

**Industrial Instrumentation**  
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**Lecture - 11**  
**Capacitance Transducers**

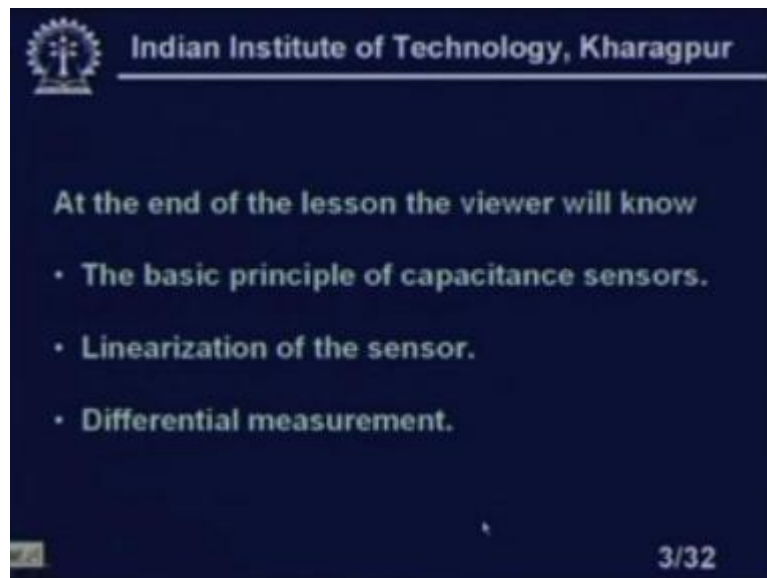
This is lesson 11 of Industrial Instrumentation. In this lesson we will study the capacitive transducers.

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You see, the capacitance transducers, the contents of this lesson - capacitance transducers as a whole, displacement transducers. Capacitance transducers in the sense that the basic principles of the sensor we will discuss and capacitance transducers are basically used as displacement transducers, level gauge or level sensor both liquid and solid, differential pressure transducers, because this differential pressure transducers are utilized in the, we will see later on in the flow measurements, the DPT or differential pressure transmitter is basically a differential capacitive transducer. Then, we have pressure pick up. We will also discuss the pressure pick up as well as we will solve some problems also, right?

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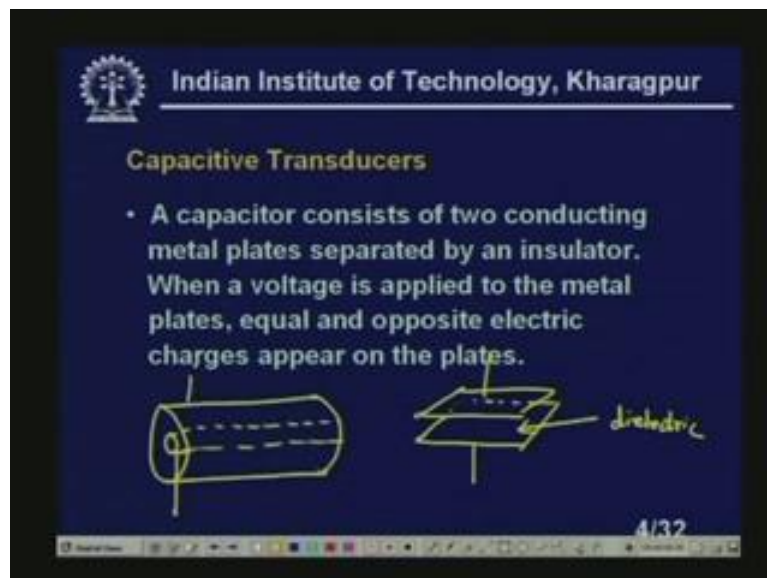
At the end of the lesson the viewer will know

- The basic principle of capacitance sensors.
- Linearization of the sensor.
- Differential measurement.

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And at the end of the lesson the viewer will know, viewer will know the basic principle of capacitance sensors, linearization of the sensor, differential measurements, right? This basically we will discuss in this.

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**Capacitive Transducers**

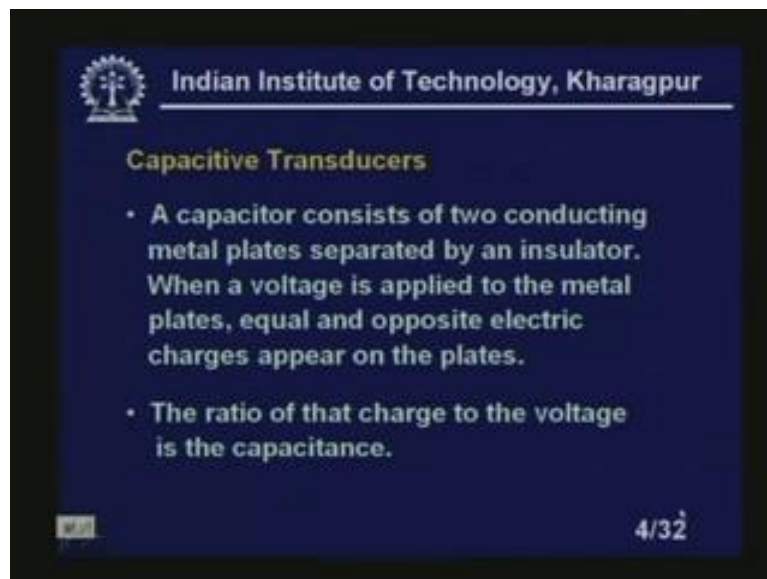
- A capacitor consists of two conducting metal plates separated by an insulator. When a voltage is applied to the metal plates, equal and opposite electric charges appear on the plates.

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Now, see the capacitive transducers, a capacitor consists of two conducting metal plates separated by an insulator, right? These metal plates can be either a, just a rectangular plates, very thin rectangular plates or it can be a cylinder also. It looks like that you see it can be a two, just two parallel plates like this one. It could be two

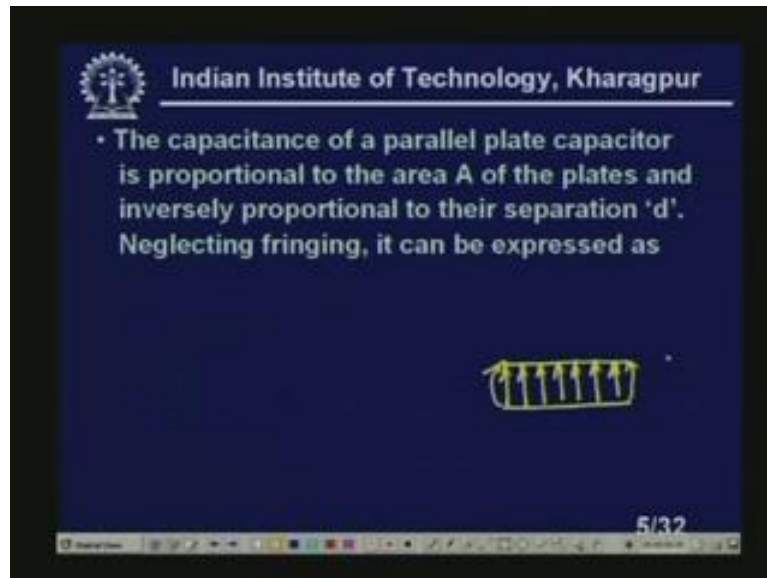
parallel plates, in between we have a dielectric, right and so it happens that a capacitor consists of two conducting metal plates separated by an insulator or dielectric medium. When a voltage is applied to the metal plates equal and opposite electric charges appear on the plates, right and interestingly this can be a, these plates can be a cylinder also. That we will see in, I mean later on. It is not necessarily, it can be a, it should be rectangle, it can be circular also, the plates might be cylinder also. That means it can have a sensor like this. One plate is like a one cylinder like this one and inside there is another plate which looks like this. So, this is another. So, we can take out the, from here and here two terminals and if you measure the capacitance, this is also a capacitance sensor.

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The ratio of that charge to the voltage is the capacitance.

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Now, see the capacitance of a parallel plate capacitor is proportional to the area  $A$  of the plates. Area can be anything, can be the, can be circle, can be, can be a cylinder and inversely proportional to their separation  $d$ . Separation between the plates are  $d$ . In the case of cylinder it will be separation which is the difference of the outer and the inner radius of the two plates and neglecting fringing, you know the fringing effect is there always in the capacitance. If we express, that means it lies that if you have two plates always it will be like this one.

Suppose I have plates, two plates, so the lines will be like this one and the end, since it will repel each other, so it will be straight, but this will be like this one. So, if we, this is called the fringing effect and actually the, for the fringing effect exactly you cannot get, I mean mathematical expression for this fringing effect. But, if you neglect the fringing, then the mathematical expression of the capacitance looks like this.

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- The capacitance of a parallel plate capacitor is proportional to the area  $A$  of the plates and inversely proportional to their separation ' $d$ '. Neglecting fringing, it can be expressed as

$$C = \epsilon_0 \epsilon_r \frac{A}{d} F, \dots \dots (1)$$

Where  $\epsilon_0$  is the permittivity of free space (a vacuum) with a value of  $8.854 \times 10^{-12}$  F/m,  $\epsilon_r$  is the dielectric constant of the material in the gap. (For air  $\epsilon_r = 1$ ).  $A$  is in (meter)<sup>2</sup> and  $d$  in meters.

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C equal to epsilon naught into epsilon r A by d Farad. F is farad. This F is basically Farad and where epsilon naught is the permittivity of free space; it is a vacuum and with a value of 8.854 10 to the power minus 12 Farad per meter. Epsilon r is the dielectric constant of the material of the gap. For air, epsilon r is equal to 1 and A is the area. So, it should be in meter square and d is in meters, right?

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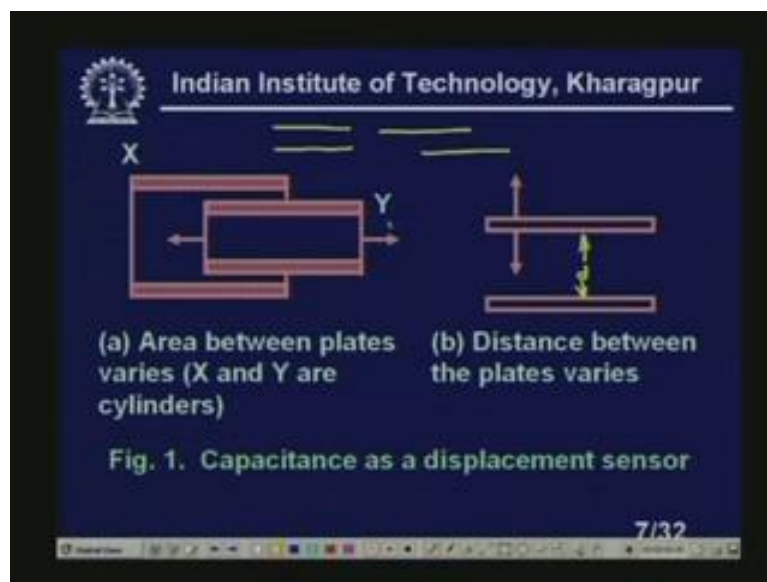
- Thus capacitance is a function of shape and size and permittivity and alteration of  $A$ ,  $d$  or  $\epsilon_r$  causes a change in capacitance as shown in Fig 1. If we can measure the change in capacitance value, it can be utilized as displacement, level, differential pressure sensor.

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The capacitance is a function of a shape and so, we can see that capacitance is a function of a shape and size and permittivity and alterations of  $A$ ,  $d$  or epsilon r

causes a change in capacitance as shown in figure 1. We will show the figure 1. So, that means you can see that if either of this one, either A, d or epsilon r changes, we will get the change of capacitance. See, if you measure this capacitance value either with a bridge or some LCR meters, so that change can be utilized to make it a displacement sensors, pressure pick up and level gauge. So, these are the basic, three basic applications of the capacitive transducer. See, if we can measure the change in capacitance value it can be utilized as displacement, level and differential pressure sensor. This actually I want to tell.

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Now, here you see there are various types of capacitance we have shown. These are basically as a displacement sensor. You see, the two area between the x and y are cylinders. You see this x and y are cylinders basically, x and y and you see the dielectric medium might be air also. There is no problem. So, if I push it this way, you see if I push this y, x is the fixed plate, x is the fixed plate and y is the movable plate. These two can be cylinders. If I push it like this one it can be simple parallel plates also.

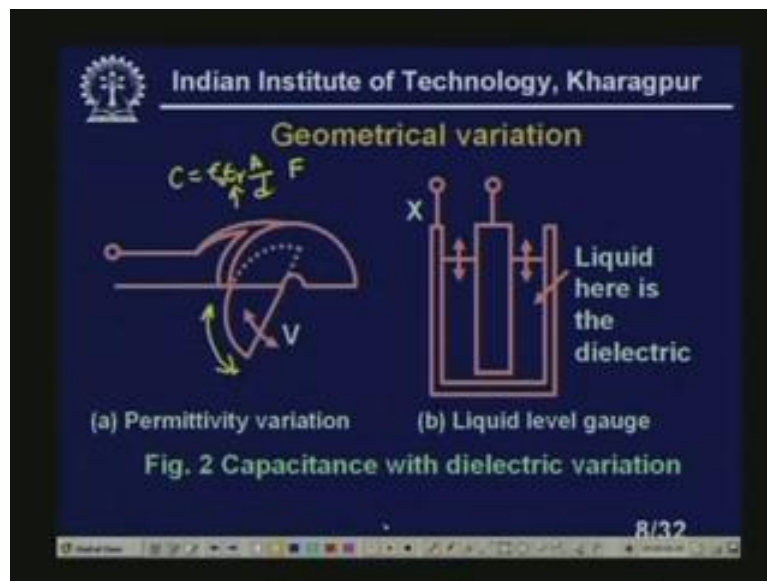
Suppose I have two parallel plates, right? You see here, suppose I have a parallel plates, two parallel plates and if I shift this parallel plate, suppose previously it was in this position, now we have shifted to this position. So, area between this one has changed, is not it? Previously the area of cross section was A, now it will be less.

Only this much of area is there. So, we can see that the, excuse me, that capacitance has been changed due to the change of area.

Instead of taking plates I can take two cylinders also; so, where if I vary  $y$  that means this way, so the capacitance value will change. This capacitance change can be measured by some LCR meter or by some bridge, so that capacitance change can be calibrated in terms of the displacements; as simple as that. Now, you see that  $d$  can be varied also. That means the separation between the plate, this is the separation. This is actually if you look at, this is  $d$ , right? This is our  $d$ , so that  $d$  can be changed also. If I change  $d$ , obviously what will happen? The capacitance will also change. The more the value of  $d$ , so the less will be the value of the capacitance. So, quite obviously this can be also utilized to make a displacement sensor, right? So, here the area between the two plates changes. Plates can be either plates or can be, it can be two cylinders. Here the distance between the plates vary, so both way the capacitance change will be there. So, that can be utilized to make our displacement sensor.

Now geometrical variation, you see, here actually what will happen?

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You see instead of, instead of the displacement between the plates or the area between the plates, now the permittivity between the, or dielectric medium between the two plates are varied. You see here, actually these are the two plates. Actually this is the,



those who are familiar with the heterodyne receivers, you know that in the heterodyne receivers we are, our radio receivers, we change the capacitance value to tune different radio stations. So, basically what will happen? There, actually I am changing the permittivity between the two plates, because this plates if you look at very carefully on the, on this one, see these plates, you see here these plates, these moves. This is a dielectric medium. It might be plastic also, insulator. So, obviously dielectric medium must be an insulator. So, this will vary in this position. So, the plates are fixed. If the plates are fixed neither area between the plates changes; so, only the dielectric medium changes.

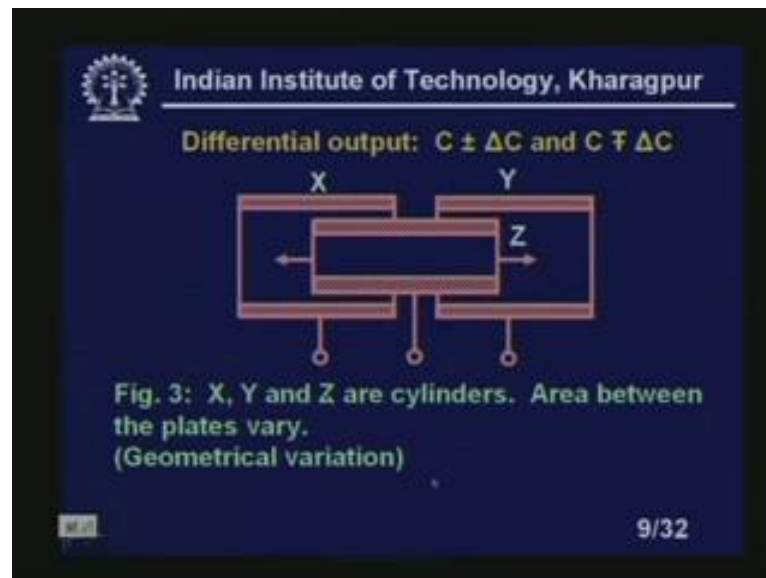
So, what will happen? If I take it out you see that the, there will be more air between the two, two plates and there be less, less the plastic, I mean that between the plates and if I move it this side, so because it is a semi circular plate, entire separation between the two plates will be filled up by this plastic. So, the epsilon r, if you look at  $C$  equal to  $C_{naught} \epsilon_r A / d$  what we said in Farad, so this epsilon r will change. So, this epsilon r it changes. So, obviously I will get a different value of the capacitance. Here actually what we are doing that we are changing the permittivity between the medium, right? So, by changing the permittivity, either permittivity or area or displacements, I can get the capacitance sensor.

Here you see, in the, this is another example of a liquid level gauge. You see the, it is, cylindrical in shape, right and we have a one inner rod also, right? So, this inner rod will consist one plate, this is one plate and this, this cylinder, out of cylinder will be another plate. Now, if you pour liquid here, you see the dielectric medium between this plate and this plate consists of two different materials. One is air, another is liquid, right? So, if the air, if it, if it, if it is more, if you fill up this, I mean this tank, what will happen? You see that there will be more liquid within, in the tank and less of air in between, in between the two plates. So, the dielectric medium changes. So, obviously what will happen? The capacitance value will, also will change.

This principle, this method, this can be utilized to make a level sensor or level gauge and this is very interesting that this can be utilized to make a level of solid as well as for the liquid, right?



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Now this all, in all the previous cases we have seen that this output is single ended output, right? But, we always prefer differential output. There is some advantage of the differential output, because non-linearity will be less. So, the output, unbalanced output, because ultimately if I want to make a very accurate measurement, please note that I have to put that capacitance in a bridge; see, if I put in a bridge, so if I, due to displacement or due the permittivity change that means due to area change, permittivity change or the, or the, or the displacement between the, separation between the plate changes, what will happen? Your output will change, right? But, in the case that if you, if you, if this output is more that will be always better for us, because our, that will simplify our measurements.

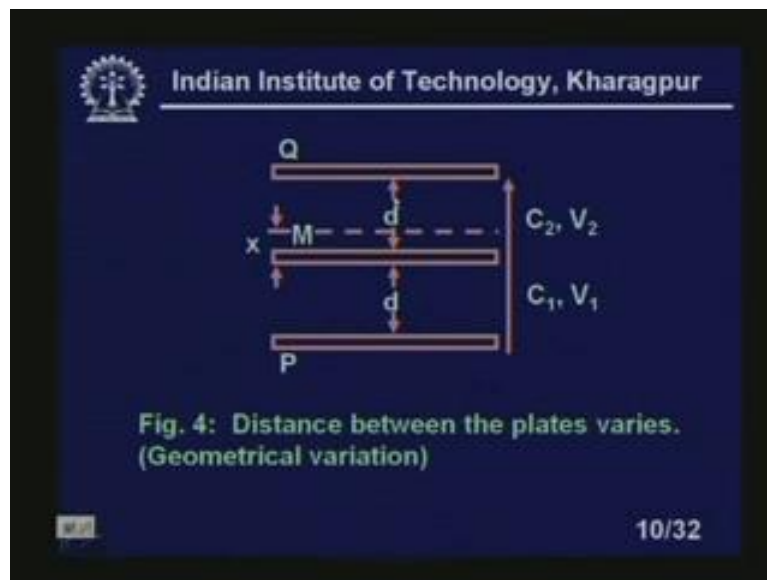
Exactly that thing we are doing in that case of differential output. You see the capacitance change can be  $C$  plus minus delta  $C$  or  $C$  plus minus delta  $C$ , all the same. See, here the X and Y and Z are cylinders, area between the plates varies. Now you see, their ... capacitance between this plates and this cylinder and this cylinder again between this cylinder and this cylinder. Now, if I shift this cylinder on this side what will happen? Area between this plate and this plate will increase and area between this plate and this plate will increase, decrease, right?

Now, you see, if it is exactly in the geometric mean position, then what will happen? The capacitance between X and Z and Z and Y will be

identically should be equal, right? That means capacitance between X and Z and capacitance between Y and Z should be exactly identical. Now, if we push it on this side, then what will happen? You see here, if I push this one this side, then what will happen? That capacitance between X and Z will increase, because it is getting more area between the plates and capacitance between Y and Z will decrease. Similarly, if I put on this direction, capacitance between X and Z will decrease, because the area will be less and the capacitance between Y and Z will increase, right?

See, if I put this in the two arms of the Wheatstone bridge, obviously my bridge unbalanced output will be doubled. So, that is the advantage of using the differential measurement. It is a differential output for a, from a capacitance sensor.

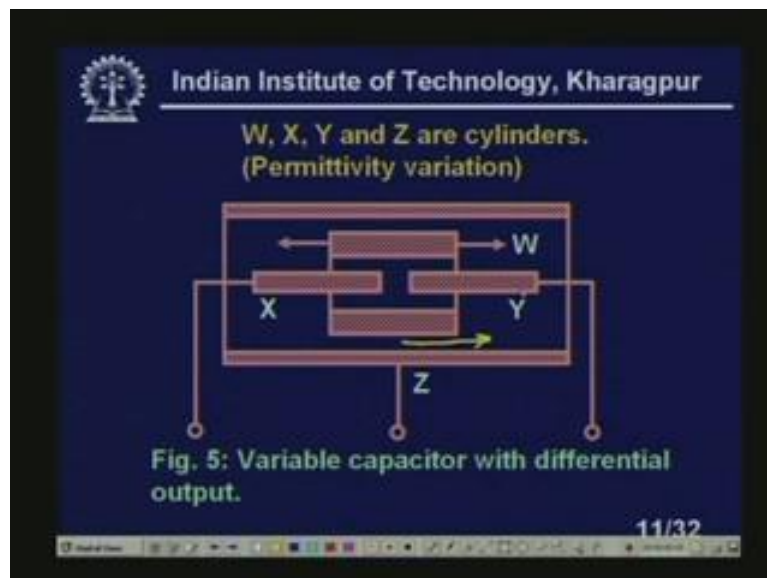
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Here also you see that I have two plates, fixed plates P and Q and one movable plate is M, right? So, I have a displacement. Separation between the two plates are d and if the area is, these are all parallel plates, if the area is actually, exactly area is d here, here, here it is d, here it is d, then what will happen? The capacitance between this M and Q and capacitance between P and M will be exactly same. If this is exactly at the **meet** position, so the capacitance between this and this and capacitance between that means capacitance between P and M, capacitance between Q and M will be identical.

Now, suppose I push this plate M slightly upward by displacement of, by displacement of X meter, then what will happen you see? If you displace, the capacitance between M and Q will increase and capacitance between M and P will decrease. Again the same advantage I am getting that if I put in opposite arm of the Wheatstone bridge, I will get the more unbalanced output, right? Here, the distance between the plates vary, geometrical variation. Again the same thing that means I am getting differential output here, right?

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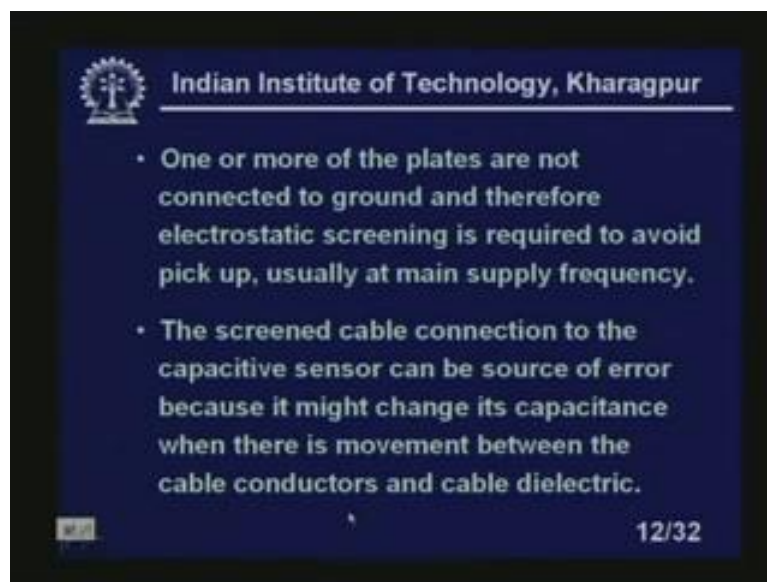


Now, **X**, W, X, Y and Z are cylinders. Now, in this case you see the permittivity variations, variable capacitor with differential output. You see the, what will happen here? This M, this is, this is Z basically, right, this outer bigger cylinders. We have capacitance between X and Z. X is a solid, solid rod, Y is also a solid rod and that Z is a cylinder. So, what will happen normally? Between, you have capacitance between X and Z and capacitance between Y and Z. So, if the dielectric medium, ... Now, here the dielectric medium or the W, I am varying that means its position is getting varied.

If the position is getting varied, then what will happen? You see, here if I move it in this side, so there will be more dielectric medium between X and Z and there will be less dielectric medium between Y and Z. So, the capacitance between this X and Z will increase and capacitance between Y and Z will decrease. Similarly, if again this dielectric W is, we shift on the right hand side, suppose I am shifting it on the right

hand side, then what will happen? That means if I show, show it like this, if I shift this on right hand side, then what will happen? The capacitance between W and Y, because I am getting more dielectric medium, so W, sorry capacitance between Z and Y will increase, because the, I am getting more dielectric medium and capacitance between X and Z will decrease, because I will get the less dielectric medium. So, this again I am getting a differential output. So, the capacitance can be, you can utilize as a, as a displacement sensors and you can have a single ended output. Also I can have a differential output, right?

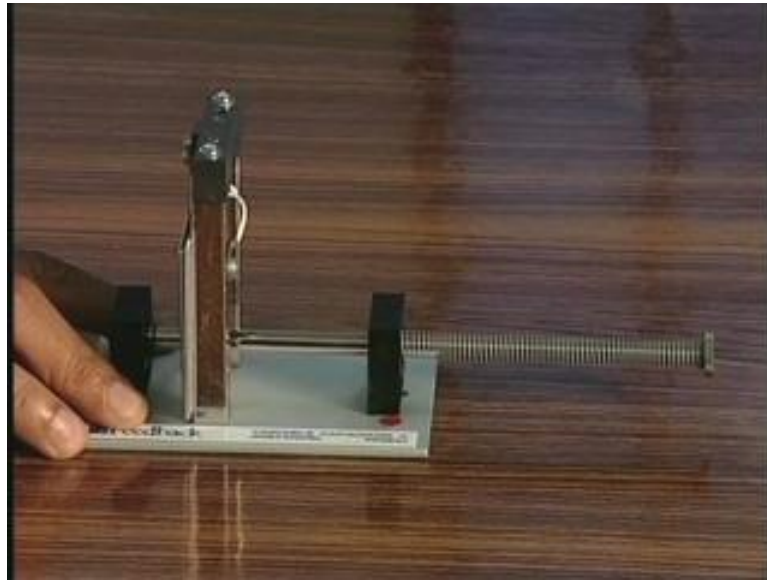
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One or more of the plates are not connected to ground and therefore, electrostatic screening is required to avoid pick up, because capacitance measurements, because these are basically the ... of the capacitance are very small and there is always stray capacitance. So, all these things you have to take care while you are making a signal processing circuitry. Usually this 50 cycles being supply frequency, all these will be picked up. So, we have to use proper shielding to get the capacitance value. Thus, screened cable connection to the capacitive sensors can be source of error, because it might change its capacitance when there is a movement between the cable conductors and cable dielectrics.

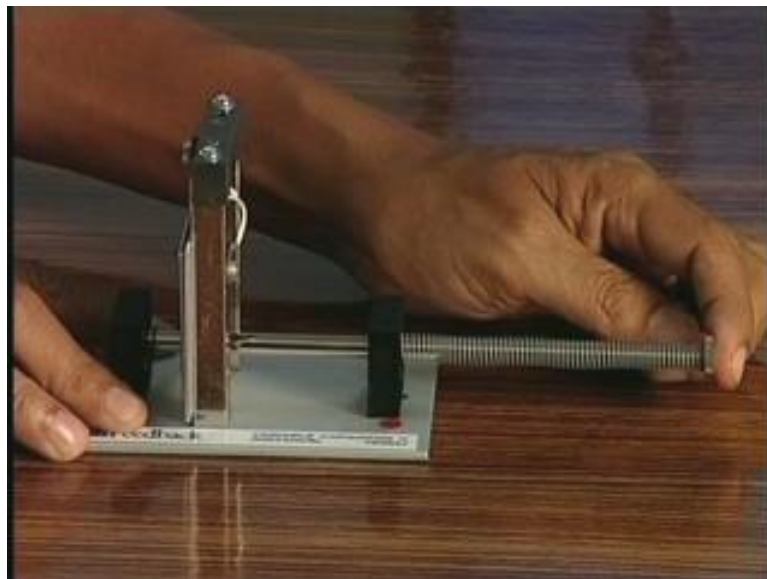
So, let us now go to the instrumentation lab and see some capacitance based sensors.

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This is another application of the capacitance sensor which can be utilized to measure the displacement. Usually capacitance sensors are based on the three different criteria. One you can vary the area of the plates, you can vary the displacement between the plates that means separation of the plates and also you can vary the position of the dielectric medium inside the capacitor. The particular gauge which you are, you are looking at now basically depends on the displacement.

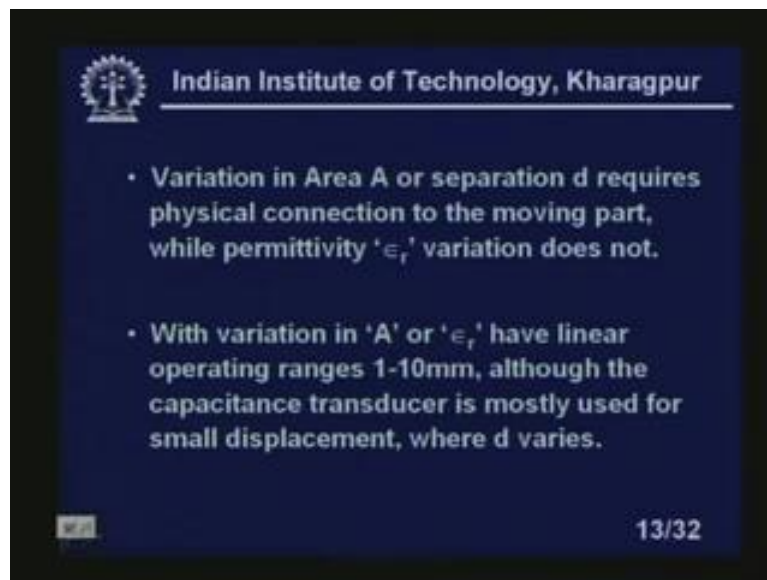
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You see, if you, if you make the displacement, here the separation between the capacitor plates changes. So, obviously if the separation changes, the capacitance value also will change. So, that, so if you put in a bridge, so obviously bridge unbalanced output also will change. So, that bridge unbalanced output can be calibrated in terms of the displacement, because ultimately we are not measuring the capacitance, we want to measure the displacement, which is our input that is converted to the change of, change of variation of the capacitance and ultimately which will give you some unbalanced voltage. This is another application of the displacement sensor based on the capacitance.

Welcome back to the class room. Now you see that we have seen some sensors already in the laboratory.

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So, we are, we have to observe, we must have observed that the variation in area  $A$  or separation  $d$  requires physical connection to the moving part, while permittivity, epsilon  $r$  variation does not because it is, it is not very simple. I mean, even though I am showing in the diagrams, I mean two plates are there and we are making the separation, physical implementation, it is not that easy. It is quite difficult to happen that type of making connection; that are two plates will be exactly parallel to each other, while you are, I mean making the separation. That mean plates, I mean two

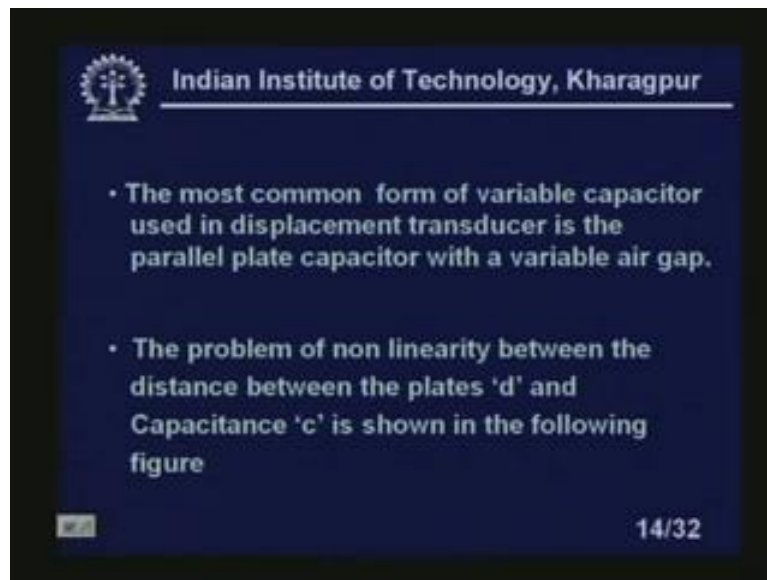
plates are like this one; see, two plates are there. So, if I make a separation like this one, I will get different value of the capacitance.

But actual implementation, it is not very easy, it is quite a task. I mean plate might be this way or that way. So, entire mathematical calibrations, I mean entire calculations will be wrong, so that the calibrations also will be, will be different. Similarly area also, if I ... I mean while we are changing the ... two plates will, two parallel plates should, should be equal exactly parallel, but in one fixed plate that is separate thing. But once it is movable, it is very difficult to keep them parallel all the way long, all the way in the entire, entire range of the movement. So, all these things you have to think of, right? But in the case of permittivity, there is no such problem arises, because it is simple.

There is no change or mechanical change of the systems, most of the cases. Especially in the level gauge we will find this is very much true, but in our case, while I am showing one differential that we are changing the another cylinder by changing the permittivity that is also the same problem we will face, right? With the variation in A or epsilon r have a linear operating range, it is usually 1 to 10 millimeter, although the capacitance transducer is mostly used for small displacement, where d varies. So, it is usually, it is used for the very small displacements; it works for very well. For larger displacements we have many other sensors like potentiometers, presets and all these things. Usually we can use this capacitance sensor for a smaller displacement measurement.

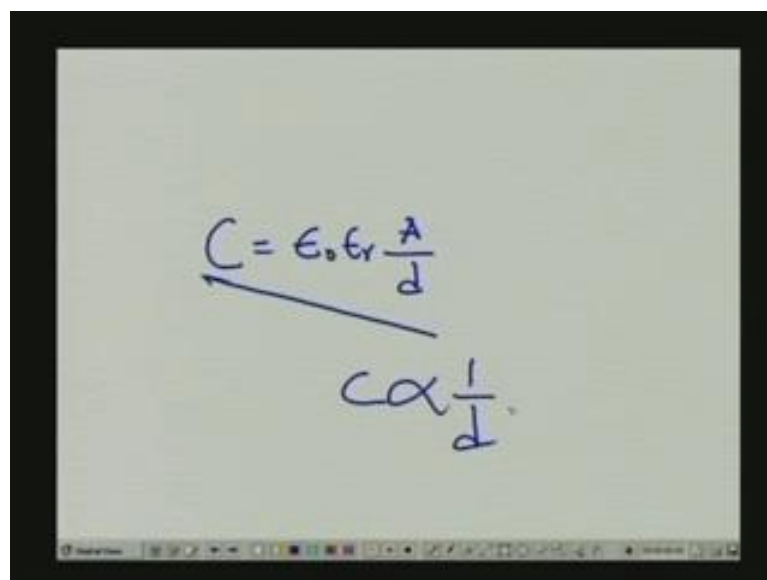


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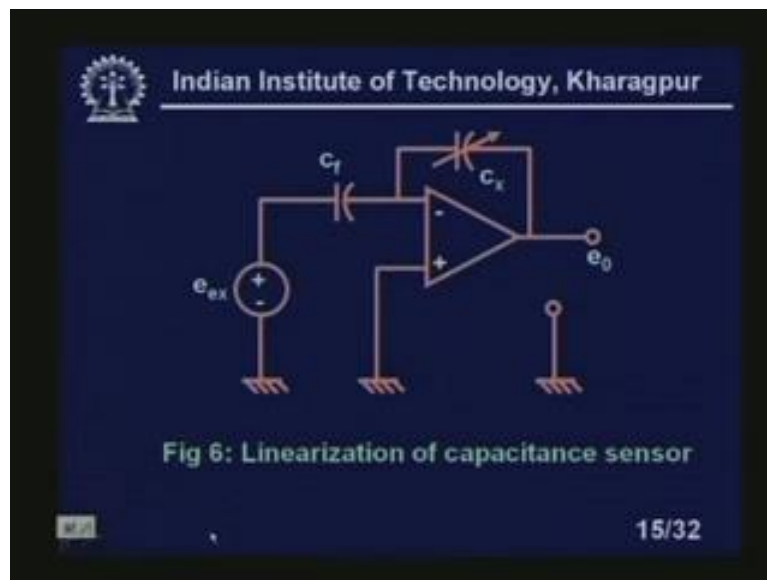
The most common form of variable capacitor used in the displacement transducer is a parallel plate capacitor with variable air gap. So, just simple air gap in between and I am varying the separation between the plates; that we have seen in the laboratory. The problem of non linearity between the distance and the plates d or capacitance c is shown in the following figure. You know that, if you can look at very carefully that the, the relation between the capacitance and the d is the change of capacitance and d is not linear, right?

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You see here if I take a, see if I, because you have seen that  $C$ ,  $C$  equal to  $\epsilon_0 \epsilon_r A / d$ , right? You can see this relation, see obviously it is not, the relation between  $C$  and  $d$  is  $C$  is **directly**, inversely proportional to  $1/d$ . So, it is a non-linear relation, because if you take a differentiation, then you find it is a non-linear relation, right? But, we can see that with the use of simple op-amp we can linearize it. This is very much necessary, because in many applications we need this type of measurements.

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See, this is a op-amp based circuit. You see here that you are using one op-amp and this is a capacitance which will be variable. That means whether you are using as a displacement sensor, level sensor, it does not matter, we put on the feedback path of the op-amp and  $C_f$  is the fixed capacitor. I am giving an excitation voltage of  $e_{ex}$  and taking the output from  $e_o$ , **if you assume**,  $e_o$  and ground. If you assume that the, this, this ideal op-amp it is offering a large input impedance, so that it is not drawing any current, what about the current coming in this frame through this path? So, quite obviously, immediately I can write the output voltage like this; I can write the output voltage like this.

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Assuming the op-amp as an ideal device

$$\frac{e_o}{e_{ex}} = -\frac{C_f}{C_x}$$

Where,  $C_f$  is the fixed capacitor  
 $C_x$  is the variable capacitor or capacitance sensor

$$\text{or, } e_o = -\frac{C_f d}{\epsilon_0 \epsilon_r A} \dots \dots \dots (2)$$

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This is a, I mean this is an ideal op-amp if you take, assuming the op-amp as an ideal devices, I can immediately write  $e_o$  by  $e_{ex}$  is equal to  $C_f$  by  $C_x$ , right? So, it is  $e_o$  by  $e_{ex}$  equal to minus  $C_f$  by  $C_x$ , right and quite obviously, where  $C_f$  is the fixed capacitor,  $C_x$  is the variable capacitor or capacitance sensors actually and immediately what we can write  $e_o$  equal to  $C_f$  by  $d$  epsilon naught into epsilon r into A. So, you see that we have linearized it. The output voltage is linearly proportional to  $d$ .

So our, I mean measurement is becoming more simple if we use this type of arrangements. But obviously if I want to, in this case if I want to vary A that will not be a very, I mean good proposition, because in this case you will find it is again becoming inversely proportional to A, output voltage is inversely proportional to A. But ..... situations we will use only  $d$  or the separation between the plates that can be utilized to make our sensor. So, obviously output voltage will be proportional to  $d$ .

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- It is clearly seen that the output voltage is now directly proportional to the plate separation 'd', thus linearity is achieved for both large and small motions.
- In commercial instrument  $e_{ex}$  is 50 kHz sine wave of fixed amplitude.
- The output  $e_o$  is also a 50 kHz sine wave which is rectified and applied to a dc voltmeter calibrated directly in distance units.

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It is clearly seen that the output voltage is now directly proportional to the plate separation  $d$ . Thus linearity is achieved for both large and small motions. In commercial instruments this  $e_{ex}$  excitation is 50 kilo Hertz sine wave of fixed amplitude, amplitude is fixed, right? The output  $e_o$  is also a 50 kilo Hertz sine wave. This will be wave, I am sorry, this will be wave, this will be wave.

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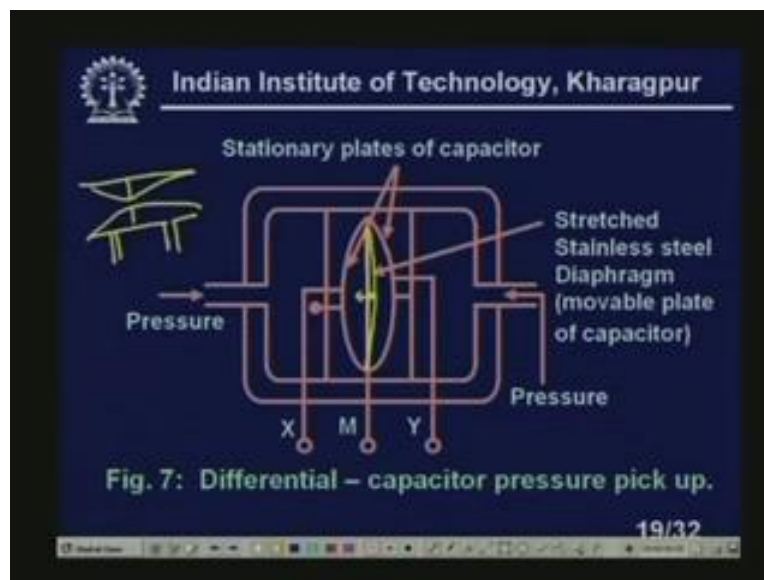
- In a differential - capacitance pressure transducer, the plates are circular and plate M is a thin diaphragm across which the pressure differential to be measured is applied.
- With equal pressure applied to both pressure ports, the diaphragm is in a neutral position, and the bridge is balanced and the output voltage ' $e_0$ ' from the bridge is zero.

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So, in a differential capacitance pressure transducer, the plates are circular. Plate M is thin diaphragm across which the pressure differential will go. I think I have skipped

something, let me go back; okay, no, no problem. If I go, yes, yes, yes, so in a differential capacitance pressure transducer, the plates are circular and plate M is, the figure will come in the next slide, plate M is a thin diaphragm across which the pressure differential to be measured is applied, right? With equal pressure applied to the both pressure ports that is diaphragm is in the neutral position and the bridge is balanced and the output voltage  $e$  naught from the bridge is zero.

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How does it look? You see this is our example of our differential pressure pick up. You see here this is our movable plates. This plate is movable plate. It is moving in this direction or this direction. If this pressure is higher than this pressure, okay, this pressure is higher than this pressure, so the diaphragm will be stretched in this direction. It will look like this one and if this pressure is higher, then the diaphragm will be stretched in this direction, right and X and Y are the fixed plates.

Actually this is, if you look at, it is a section of a, section of a sphere. Actually if you look at a section of the sphere and this inner side is coated with metals, so that inner that coating will work as a plate of the capacitor. Now, this type of pressure transducers has a, differential pressure transducers has tremendous applications. In modern day instrumentations you will find everywhere I am using flow sensors and flow sensors as you know, in the most process industry these are huge in number and in all flow measurements specially our, in the case of orifice meter, Venturimeters and

pitot tube, we use some differential pressure pick up, because these sensors, these output is to be transmitted to the control room and this signal is to be transmitted to the control room. So, I need this differential tapping.

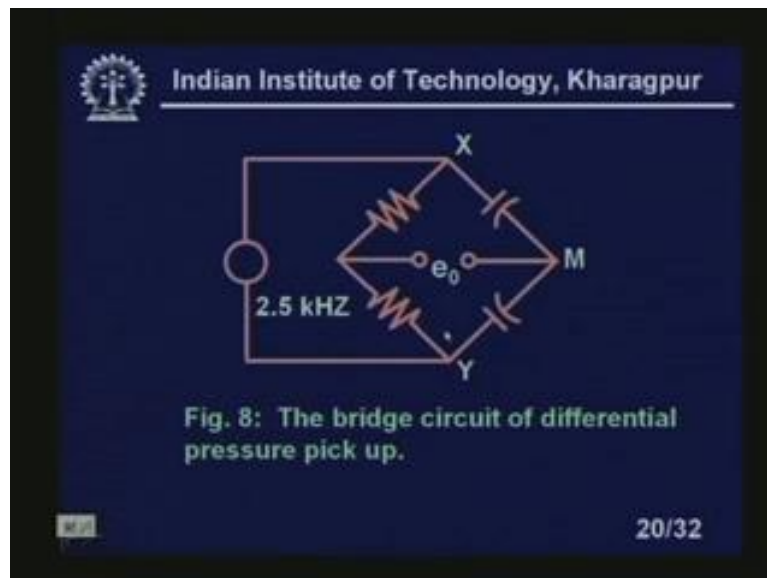
It looks like this one in the flow measurements. Why this is important? You see, we have a pipe here and this orifice. We will discuss orifice later on, so we have a tapping here, we have a tapping here, right? So, liquid is flowing like this one. So, there is a high pressure, this is a high pressure area port and this is a low pressure port. This high pressure port is connected here and this low pressure port is connected here. Then, what will happen? This diaphragm will be bent like this one and then what will happen? If it bends like this one, since I told you this inner side is coated with metal, what will happen?

This is a section of a, section of a sphere, so inner side is coated with a metal. Then what will happen? You see, this plate will move this side and the capacitance between this plate and this plate will decrease and capacitance between this plate and this plate will increase or capacitance between X and M will increase, capacitance between M and Y will, sorry capacitance between X and M will decrease and capacitance between M and Y will increase. So, if this differential, if we put on a bridge we will see in the next slide we will put on a bridge, I will get a large bridge balanced output that can be converted to the current of 4 to 20 milliamperes and transmitted. That 4 to 20 milliamperes of current will correspond to the 3 to I mean 15 psi of pressure, right?

So, that is the reason I am saying stretched stainless steel diaphragm movable plates of capacitors. Actually in that process you will find that we are using pressure capsule, actually capsule, so that it is not necessarily directly you have to give. The pressure will come down here, because this liquid will directly come down here. So, in between there is another liquid, so the, it will in turn make a pressure on this side, so that it will be stretched like this one, right?

Now, you see, these are our signal conditioning circuit. This is bridge circuit of the differential pressure pick up.

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We have X and Y and M movable plate and two capacitors. What will happen? If this is increased, this will decrease. That means if this increases, I am sorry, if this increase, let me go to the previous slide.

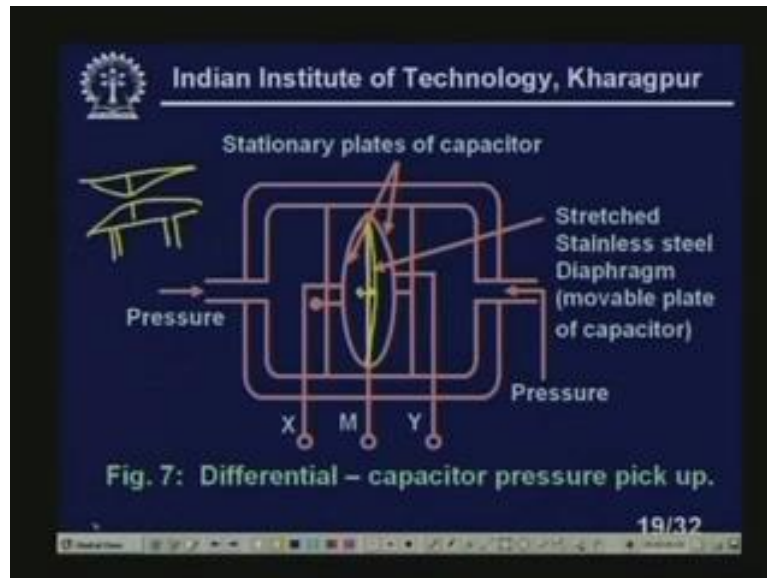
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- 
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- If one pressure is greater than the other the diaphragm deflects in proportion, giving an unbalanced output at ' $e_0$ ' in proportion to the differential pressure.
  - For the opposite pressure difference, ' $e_0$ ' shows a  $180^\circ$  phase change.
- 21/32

Yes, so if one pressure is greater than the other, so obviously what will happen? The diaphragm deflects in proportion and giving an unbalanced output at  $e_0$  and in proportion to the differential pressure, quite obviously. For the opposite pressure difference,  $e_0$  shows a 180 degree phase difference. What is that?

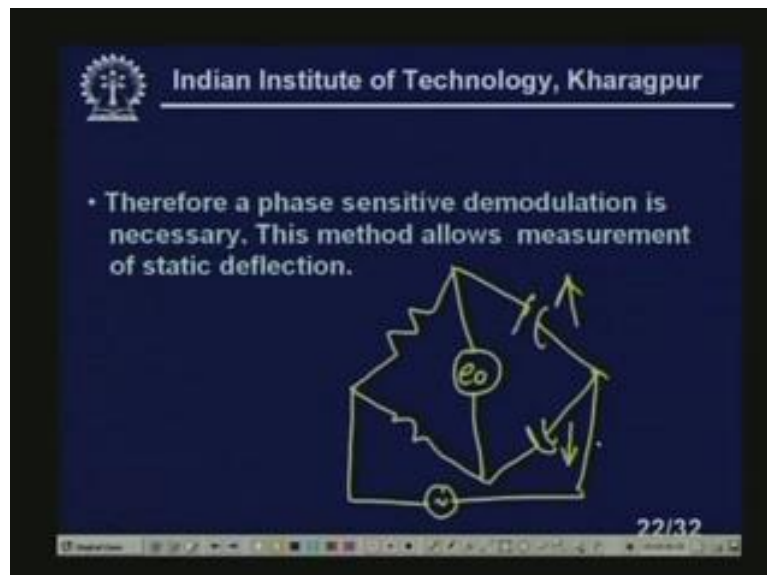


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If you look at very carefully, you see here what will happen? You see here that if I put on a bridge, so it is very difficult to know, if you look at, because if this is, if, if the, if the diaphragm moves in this direction, then what will happen? The capacitance between X and M will decrease and capacitance between M and Y will increase, right? Now, if the capacitors, if the, suppose the pressure on this side increases, so the diaphragm is stretched like this one. Diaphragm in that case will be stretched like this one. Then, what will happen? You will find that the capacitance between this and this will increase and capacitance between this and this will decrease, right, is not it?

(Refer Slide Time: 31:09)



So, therefore a phase sensitive demodulation is necessary, right? Even though I am saying, you see that I am saying that like this one, let me see, so I said that I have a capacitance here, I have a capacitance here, right? So, if I put a signal here and measure the output voltage  $e_{naught}$  here, so if this is increased, this will decrease; that is no doubt about that, so I will get an unbalanced voltage, right? Now, if this decreases and this increases also I will get unbalanced, but how will I know that which side it is?

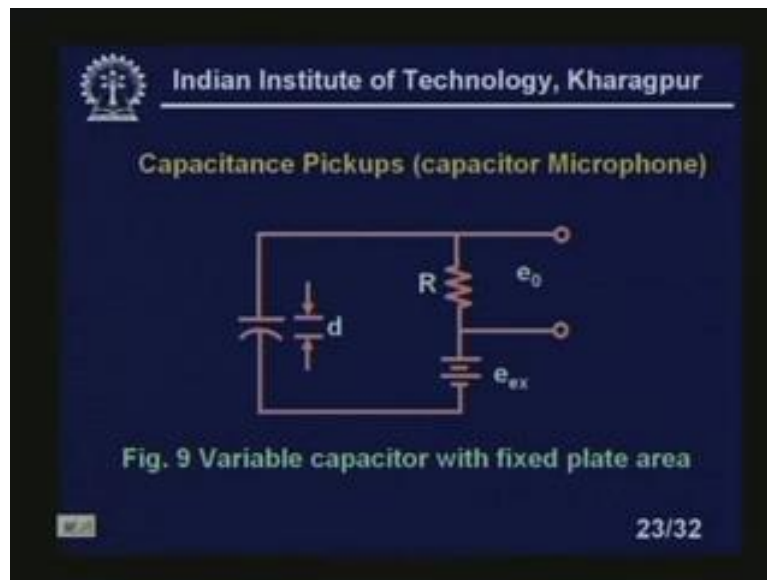
So, for that reason, we have seen as, it as, it as we did in the case of LVDT, I need some phase sensitive demodulation. With a phase sensitive demodulation this type of problem can be easily, I mean solved.

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Now, see this method is basically, I, I should tell that this method is basically for, therefore this method allows measurements of static deflections, because it, if it is a, a static deflection, so I can easily measure by this type of method, right? Such differential capacitor arrangement also shows the considerable greater linearity than do the single capacitor types. You will find that the linearity will be more in this type of capacitor arrangement right?

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Now, capacitance pickup or capacitor microphone is a very important device, is, is a, I mean you will find that this is basically a capacitance sensor and the separation between the plates changes in that type of situations. You see here, this is a capacitance sensor. This separation between the  $d$  will change and I am measuring the output  $e_0$ . Now, the only problem with this type of capacitors that is pickup is that it is only for the dynamic displacement measurements.

For static displacement measurements, I won't get any output. I am using an excitation of  $e_{ex}$ ,  $e$  subscript  $ex$ . So, what will happen that if there is a, if this is fixed, so there is no current will flow through the capacitors. So, I will get the, I won't get any output. Whenever this moves, as it happens, I want to say, talk, this microphone works. You see, this microphone is also a capacitive transducer. You can see here this microphone is also a capacitive transducer. So, when I, I am talking, so this capacitance between the plates ((in)) changes. So, I will get an output here, right?

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We know

$$\frac{\Delta c}{\Delta d} = -\frac{c}{d}$$
$$\frac{\Delta c}{c} = -\frac{\Delta d}{d}$$
$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

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We know that, you see that we have already seen, because you see what will happens that C equal to, I said equal to epsilon naught epsilon r A by d. So, from that equations I can write delta c by delta d, c by d, right? Similarly, delta c by c, delta d by d, right? So, that means, sorry this will be delta c by c, this will be, no delta c will be there, so delta c by c, delta d by d.

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We know

$$\frac{\Delta c}{\Delta d} = -\frac{c}{d}$$
$$\frac{\Delta c}{c} = -\frac{\Delta d}{d}$$

When the capacitor plates are stationary with separation ' $d_0$ ', no current flows and  $e_0 = 0$

If there is then a relative displacement  $d_1$  from the position ' $d_0$ ' a voltage ' $e_0$ ' produced and is related by ,

24/32

So, when the capacitor plates are stationary with separation d naught, no current flows and the output voltage will be zero, as I told you earlier, right? If there is, if there is

then a relative displacement  $d_i$  from the position  $d_o$ , a voltage  $e_{naught}$  produced and is related by this expression.

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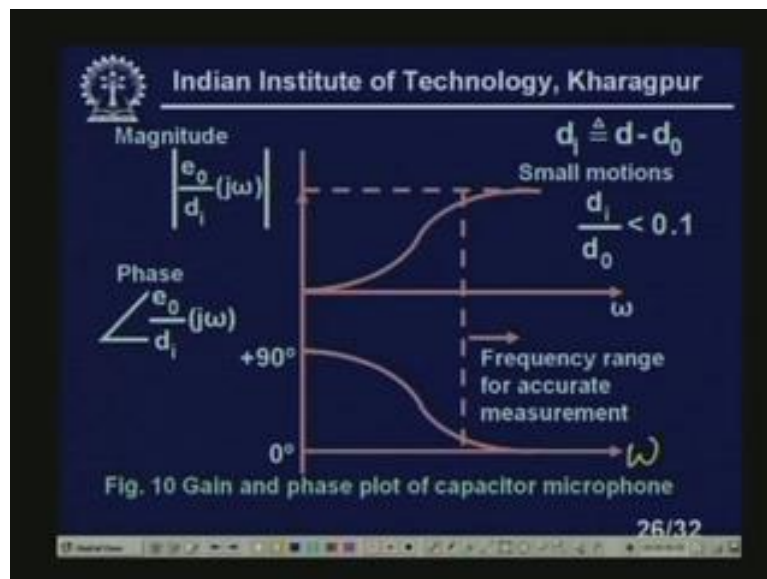
$$\frac{e_o}{d_i}(D) = \frac{KD}{\tau D + 1}$$

Where,  $K = \frac{e_o}{d_o} \text{ V/m}$

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$e_{naught}$  by  $d_i K D \tau d + 1$ . As you know that, sorry, I am sorry, they should go away, I think I should escape from here. So, what will happen?

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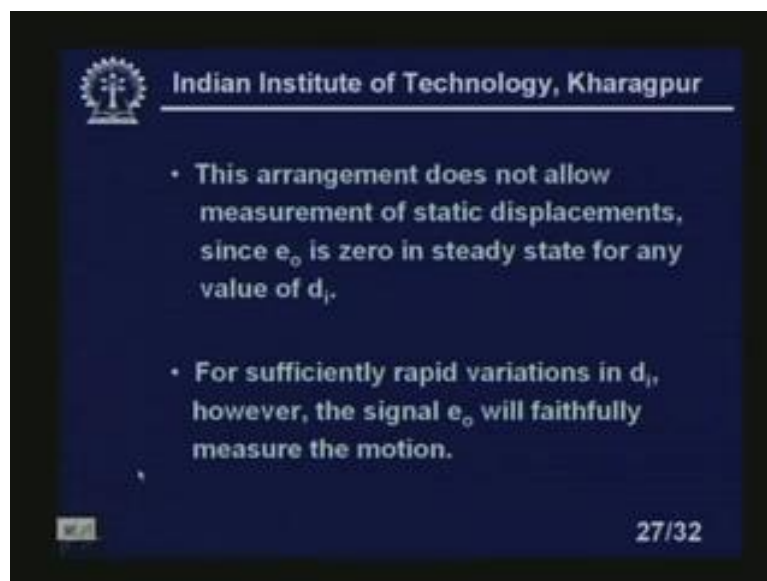


You see that this is our magnitude and phase plot of the capacitance sensors. You can see here that magnitude is  $e_{naught}$  by  $d_i$ , because  $e_{naught}$  is the input,  $d_i$  is the,  $e$

naught is the output and  $d_i$  is the input, right? It is from the nominal positions, so I am making and  $e_x$  is the excitation that is not a, I mean that is not the input to the systems and the phase plot will be like this and the magnitude plot will be like this one and the phase plot of this one will be, look like this one, right?

So, we can see here that the frequency range of this one will be, after some certain point there is a large phase shift at the beginning, when the  $\omega$  is low. Otherwise, there is a, I mean as the frequency increases, so I, we can see here this is also, please note this is also  $\omega$ . As the frequency increases, the phase shift is also becoming zero and your representation or of the original signal also will be better and better.

(Refer Slide Time: 36:38)



Now, as I told you, as I told you earlier also, this arrangement does not allow measurements of static displacement, since  $e_{naught}$  is zero in steady state for any value of  $d_i$ . For sufficiently rapid variations in  $d_i$ , however the signal  $e_{naught}$  will faithfully measure the motion.

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As we know

$$\frac{e_o}{d_i}(j\omega) = \frac{kj\omega\tau}{j\omega\tau + 1}$$

For  $\omega\tau \gg 1$

$$\frac{e_o}{d_i}(j\omega) \approx K,$$

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You can see that  $e_o/d_i(j\omega) = \frac{kj\omega\tau}{j\omega\tau + 1}$ , where  $\tau$  is the time constant of the systems, for  $\omega\tau$  much, much greater than 1, right? Instead of  $\omega$ , I am writing  $\omega\tau$ ,  $\omega\tau$  much, much greater than 1  $e_o/d_i(j\omega) \approx K$ , right?

(Refer Slide Time: 37:25)

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- A microphone usually need not measure sound pressure smaller than 20Hz and so above arrangement is perfectly satisfactory.
- To make  $\omega\tau \gg 1$  for low frequencies, it requires a large  $\tau$ .

$$\frac{e_o}{d_i} = K.$$

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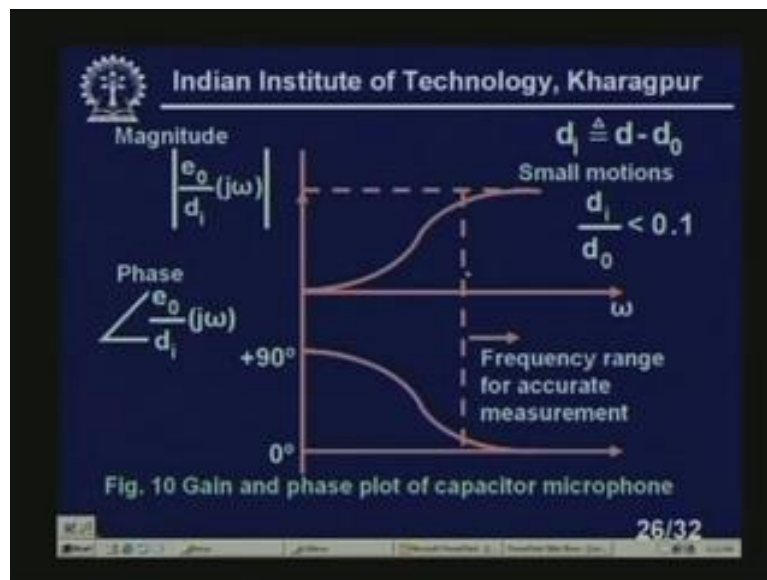
So, microphone usually need not measure sound pressure smaller than 20 Hertz, because usually we talk between 20 Hertz to 20 Kilo Hertz. That is the reason we have to tune all musical instruments also within this range 20 Hertz to 20 kilo Hertz.



So, above **such** arrangement is perfectly satisfactory, because as you have seen, the plot, phase plot and the gain plot, so low frequency production is not very good, but the high frequency is quite good. So, if you go above 20 Hertz, so there is a faithful reproduction of the original signal. Our goal is to reproduce the original signal that means the sound pressure on the microphone.

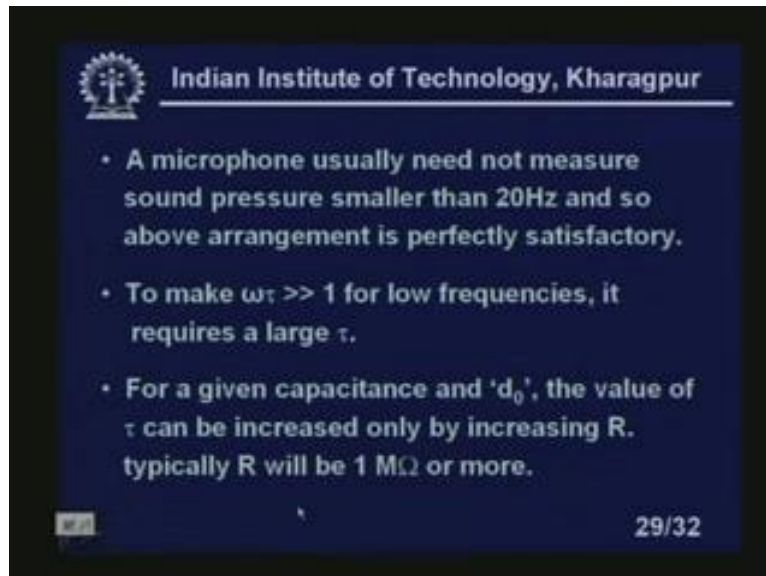
To make  $\omega\tau$  much, much greater than 1, for low frequency it requires a large  $\tau$ . So, to make, how can I make  $\omega\tau$  much, much greater than 1? Only if the, at low frequencies only possibility is,  $\tau$  will be much, much greater than 1. Only then in that case it will be more than 1. If it is more than 1, so I will get the input output. My relation is, the input output relations will be  $K$ , that  $e$  naught by  $d$  will be equal to  $K$ , approximately will be equal to  $K$ , is not it? So, that is possible, right?

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Now, that we can see it again; here, you see that we can go back. You see here, so no problem, we can see here that if the, this  $e$  naught by  $d$  is better and better faithful reproduction of the original signals, **so  $\omega\tau$  for low one.**

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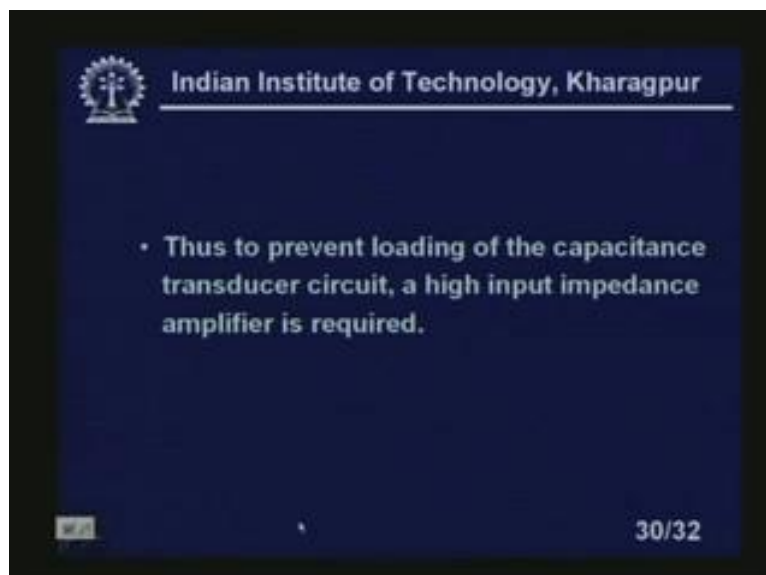
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- A microphone usually need not measure sound pressure smaller than 20Hz and so above arrangement is perfectly satisfactory.
- To make  $\omega\tau \gg 1$  for low frequencies, it requires a large  $\tau$ .
- For a given capacitance and ' $d_0$ ', the value of  $\tau$  can be increased only by increasing R. typically R will be 1 M $\Omega$  or more.

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Yes, for a given capacitance and  $d_0$ , the value of  $\tau$  can be increased only by increasing R. Typically, typically R will be 1 megohm or more. So, if you can make 1 megohm or more, obviously  $\omega\tau$  will be quite large. So, even for low frequencies, so I can faithfully reproduce my original signal, right?

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- Thus to prevent loading of the capacitance transducer circuit, a high input impedance amplifier is required.

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Thus to prevent loading of the capacitance transducer circuit, high input impedance amplifier is required, a buffer amplifier is required. So, there are various types of

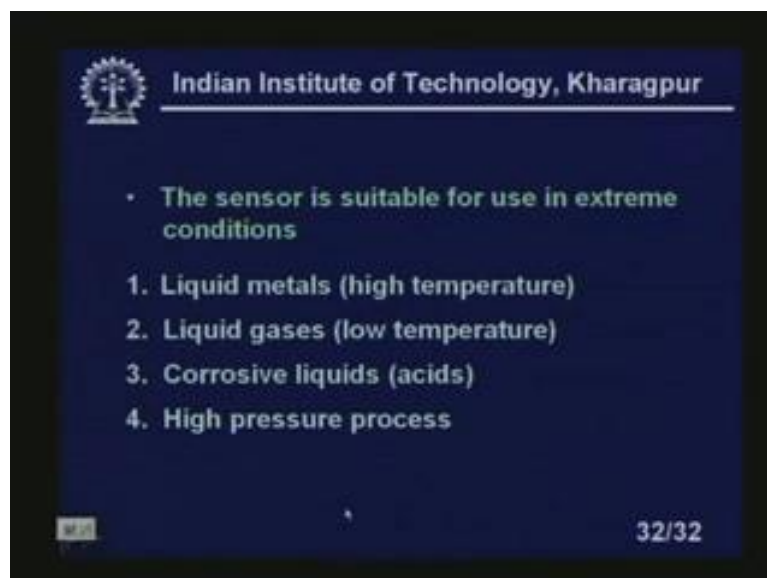
buffer amplifiers. It is not very big deal, nowadays to have, to have a good buffer amplifier. We can have a good buffer amplifier and can make the reproduction.

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Capacitive sensors are now widely used for the, as I told you earlier also, the, for the levels of liquids and the solids in powdered or granular form.

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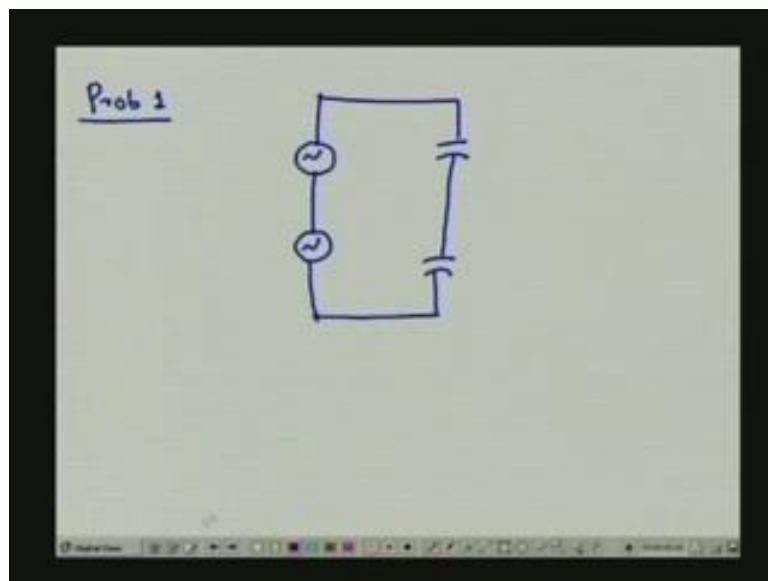


So, sensor is suitable for use in extreme conditions - liquid metals at high temperatures we can measure it which is not possible in other, liquid gases - low

temperatures also we can measure. Corrosive liquids like acids and all these things, where I mean or caustics, where it is very difficult to measure with, with any other sensors, but capacitive sensors .... You can have two stainless steel, stainless steel containers and within that I can pour some corrosive liquid and make the level measurements. High pressure process, where the other sensors will fail in that type of situations also capacitor sensors works, work very good, because it is totally independent, measurement is totally independent of the pressure of the liquid, right?

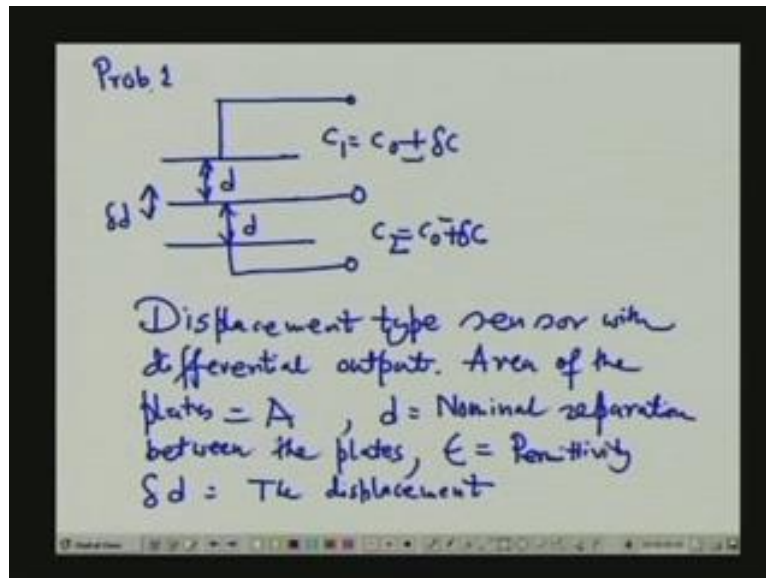
Now, we will solve some problem, so that for the digital class, let us look at, so the problem is like this one.

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You see we have, let me take a new, we will solve some problem later on also. Problem 1 - problem is like this that I have a sensor, right. Rather, I should first draw this.

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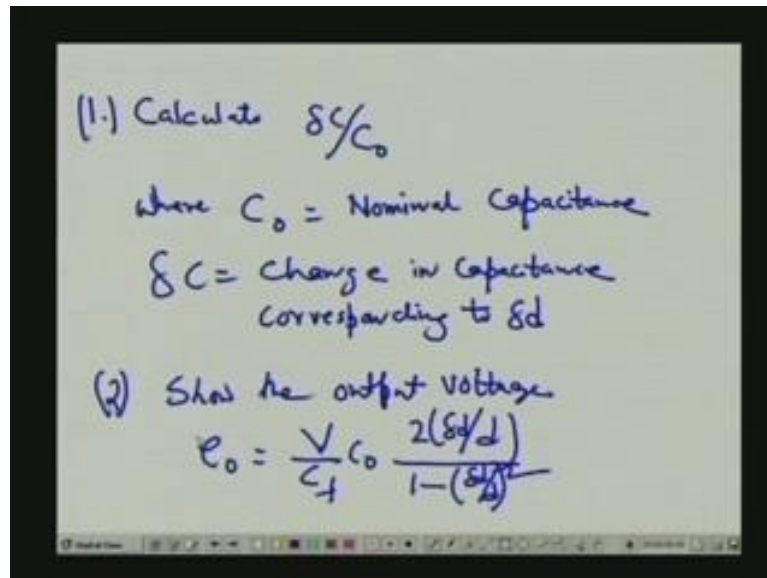


It looks like that I have a capacitance, a differential capacitor, sorry differential capacitor like this one, right? So, separation is  $d$ , this separation is also  $d$ . So, there is a movement of this one, which is we are assuming  $\Delta d$ , right? This is problem number 1, right? So, I have plates. So, this is also I am taking connection, there is another connection and there is another connection here. So, this will be  $C_1$ , will be equal to  $C_0$ .  $C_0$  is the, when you, when the capacitance plate is exactly at the meet position, capacitance between that two are same. So, that is  $C_0$  plus minus  $\Delta C$  and this will be  $C_2$  capacitance between this and this equal to  $C_0$  plus minus  $\Delta C$ , right?

If I draw the equivalent circuit of this one, it looks like ... Our goal is that is a variable area, this is a displacement type sensor, displacement type sensor with differential output, differential output, right, where area of the plate, of the plates equal to  $A$  meter square,  $d$  is the nominal separation between the plates, between the plates and  $\epsilon$  is the permittivity, permittivity. Actually in this case we have a combined  $\epsilon_0$  and  $\epsilon_r$ . So far in the text whatever we have discussed  $\epsilon_0$  and  $\epsilon_r$ , we have combined in  $\epsilon$  here, right? No problem and  $\Delta d$  is the displacement. It is a displacement sensor, so  $\Delta d$  is the displacement, right?

Now, what you have to do?

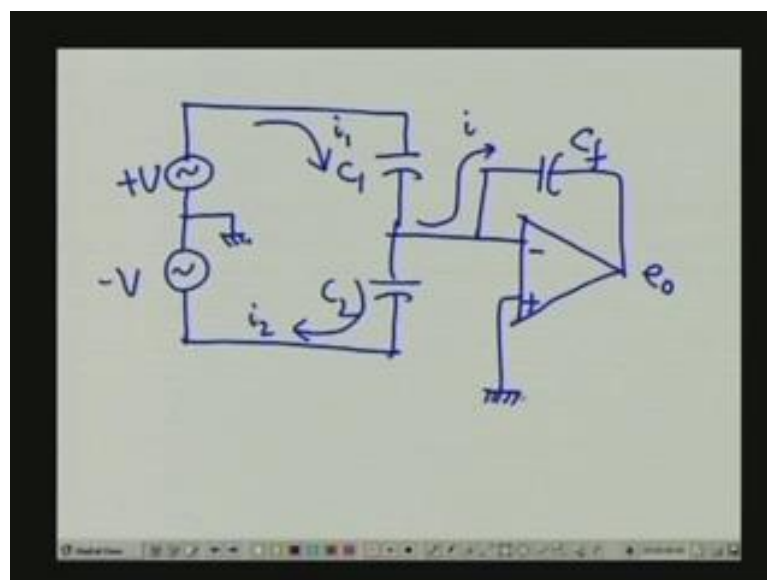
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Calculate, number 1, calculate delta C by C naught, where C naught is the nominal capacitance and delta C is the change in capacitance corresponds to, to delta d, right? Also we have to find, number 2 show that, excuse me, the output voltage e naught is equal to V by C f C naught 2 delta d by d upon 1 minus delta d by d square, right?

Now, the push pull configurations we will show in the next slide. The circuit looks like this.

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I have an arrangement here. This is grounded. C f, this is C 1, this is C 2, this is plus V, this is minus V, this is our, this is our output e naught, right? This is our circuit. So, we assume two current. Suppose this current is i 1, this current is i 2 and total current is i, right and op-amp, we are assume is an ideal op-amp, so it is not taking any current inside, right?

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The image shows a whiteboard with handwritten mathematical derivations. At the top, it states  $\epsilon = \epsilon_0 \epsilon_r$ . Below that, it defines capacitance  $C = \frac{\epsilon A}{d}$  and its differential change  $\delta C = \left(\frac{\delta C}{\delta d}\right) \delta d$ . The next line shows the derivative  $\frac{\delta C}{C_0} = -\left(\frac{\delta d}{d}\right)$  and a simplified form  $= -\frac{\epsilon A}{d^2} \delta d = -C_0 \frac{\delta d}{d}$ . Finally, it derives the current  $i = i_1 - i_2 = V(\omega C_1 - \omega C_2) = V\omega(C_1 - C_2)$ .

See, if this is a situation, now we can write, let me take a new page, see for the part a or part, sorry it is not part a, I will take a new page; part 1, C equal to epsilon A by d or delta C equal to, I can write delta C by delta d into delta d, is not it, which we can write quite obviously, minus epsilon A, here the epsilon, please note, it is epsilon equal to epsilon naught into epsilon r; epsilon A by d square into delta d with first order, I mean without, with approximation first order approximation. So, this will become again minus C naught into delta d by d.

Now, you see, so I can write delta C by C naught equal to minus delta d by d, right? Now, current i, actually you can see here i 1 minus i 2, right? So, which we can write equal to V, voltage omega C 1 minus omega C 2 or which we can write V omega, omega take out, it will be C 1 minus C 2, right?



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$$\begin{aligned}
 e_o &= -\frac{i}{\omega C_f} = -\frac{V}{C_f} (C_1 - C_2) \\
 &= -\frac{V}{C_f} \left( \frac{\epsilon A}{d + \delta d} - \frac{\epsilon A}{d - \delta d} \right) \\
 &= \frac{V}{C_f} \cdot \frac{\epsilon A}{d - (\delta d)^2} \cdot 2\delta d \\
 &= \frac{V}{C_f} \cdot C_0 \cdot \frac{2(\delta d/d)}{1 - (\delta d/d)^2}
 \end{aligned}$$

See, if I take a new page, so the output voltage  $e_o$  is equal to  $i$  minus  $i$  upon  $\omega C_f$  equal to  $\frac{V}{C_f} (C_1 - C_2)$  equal to  $\frac{V}{C_f} \left( \frac{\epsilon A}{d + \delta d} - \frac{\epsilon A}{d - \delta d} \right)$ . So, this will become  $\frac{V}{C_f} \cdot \frac{\epsilon A}{d - (\delta d)^2} \cdot 2\delta d$ . So, this will become  $\frac{V}{C_f} \cdot C_0 \cdot \frac{2(\delta d/d)}{1 - (\delta d/d)^2}$ , right? So, this is how we have seen that, so this is our proof actually. So, we have seen that, in these cases that how we can use a differential pressure pick up and I can use a sensor which has a differential output and how can I connect in the bridge all those things are we have discussed.

Basically, in instrumentation we will find this capacitance sensors have basically three uses. One is as a displacement sensor as you have seen - either permittivity variations or the variations of the area or variation between the, separation between the plates - number 1. Number 2 is the level gauge or level sensors. That means level will increase that means the permittivity will change. So, obviously the permittivity will change and the capacitance will change and third is the differential pressure pick up, which is extensively used in all process industry for measurements of flow, okay DP transmitter. This is, basically it is called DP transmitter.

We have seen that if I change the capacitance of the differential pick up, I will get a change of voltage that can convert voltage to the current and transmit it, right? So,

these are the basic three uses of the capacitive sensors instrumentation, but we have other applications, as I told you earlier also. We have discussed also, that in this case that we are using the sensor as a, as a pressure pick up. That means some pressure measurements also we can utilize this type of capacitance sensors. Capacitance sensors are very, I mean very nice to use, because it is independent of temperatures and all those things. That is a great advantage of this one.

It can be used in the corrosive environments, all those things are very much true, but please note another two most important things of capacitor sensors that those cables which is connected to this should be, we have taken, so the parasitic insensitive measurements you have to make, because whenever we are measuring very small capacitance value, whether you are using measuring in a bridge or LCR meter, it does not matter, so the, the parasitic, I mean capacitance will influence your measurements and it will pick up the signals like 50 Hertz signals and all those things. So, you should be very careful about those parts. So, that non-shielding should be very much good, so that if at least one part of the shielding should be, should be grounded, so that the, you can make the measurement faithfully.

With this, I come to the end of this capacitive sensors.

Thank you!

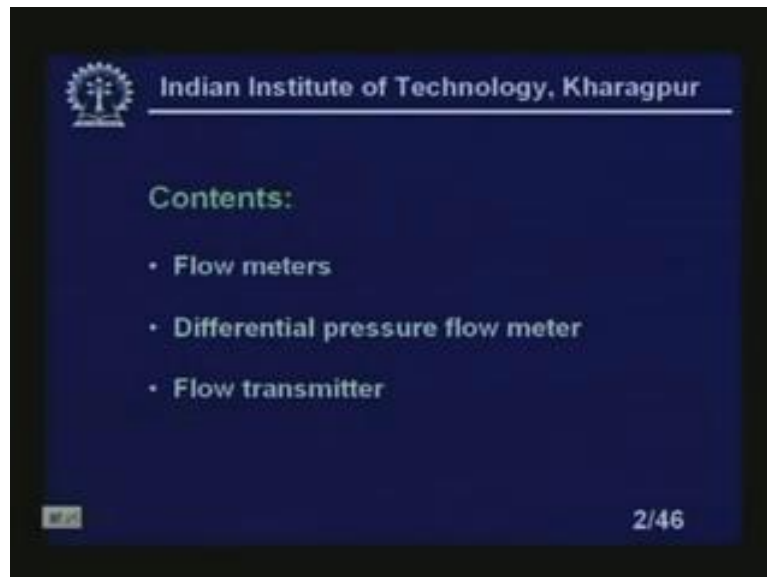
Preview of next lecture:

Welcome to the lesson 12 of Industrial Instrumentation. In this lesson, we will basically study flowmeters. As you know, the basic three process parameters are pressure, temperature and flow. However, if you look at the number of sensors available or the varieties of the, varieties of the particular process parameters like pressure, temperature is much less compared to the flow. The reason is that the flow you will find, I mean not only the, the type of liquid flowing through the pipe or it also basically depends on the what type of liquid is flowing. So, depending on that there are various types of flowmeters available and used in the process industries.

There are, sometimes there are volumetric flow, there are sometimes mass flow, there is sometimes .... displacement flow, there is open channel measurements, there is a

closed channel measurements. So, depending on this, all these circumstances, the number of flowmeters are the highest among them, all the process parameters if you look at. Now, in this lesson, basically we will discuss some of the contents of this lesson, rather.

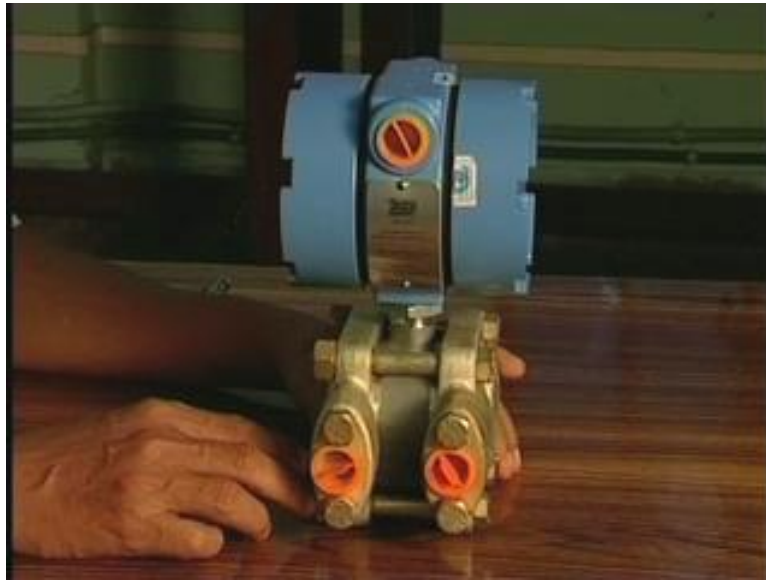
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The flowmeters, we just give the name of the different flowmeters, then we will discuss in details the differential pressure flowmeter, flow transmitter also we will discuss in some brief and also we will show the, I mean separate, the separate video on the flow transmitter.

Now, let us go to the instrumentation lab and look at one of the transmitter, one of the differential pressure transmitter used extensively in the industry.

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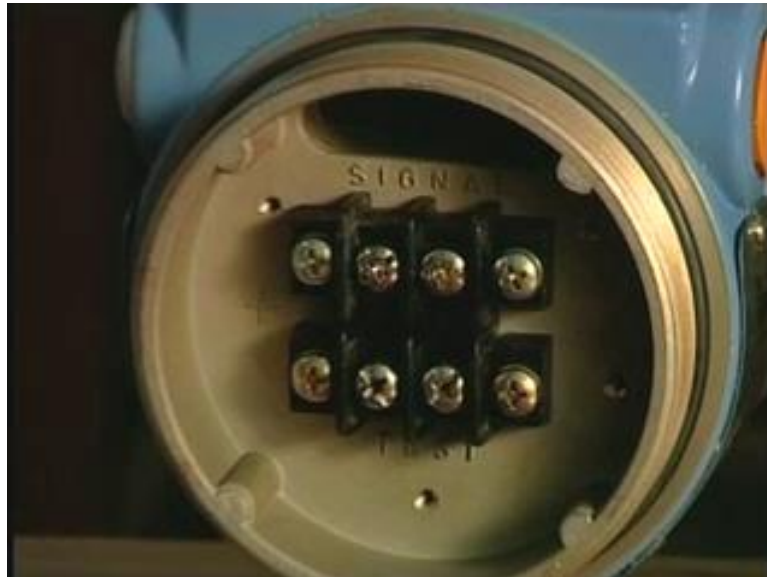


This is differential pressure transmitter. As you know that in the flow measurements, actually the flow is calibrated in terms of pressure. So, in all flowmeters, I mean, I am talking on the variable area like orifice meter and Venturimeter, so there is an upstream pressure tap and downstream pressure tap. We have seen in the class that, we have shown one nanometer sort of thing, by which I am measuring the pressure. But unfortunately in the process, actual process, I need some instrument or some equipment, which will give some signal that will be transmitted to the control room.

Now, for that reasons we need some electrical output. So, what they do? In this case of this differential pressure transmitter, because there are two pressure tap, one is upstream pressure tap, another is down downstream pressure tap, now you can see here, this is basically a capacitive type, DP transmitter. Here, here we have a upstream pressure tap and here you can see the downstream pressure tap. See, you can open it and connect to the upstream pressure tap here. So, inside what we have? We have a capacitor with movable plates, so and the inside of the two capacitors are plated with some metal. So, you will get, once the capacitors, suppose this side is high and this side is low, the capacitor movable plates will move on this side. So, I will get a push pull sort of variations of the capacitance, which can be calibrated in terms of pressure and ultimately that will be calibrated in terms of flow.

Now, this is, basically this capacitive sensors inside and this measurement circuits and signal conditioning circuits are here on this side.

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You can see here if I open, there is a connection for the signals. You see here that we have positive signals, because the, in the process the output is 4 to 20 milliampere and the supply voltage maximum is 45 volt DC supply, because in all the process, as you know it is, you cannot give this ... voltage much higher. That is also not necessary and it will give the, according to the variation first of all this, this circuit will first measure the variation of that capacitance and that variations of the capacitance will be converted in terms of current - 4 to 20 milliampere of current. So, ultimately that 4 to 20 milliampere of current will be calibrated in terms of flow. But please remember, we have also differential flowmeters like, pitot tube is also differential flow, pressure flowmeter, elbow meter is also differential pressure flowmeter, in next session which will be discussed. So, this ends the lesson 12 of Industrial Instrumentation.