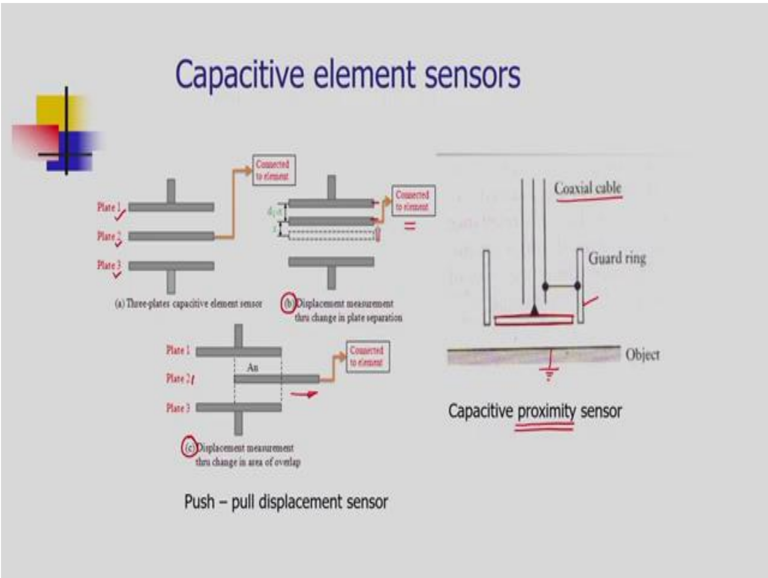

We are taking three plates; plate number 1, plate number 2 and plate number 3. Now the second plate is attached to the element of which we need to measure the displacement.

In this figure b, we can see the middle plate has been moved in a upward direction which is closer to the top plate. When we are moving it towards upward direction, there is increase in separation dip distance between plate number 2 and plate number 3 and there is decrease in separation distance between plate 1 and plate 2.

As the principle of the capacitive element sensor is suggesting when the separation distance is decreasing; there is an increase in the capacitance between plate 1 and plate 2 and there is decrease in capacitance between plate 2 and plate 3 or somebody will use the movement of the plate number 2 in a lateral way.

When plate is moving in a lateral way, the area of overlap is getting changed. In this case the complete area of plate 2 is being overlapped by plate 1 and plate 3; however, there is only half area which is being overlapped with plate 1 and plate 3. Thus, naturally there is a decrease in capacitance.

The decrease in capacitance can directly be calibrated to the displacement. The capacitive element sensors are widely used as proximity sensors. In this case, we are using a simple arrangement. We are using a coaxial cable and there is a guard ring, which is protecting the coaxial cable. At the end of the coaxial cable we are attaching a plate, which is the charge plate. When this charge plate comes closer to object which is the earth object connected to the earth.

Then the capacitance between these two objects will change and that triggers a signal which may be utilized to take the action. Consider these kind of sensors are used as a proximity for automated guided vehicles, which are mounted on the front side of the automated guided vehicles; when the split will come in the proximity or vicinity to an object, it produces a signal and that signal will stop that vehicle.

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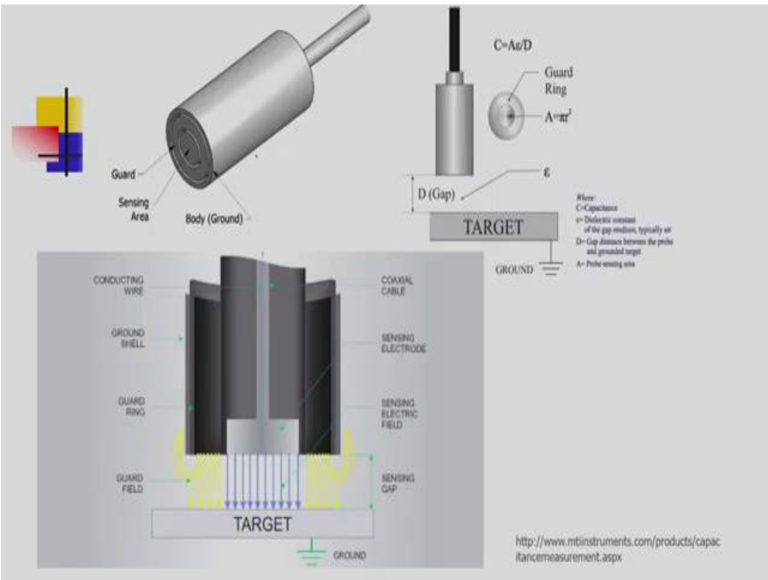

A typical industrial construction of these capacitive sensors are shown. This is the sensing area which is small; however the sensing area is guarded by the guard area, and the guard construction and the sensing construction are enclosed in a body. Capacitive proximity switches are working with target, only condition is that the target should be grounded. When these capacitive sensors are coming closer to the target, it produces the signals.

A charge is applied to the coaxial cable and when they are coming closer to a target; then there is a change in capacitance which will be useful to generate the signal.

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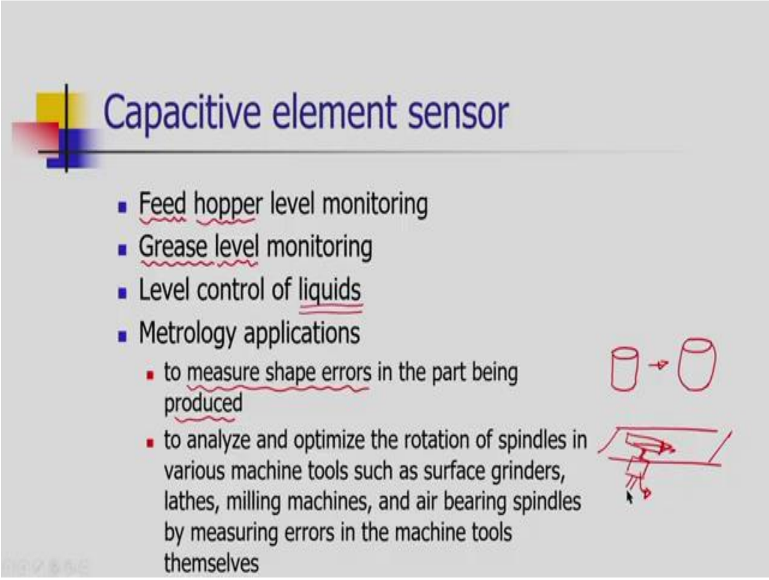

What are the applications of capacitive element sensor? They are used to monitor the feed in hoppers. Hoppers are nothing, but a material handling device through which the commodities inside automated system are fed. Let us consider an injection molding; the hopper is nothing, but a conical flask which is mounted on the injection molding machine, through which we are feeding the granules of the polymers inside the mold area.

The machine tools or the machineries which are used in automation, need to be continuously lubricated. For that purpose the grease is being used and to monitor the grease level, the capacitive element sensor is used. Then liquid level also can be monitored using capacitive element sensor.

Capacitive element sensors are very useful for metrology applications. When the shape errors in the part is to be measured; then the capacitive element sensors are useful. Let us consider a cylindrical part that to be manufactured by using the casting. However, due to manufacturing errors, we have not achieved a proper shape of the casting; for example there is a bulge in the casted component.

When such component is moving over the conveyor; this bulge is easily sensed by the capacitive element sensor. If these kind of atoms are moving over the conveyor continuously, the capacitive element sensors are mounted over here. When these elements are moving, there is a constant gap or the known gap; when there is an abnormality or non-uniformity or error in the shape,these known gap will be changed.

And that known gap will trigger signal inside these capacitive elements. This will be useful to monitor the product shapes during the manufacturing operation. Moreover, they are used to monitor the rotation of the spindle in various machine tools that is in the health monitoring of the machine tools such as grinders, lathes, milling machines.

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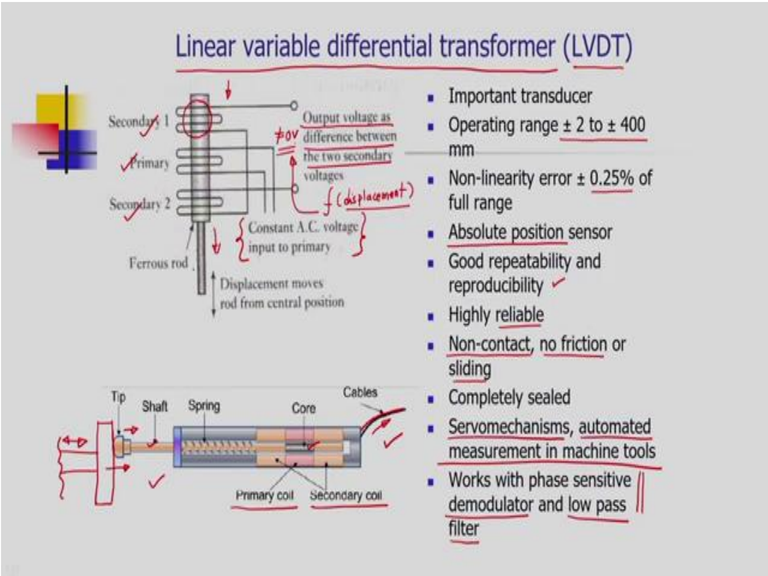

The next important and useful transducer which is used in automation is linear variable differential transformer and it is widely known as LVDTThese kind of sensors are used to measure the displacement between plus or minus 2 mm to say about 400 millimetres; these sensors has non-linearity error of 0.25 percentage.

The principle of operation is very simple. In linear variable differential transformer, three coils are used; the first coil is the primary coil; then a set of secondary coils, secondary coil number 1 and secondary coil number 2.

These three coils have equal number of turns; constant alternating current voltage is applied to the primary coil. And the secondary coil number 1 and second coil number 2 are attached or connected in such a way that their output voltage difference is zero.

There is a phase change in the connection of secondary coil number 1 and secondary coil number 2. Inside these coils, a ferrous rod is moved . When this ferrous rod has equal overlap with secondary coil number 1 and secondary coil number 2, then 0 output voltage is obtained.

When constant AC voltage input is applied to the primary coil, it generates alternating magnetic field; that alternating magnetic field will generate the electro motive force in secondary coil number 1 and secondary coil number 2 through the ferrous rod. When the overlap of ferrous rod one in secondary coil number 1 and secondary coil number 2 is equal; then the output voltage is obtained as 0. Why it is 0? Because the secondary coil 1 and secondary coil 2 are connected in opposite direction.

Their magnitudes are same, but the signs are different opposite. Now, how the displacement is measured by using LVDT sensors? The ferrous rod which is generating the resultant emf across the leads or the connections of secondary coil 1 and secondary coil 2; that ferrous rod is attached to the mechanical element of which we want to measure the displacement.As the rod moves in a downward direction; then the overlap of ferrous rod one in secondary coil 1 is reduced, while the overlap in secondary coil number 2 is the same constant.

As the overlap in coil one is reduced, the emf generated in coil number 1 will also be reduced. In this way nonzero voltage is obtained at the output. This nonzero voltage at the output is the function of the displacement.

LVDT is again calibrated in the laboratories; for known displacement, we can get the generation of the voltages in these coils. A typical construction of LVDT which is used in the industry is shown in the next figure; we can see a set of secondary coils and a primary coil, and the core is attached to a shaft.

The shaft is having a tip; the shaft is spring loaded so that we can measure the displacement. And after measuring the displacement of the tip, it will regain its original position. Thus, to go to its original position, the springs are used.

The output will be taken through cables and further the output will be processed, signal conditioned and then it will be sent to the microprocessor. The tip is in contact with the mechanical elements; consider we are having a plate which is connected to some mechanical element.

And as there is a moment of this mechanical element, this plate will push the tip and accordingly we are getting signals in the cables. The absolute position can be measured by using the LVDT sensors. These sensors have good repeatability and reproducibility and they are highly reliable. The construction has no contacts.

There is no friction or there is no sliding. There is no wear and tear of its construction elements. The cores do not have contact with the coils, so it is non-contact. The measurement mode is the contact; so these tips are to be in contact with the mechanical elements or the machineries. LVDTs are used in servo mechanisms, automated measurement of machine tools.

We need to have the phase sensitive demodulator and low pass filters to know in which direction the rod is moving. How can we say the ferrous rod moving in upward direction or the downward direction? For that purpose, the phase sensitive demodulator is used; and to have a quality signal, low pass filters are used in addition to the LVDT sensors.

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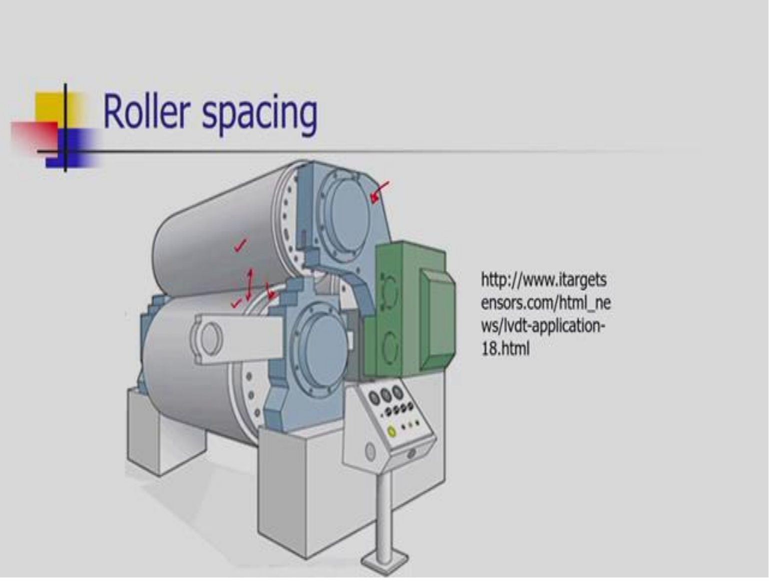

What are various applications of the LCDT sensor? We can see a mill, the mill has two rollers and this mill is used to reduce the thickness of a metal sheet. There is an arrangement here to adjust the spacing between these two rollers.To adjust the spacing between these two rollers, we have to mechanically move the upper roller with respect to the second roller which is at the down side.

When we move mechanically, we have to monitor whether the movement is appropriate, whether the movement is desired. To monitor this movement, LVDT sensors are used. If there is more movement or excessive movement of the upper roller, the quality of the product will be affected. To restrict that extra movement due to the inertia of these rollers, the LVDT sensors are used.

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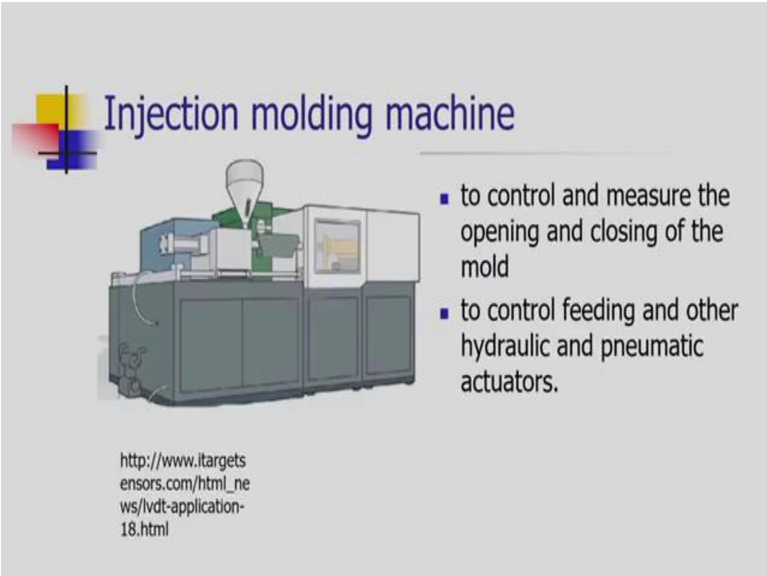

The next example is an injection molding machine, this is used to manufacture plastic components. In injection molding machine, we have molds which are having two parts;, so we should have a precise opening and closing of the molds. For that purpose, we have to control its operation; the molds' inertia and weights are also very high.

To have the control movements, the LVDT sensors are used. In addition to the injection molding operation; to control the feeding and the other hydraulic and pneumatic actuators, the LVDT sensors are also used for feeding mechanisms and hydraulic pneumatic actuator.

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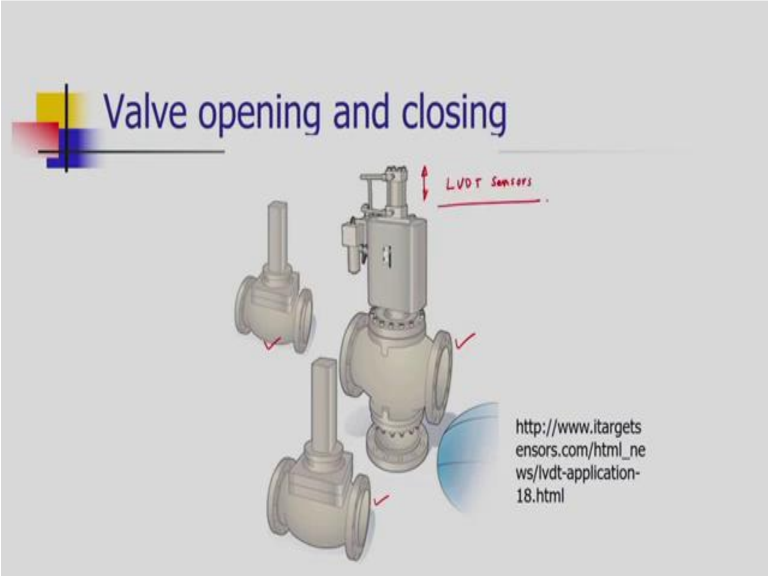

There are very huge size valves which are used for controlling the direction of the fluids, the water. To control the flow of water, these huge types of valves are used. These valves' openings and closing are operated by using an electric motor; when these electric motors are operating , there is movement of its spools.

When the spools are moving, we need to continuously monitor the movement of the spools to have the precise control over the valve opening and closing. For that purpose,the LVDT sensors are used.

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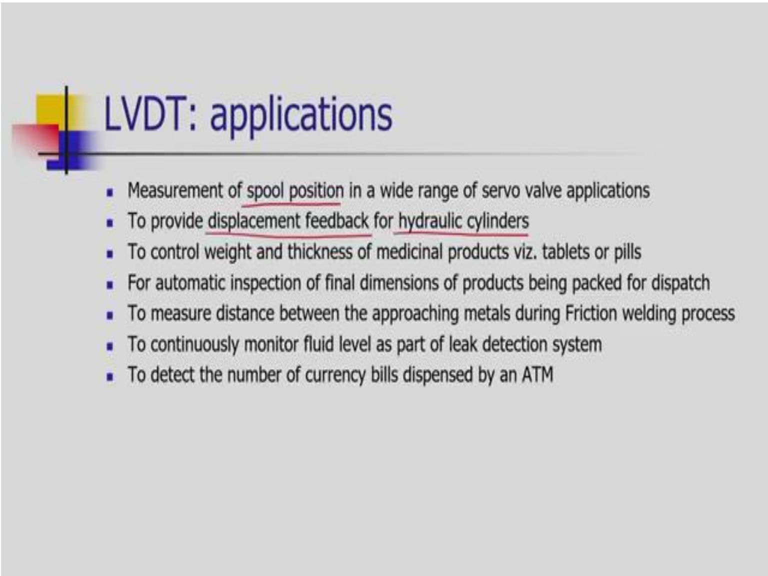

Another application is the spool position measurement or control of spool position. Then displacement feedback in hydraulic cylinders; because hydraulic cylinders are being operated by high pressurized fluid.

Based on the viscosity of the fluid, there may be chances of having over travel. To control the over travel, LVDT sensors are used. LVDT sensors are having very important application to control the thickness of the tablets and pills in pharmaceutical industry to manufacture the medicinal products.

To have the precise thickness, LVDT sensors are used; if the tablet or the pills do not have the precise thickness, they may be discarded. Then to automatically inspect the final dimensions of the products, these sensors are used.

In friction welding process, we need to control the distance between the two metal sheets which are to be welded. The precise moment of the one plate with respect to the other plate is monitored by using LVDT sensors. Then in leak detection system as well, the LVDT sensors are used, where the fluid level is continuously monitored.

In currency bills which are dispensed at the automated teller machines, so the number of currency bills that are to be dispensed are sensed by using the LVDT sensors.

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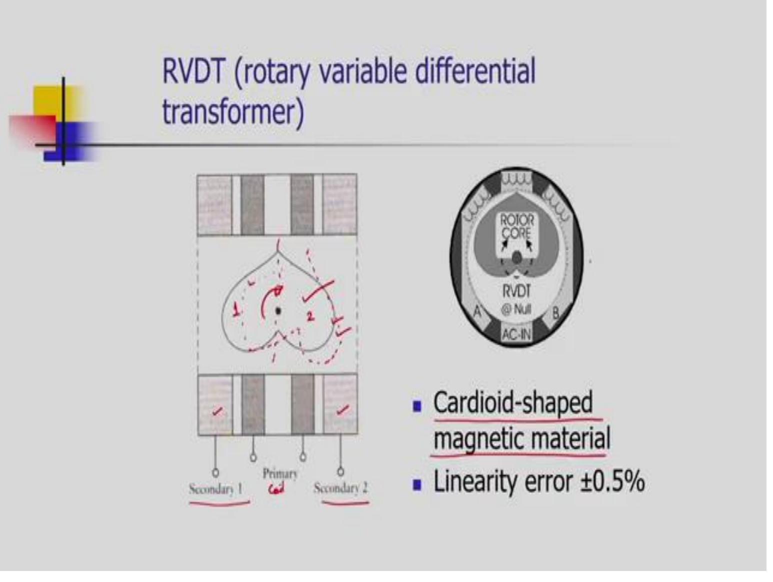

In the linear variable differential transformers, the lens are quite long. And in many cases, that long length linear variable differential transformers are not that convenient.

There is another variation of linear variable differential transformer and that is used to measure the angular velocity. Instead of having the linear variation, the rotary variation is used, the cores are rotating instead of moving in a linear way.

An arrangement of RVDT that is rotary variable differential transformer is shown on the screen; the construction is very interesting, it has cardioid shaped magnetic material core which is the cardioid shift magnetic material. We are having a primary coil and a set of secondary coil that is secondary coil number 1 and secondary coil number 2. The principle of operation is very similar to the LVDTs.

As we rotate the core, we may get difference in the overlap of the core with secondary coil number 1 and secondary coil number 2. Due to the difference in overlap, there is nonzero voltage at the output, and that nonzero voltage is nothing, but the indication of angular motion of the shaft or the pin to which it is attached. This is the ideal position or the normal position,.

The portion 1 and portion 2 has the equal overlap with secondary coil 1 and secondary coil 2. As the cardioid shaped magnetic core is rotating, then there is more overlap for the secondary coil 2 than secondary coil 1. A typical construction is shown in the second diagram; these sensors are having a linearity error of about plus or minus 0.5 percentage.

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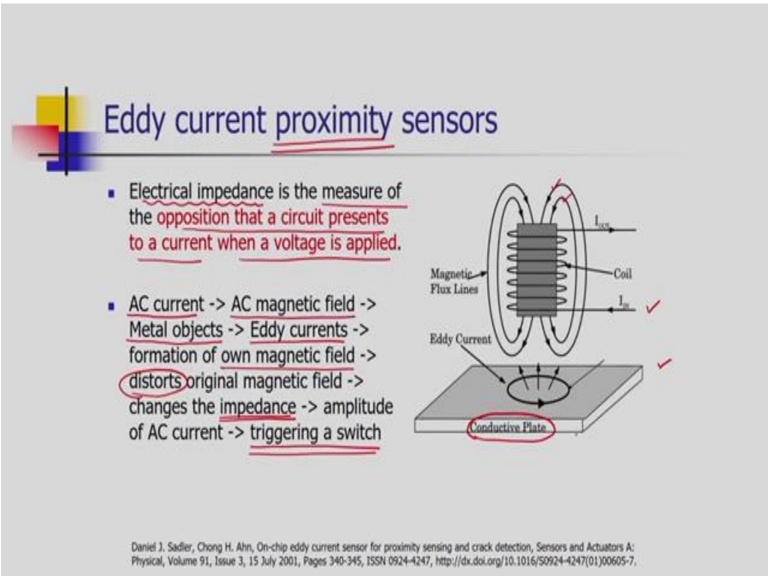

The next proximity sensor is eddy current type proximity sensor and it works on the principle of electrical impedance. Impedance is the measure of the opposition that a circuit presents to a current when voltage is applied. Consider a circuit in which the current is flowing; when the voltage is applied , the circuit will oppose the current. This is called as the electrical impedance.

By using this property, a proximity sensor is designed and developed and that is called as eddy current sensor. There is a coil which is wound over a core. An alternating current is applied to this coil and due to that alternating current; magnetic flux is generated. When this alternating current carrying coil is coming in the vicinity of a conductive plate; then eddy currents are generated. The AC current is applied. We are getting AC magnetic field; which when comes in close vicinity of the metal objects, eddy currents are generated. These eddy currents will generate their own magnetic field and that field which is generated due to the eddy currents will distort the original magnetic field or the parent magnetic field.

Change in magnetic field of the coil will change the impedance. So, what is impedance? A voltage is applied and that is creating the opposition to flow of the current. This change in impedance will trigger a switch. In this way, conductive elements or a conductive plate or conductive materials can easily be detected by this eddy current based proximity switch.

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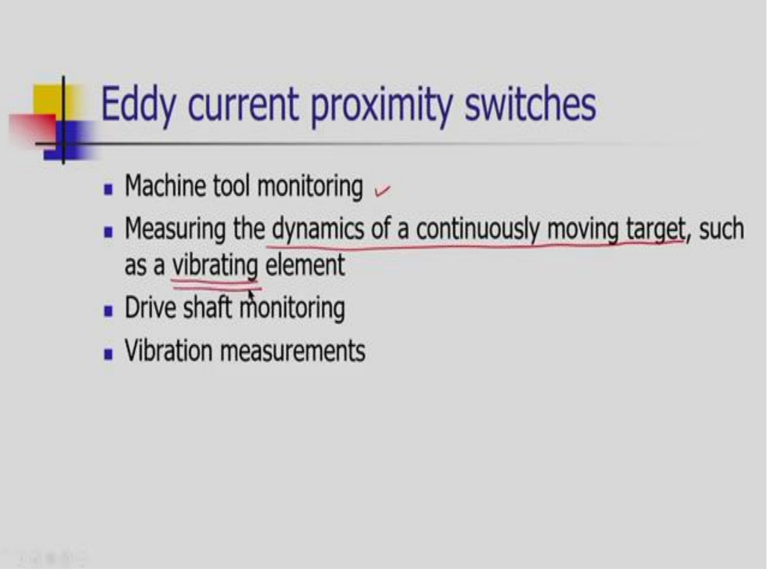

Various applications of the eddy current proximity switches can be seen on the screen; these are used to monitor the machine tool performance. The eddy current proximity switches are very useful to continuously monitor the moving targets and that is the vibrations.

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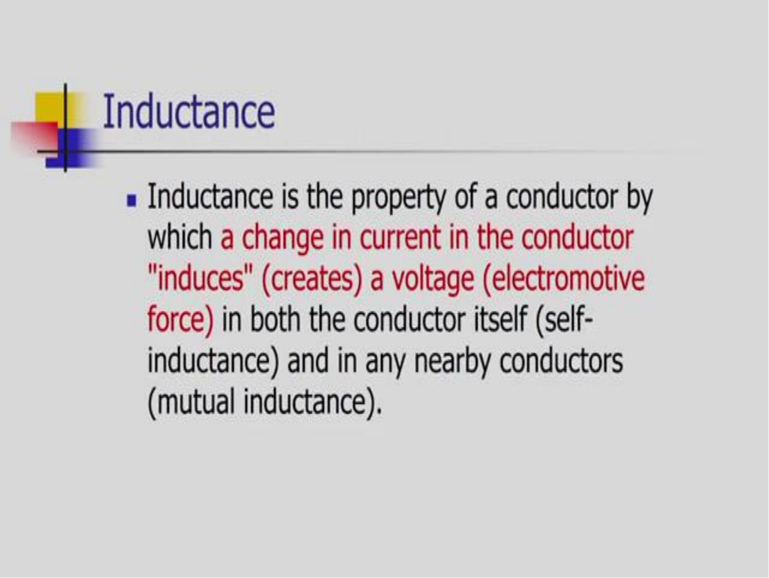

The next electrical property which is helping us to design a sensor is inductance, which is useful to develop a sensor.

It is defined as the property of a conductor by which a change in current in the conductor creates a voltage emf electro motive force in both the conductor itself and any nearby conductors. The change in current is creating voltage; if we are getting the change in voltage in the conductor, it is called as self-inductance. And if it is created in nearby conductors, it is called as mutual inductance.

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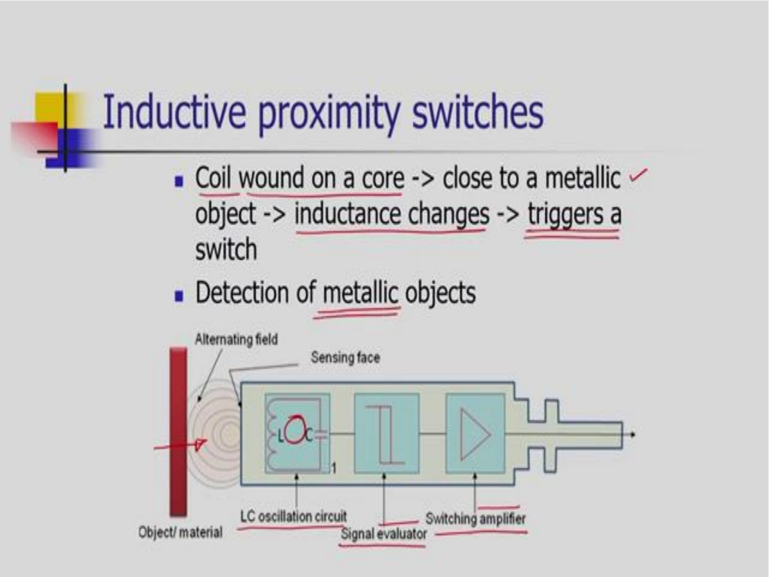

This electrical property is helping us to develop inductive proximity switch. A typical construction is shown on the screen. We are having the LC oscillation circuit, inductance capacitance oscillation circuit; then there is a signal evaluator and then switching amplifier. Evaluator and amplifier are signal processing devices. When inductive proximity switch comes in vicinity of object of material, an alarm is generated.

Inside the inductive proximity switches, there is a coil which is wound on a core; it comes close to the mechanical object which are metallic, there is a change in inductance and that change in inductance is triggering the switch. As the metallic objects are coming close to the sensor, there is a change in inductance of the circuitry and that is triggering.

Basically to detect the metallic objects, the inductive proximity switches are used.

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Various applications are there, these are used to count the products which are moving on the conveyers; but this product should be made up of the metals. Inductive proximity switches are very widely used in security for the detection of the metal objects, arms and landmines.

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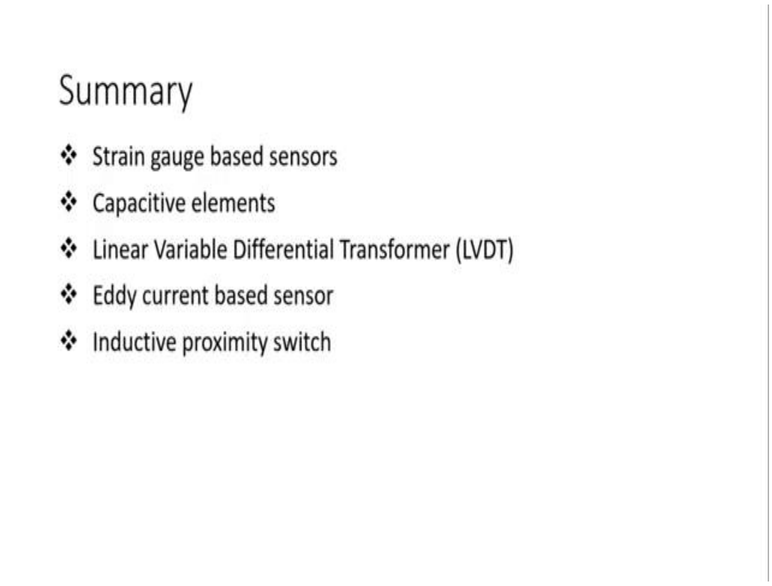

In this lecture we have seen the construction details of strain gauge based sensor, principle of operation and the applications of the sensors. Then we have seen the capacitive element sensors; LVDTs that is linear variable differential transformer, a very useful sensor in the automation industry, Eddy current based sensor and inductive proximity switch.

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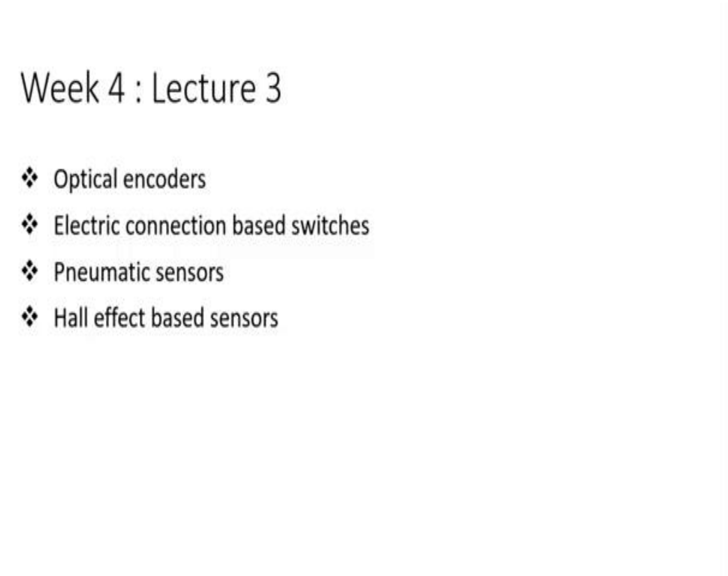

In the next lecture that is lecture 3 of week 4; we will be learning a variety of other sensors such as optical encoders, electric connection based switches, pneumatic sensors and Hall effect based sensors. Thank you.