Industrial Instrumentation

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Lecture - 10
LVDT

Good morning! Welcome to the lesson 10 of Industrial Instrumentation. In this lesson, we will study LVDT. The full form of LVDT is the linear variable differential transformer. It is basically an inductive based sensor or inductance based sensor and primarily it is used for the measurement of displacement. However, I can use it for measurement of pressure and other process parameter also. In this particular lesson we will consider, the lesson, I mean the basic concept of the LVDT, its circuitry, its signal conditioning circuits and its basic constructions and how will you design an LVDT? These are the basic things which we will discuss.

Even though I have not written, the contents of this lesson will be the LVDT, its construction, its signal conditioning circuit, lead network, lag network and a phase sensitive demodulation circuit, as well as some design equations of LVDT. So, at the end of this lesson, the viewers will know the basic construction of the LVDT, what are the signal conditioning circuits have to be used, what are the precautions you have to make it, its sensitivity, all those things will be studied in details in this particular lesson.

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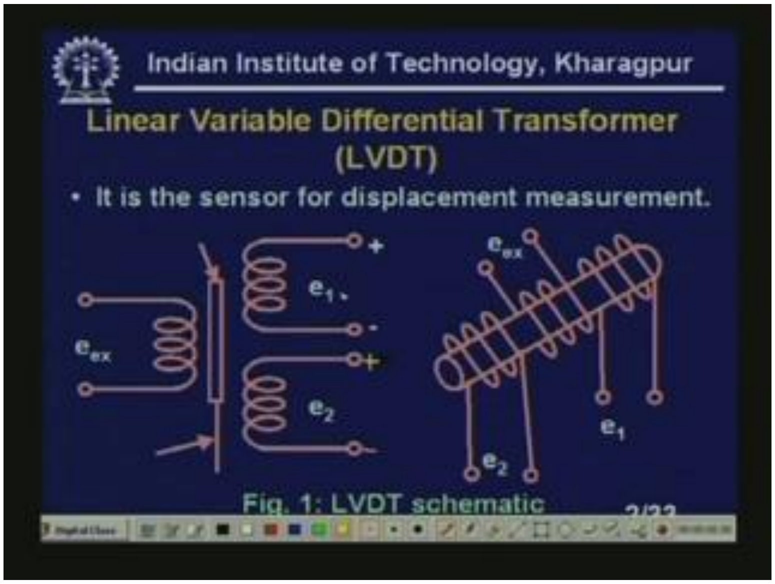

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Linear Variable Differential Transformer (LVDT)

- It is the sensor for displacement measurement.

Fig. 1: LVDT schematic

It is the sensor for displacement measurement. You see, this is our basic LVDT. You can see here that we have a primary here. There are three windings. Look at very carefully, we have one primary and two secondaries, two similar exactly identical secondaries, right? Actually here, should be also, if I take, should be also, so the excitation voltage will be here. It will come here, an E ex excitation voltage. So, it will be, any voltage between 3 to 15 volts and 50 to 20 kilohertz and two different secondaries.

Here you can see the basic construction. You see here the, on a …… the primary are wound, primary is wound and the two secondaries are wound in this fashion, right? Later on we will see that we will connect these two secondaries in opposition that will come later on and you see there is a core, iron core which will move up and down, this iron core which will move up and down. Interestingly you see that if this core moves up, so there will be no linkage between this and this, so the mutual inductance between this coil and this coil will increase and the mutual inductance between this coil and this coil will decrease. So, at geometrical null position, mutual inductance between this and this, this primary and this secondary, and this primary and this secondary will remain the same, right?

Now, let us go to the instrumentation lab of IIT Kharagpur and have a look on the LVDT.

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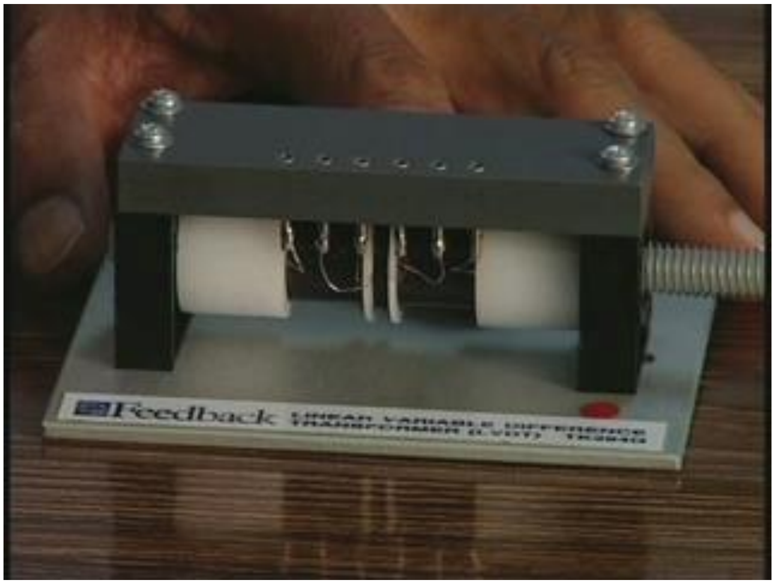

You see here, this is an LVDT - linear variable differential transformer. It has one primary and two secondary. The secondaries are usually connected in opposition to get a null position and through, after doing the phase sensitive demodulations, I can sense on which side of the, which side of the null position my, the core lies?

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You see here, the core is there, soft iron core which will move like this, which will move like this, so and I am moving, I mean it is, it will move like this and since there are two secondaries what will happen if you put in opposition? Obviously, you will get some output voltage and at null point it is at the, exactly at the null positions, the two secondary coils will be, output voltage will be nullified and I will get zero voltage. At any position other than that will give you nonzero output voltage. So, LVDT already we have discussed in details, so this is actually pictorial view of the LVDT.

Welcome back to our classroom again. So, we have seen the construction of an LVDT and how it works.

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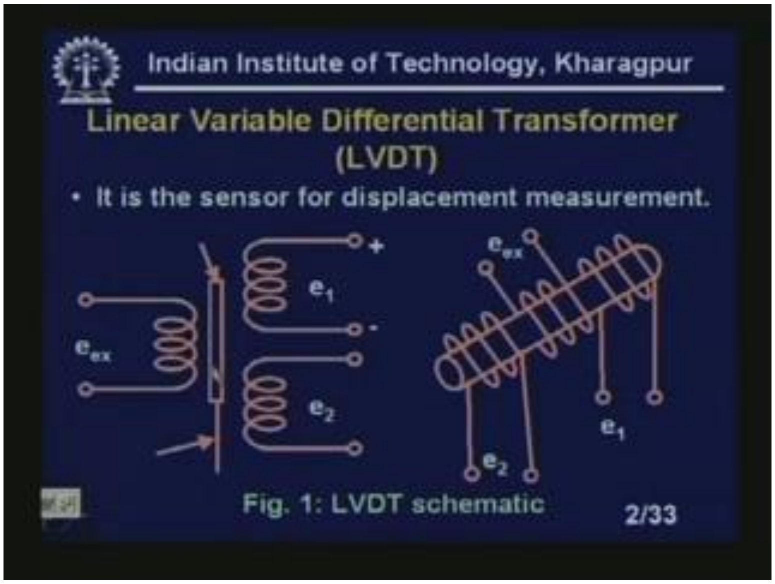

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Linear Variable Differential Transformer (LVDT)

- It is the sensor for displacement measurement.

Fig. 1: LVDT schematic

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Actually this core will, if you look at this core, this core will move up and down; this core will move up and down and I will get the different mutual inductance. Also, the voltage also will be changed and there will be the phase difference between the input and output.

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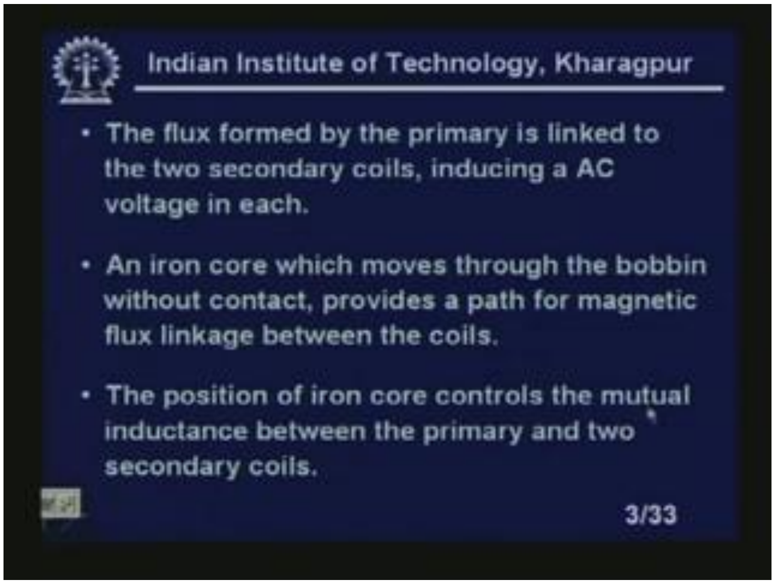

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- The flux formed by the primary is linked to the two secondary coils, inducing a AC voltage in each.
- An iron core which moves through the bobbin without contact, provides a path for magnetic flux linkage between the coils.
- The position of iron core controls the mutual inductance between the primary and two secondary coils.

So, that is actually we, we have written in a, in a nice way. You see, the flux formed by the primary is linked to the two secondary coils inducing an, a, it will be an, an AC voltage in each. An iron core which moves through the bobbin without contact provides a path for magnetic flux linkage between the coils. The position of the iron core controls the mutual inductance between the primary and two secondary coils; this is most important thing, right and usually we will find the entire …… assembly we put, in some cases we will put in another casing, so that it will not be influenced by the other external magnetic field; obviously, it depends on the magnetic fields.

So, in some cases we will find that the, we put the entire assembly, so that the external magnetic field will not affect the output voltage, because the out, we want that the output voltage will be, will be a function of the position of the core of the LVDT.

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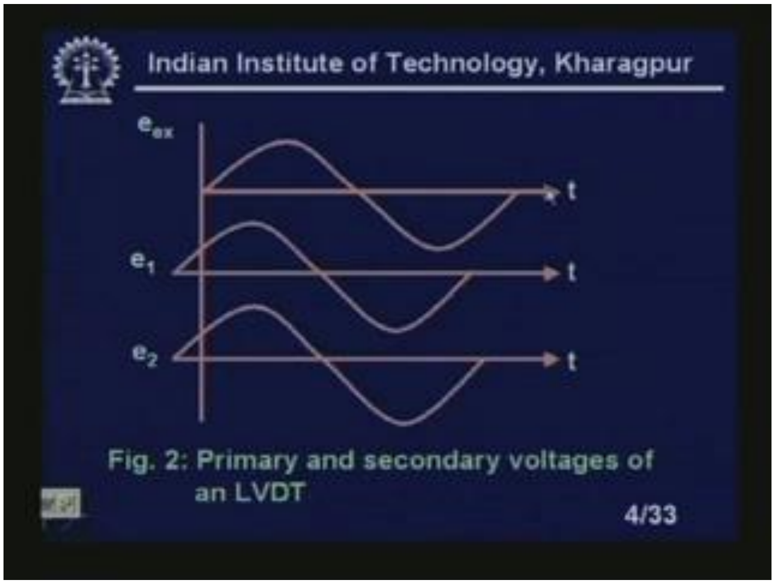
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Fig. 2: Primary and secondary voltages of an LVDT

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Now see this is the, we have given the, if you look at the screen, you see we have given the excitation voltage, a sinusoidal voltage in the primary and the two secondaries are identical. So, obviously I will get two secondary voltages e 1 and e 2. We are assuming in these cases that the core is in null position that is geometric null position, so I am getting excitations of equal phase difference between, in the, between input and output. This is our input or excitations. I am not giving, telling it input, because input in the case of LVDT is the displacement which we will give on the core and output is the output voltage and in this case it is e 1 and e 2, right?

Now, you see that there is an equal phase difference between input. This is, the two secondary coils are identical in nature, so there will be equal phase difference in the two. So, you have seen that if you not consider, might be there will be some attenuation. Obviously there will be no question of ……, so there will be some attenuation we will get, but we have ignored that part. So, we have assumed that the, I will get the equal magnitude in both the secondaries.

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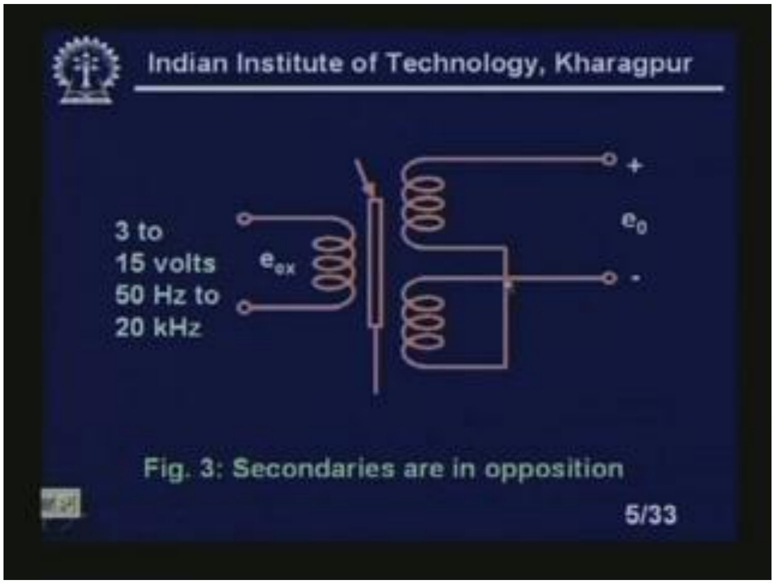

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Fig. 3: Secondaries are in opposition

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Now a secondary is, now you see a LVDT, we never use two secondaries separately; we always put the two secondaries in opposition. What is that thing? If you look at the board, our digital board, you will see here that excitations we are giving here. This is the core positions. We have 3 to 15 volts, 50 hertz to 20 kilohertz we are giving and output voltage. You see the two secondaries here, these two secondaries in opposition, there is no connection at this point. Please note there is no connection at this point. So, this is one secondary and it is connected to the bottom and it is coming like this one.

What is the advantage of this one? You see, in these cases advantage is, when this core is at the geometric null position you will find that the output voltage e naught will be zero. So, if I put this core slightly up and slightly down, I will get a non-zero output voltage, right? So, if I put this core slightly up, I will get a non zero output voltage. Because, what will happen? In this case, the two secondary output voltage are exactly in oppposition and this two will cancel out. I will not get any voltage at the output, right?

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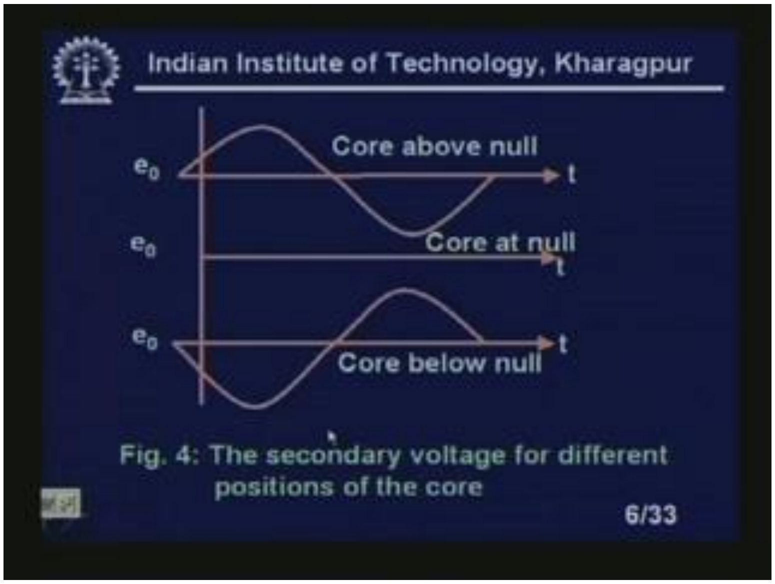
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Fig. 4: The secondary voltage for different positions of the core

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Now, see this is the output voltage we have drawn with respect to time, when for the different positions of the cores. Since these two cores, since these two secondaries are in opposition, we will find, if you look at the board, are in the oppositions, we will find that core, this is the core at the null positions, theoretically this should be exactly zero. So, see here, even though we are giving some excitation voltage which is sinusoidal voltage, I am not getting the output voltage since the two secondary voltage will cancel each other. Whereas, you see, when this core is above null, I will get a voltage like this one with a phase shift. If the core is below null, I will get a phase shift, a 180 degree phase shift, separate or opposite to the core above null, exactly, got it?

This is necessary, because in some situations, I must know in the, which position of the, core lies in which position, whether it is above null or below null. You see here, what will happen? It is slightly, we are getting like this one, right? So, you see, these two phases are exactly out. That means if this is 180 degree out of phase and there is a phase difference between this input voltage and this or excitation voltage and this and excitation voltage and this, but these two voltages, when the core is above null and when core is below null, the two phase difference is exactly 180 degree out of phase.

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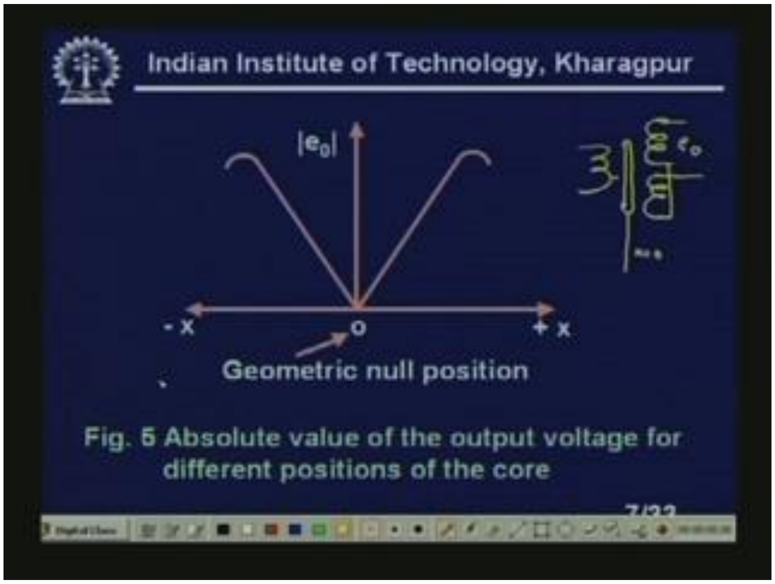

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Fig. 5 Absolute value of the output voltage for different positions of the core

Now you see this is the, now we have, I mean taken the magnitude of the output voltage, right? We have taken that is the reason we have written here e naught mod, absolute value of the output voltage we have taken. Now, I change the position of the core, I measure the output voltage right? For, suppose for a x centimeter, 1 centimeter, what is the output voltage I have plotted, then for x equal to 2 centimeter what are the output voltage I have taken, for x equal to 3 centimeter what are the output voltage I have taken, right and these voltages I have plotted like this, clear?

So, you see, we are getting a linear curve that means the relation between the displacement and the output voltage when the core is in, when the secondaries are in oppositions, exactly we are getting a relationship of linear, I mean linear relationship we are getting. So, at the geometric null position, so you see, we are not getting any output voltage, right? Now, this is the, what is plus x, what is minus x? Plus x, if I move the core in one side of the, suppose I mean, if I take the, looks like this one.

Suppose I have a core here, right, this is my output voltage, is not it? So, this is the position x is equal to suppose zero, if I put it up suppose in this position, so if I put it, I, I am taking it a positive displacement, if I put it down I get a negative displacement. So, in that respect, I am calling it as plus x and minus x. Now, if I put on the other side of the null position, I will also get the voltages, obviously with phase shift, but if I take a magnitude, so I won't, the phase shift, I cannot identify that phase shifts. Just if I take the absolute value, so you see that I will get a curve like this one and this, I mean you see it is falling down, because at that position what will happen?

I am taking the core totally out of the bobbin. In that type of situation, it will fall like this in both the cases. It is, when it is going up it is going out and it is when it is going down like this one, you see I am getting a straight line, straight line relationship like this one. So, this is our, I mean the absolute value, the, that means the output voltage of the LVDT, when in series opposition versus the opposition of the core, right?

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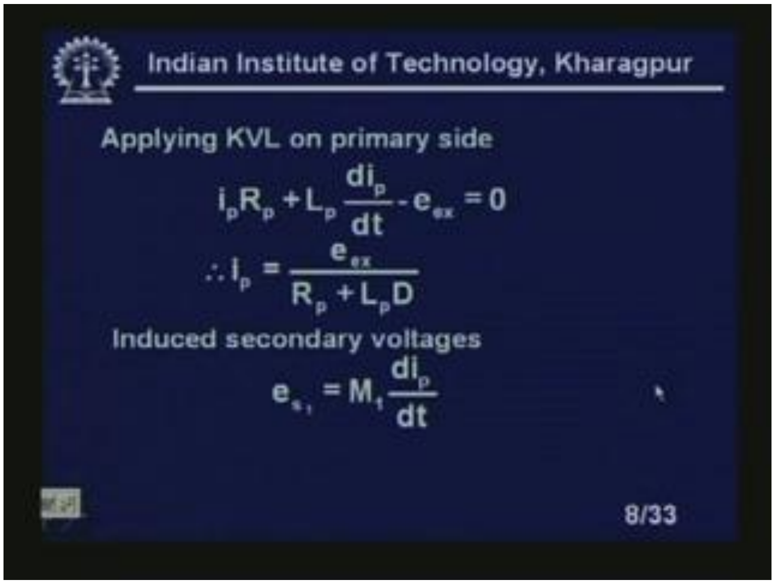

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Applying KVL on primary side

$$i_p R_p + L_p \frac{di_p}{dt} - e_{ex} = 0$$

$$\therefore i_p = \frac{e_{ex}}{R_p + L_p D}$$

Induced secondary voltages

$$e_{s_1} = M_1 \frac{di_p}{dt}$$

Now applying KVL if I take the equivalent circuits, if I, if you look at, I mean, I mean applying the KVL on the primary side, I can write you see i p R p plus L p di p by dt minus ex equal to zero and i p equal to ex R p plus L p D. Second, if I go back, if I look at, I mean that will be better, if I go back here, this is actually should be, yes, I am sorry, you see this is our equivalent circuit of LVDT.

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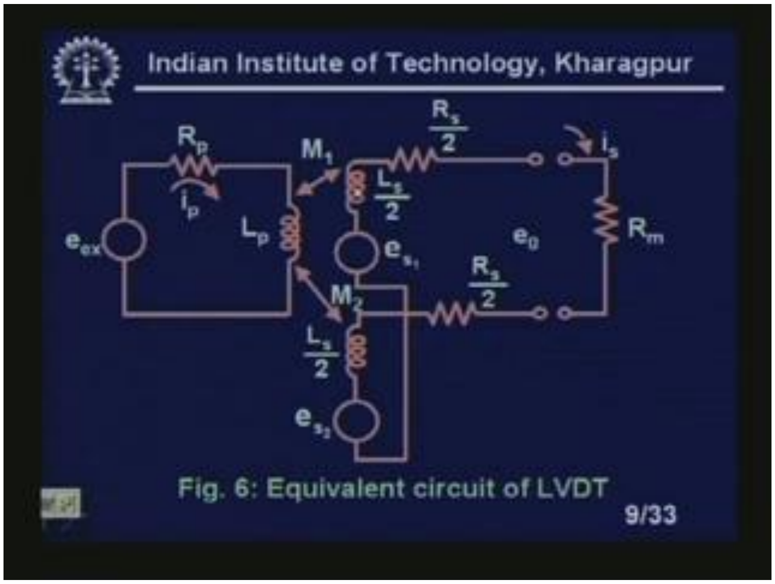
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Fig. 6: Equivalent circuit of LVDT

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We have taken here, this inductance is L p. Primary inductance, this is primary resistance R p, this is excitation voltage ex and this is the resistance of the, there are two secondaries, we are taking the, if we assume that two exactly identical, so I can take this inductance is L s by 2, this resistance is R s by 2. So, we will get a simplified equation. This is the, M 1 is the mutual inductance between the primary and the one of the secondary.

This M 2 is the mutual inductance between primary and one of the secondary. This is the output voltage e s1 and this is the output voltage e s2. That means voltage source here and this R s2 and this, for the time being we have not connected, so we are connecting an R m, a meter impedance. When there is a, current is flowing through the, this circuit, right? See, if I now draw the, I mean write the KVL around this loop, I want to write the KVL around this that means in the primary side I will get, if I go back, see if I, now see e s1 and e s2 will try induce voltage in the primary.

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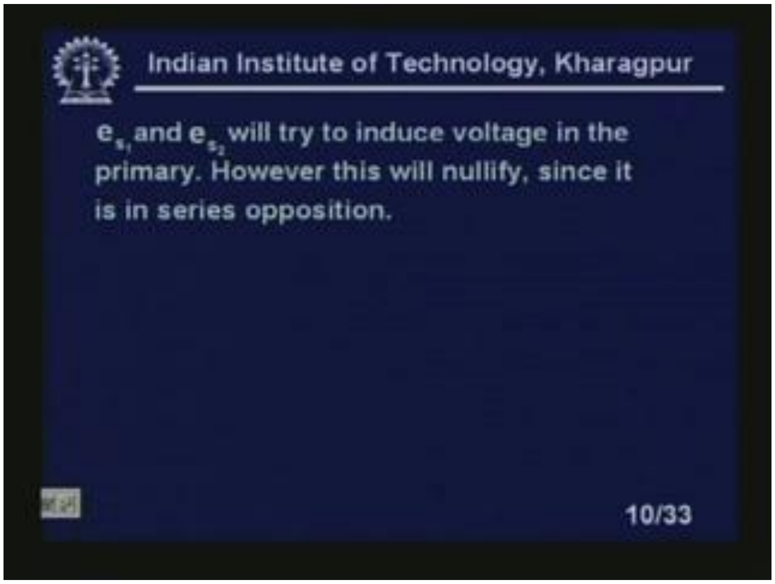

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e_{s_1} and e_{s_2} will try to induce voltage in the primary. However this will nullify, since it is in series opposition.

However, this will nullify, since it is in series opposition, right? What is e s1 and e s2? So, already we have seen, so if the e s1 and e s2 will try to induce the voltage in the primary and this will nullify, since it will be, is in series opposition. Now, if I go back, you see, can see here, so you see, this is our basic equation, I am sorry.

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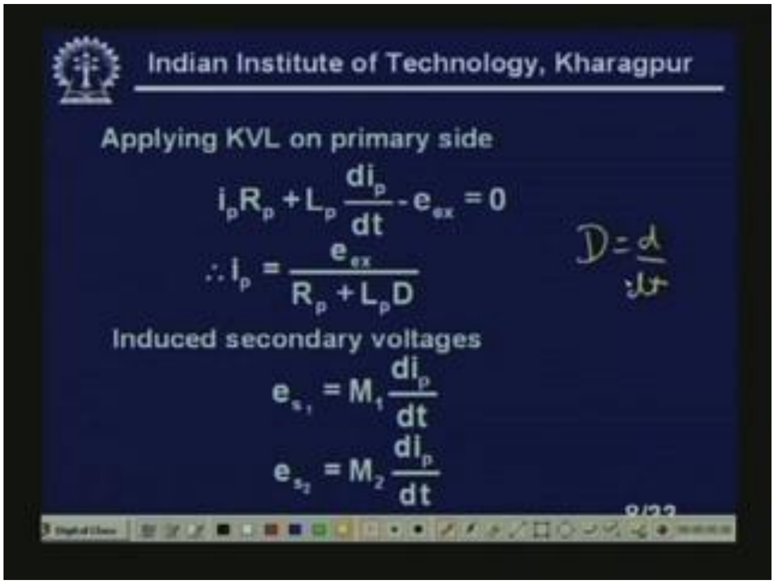

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Applying KVL on primary side

$$i_p R_p + L_p \frac{di_p}{dt} - e_{ex} = 0$$

$$\therefore i_p = \frac{e_{ex}}{R_p + L_p D}$$

$$D = \frac{d}{dt}$$

Induced secondary voltages

$$e_{s_1} = M_1 \frac{di_p}{dt}$$

$$e_{s_2} = M_2 \frac{di_p}{dt}$$

Now, see here, if I apply a KVL around primary sides I will get the equation like this and already we have seen the equivalent circuits of an LVDT. So, if I apply the KVL, I will get equation like this one - i p R p plus L p di p by dt. Now, you see and so, i p equal to ex, where D is that operator. So, as before we know what is D? We know that D equal to, D equal to d by dt, right, d by dt, so that is the operator. So, I can come back, you see here and ex equal to R p plus L p D. An induced secondary voltage e s1 is M 1 di p by dt and e s2, e s2 and e s1, already we have seen what was this?

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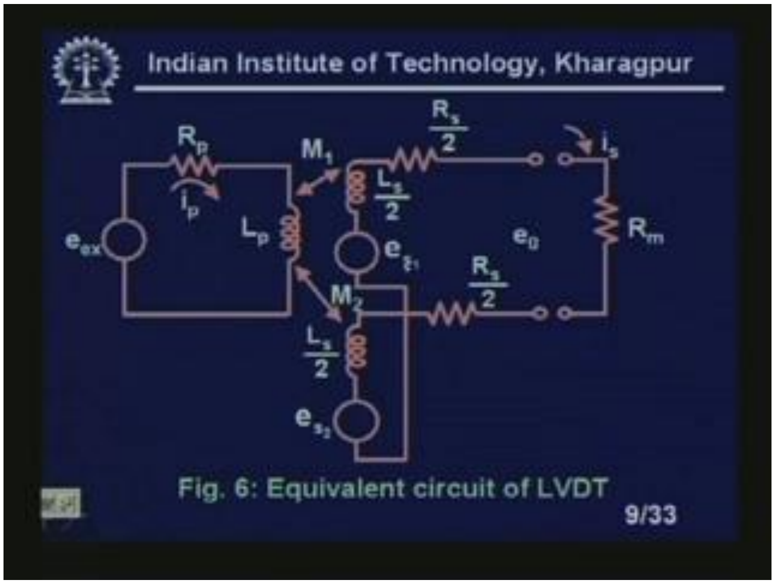
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Fig. 6: Equivalent circuit of LVDT

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If I go back, you see, e s1 is this one and e s2 is this thing, right? So, this is the induced secondary voltage, right? So, this is our actual equation. So, you see the induced secondary voltage. This is applying on the primary sides. But in the secondary side this will induce a voltage like this one, e s1 equal to e s2; e s1 equal to M 1 di p by dt and e s2 equal to M 2 di p by dt. So, all, with respect to the, the primary current, right?

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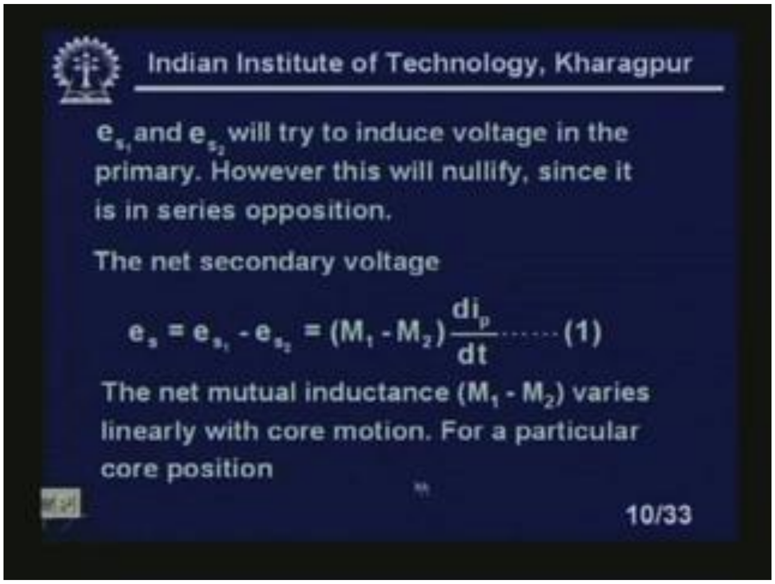

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e_{s_1} and e_{s_2} will try to induce voltage in the primary. However this will nullify, since it is in series opposition.

The net secondary voltage

$$e_s = e_{s_1} - e_{s_2} = (M_1 - M_2)\frac{di_p}{dt} \cdots\cdots (1)$$

The net mutual inductance ($M_1 - M_2$) varies linearly with core motion. For a particular core position

Now, you see, this already we have discussed, now let us look at, so e s1 and e s2 will try to induce voltages in the primary. However this will nullify, since it is in series opposition. So, find the problem. So, the net secondary voltage, if I look at e s or e naught, whatever you say, equal to e s1 minus e s2. This will be equal to the, if you look at the expressions which you have seen, say M 1 minus M 2 di p by dt, because e s1 equal to M 1 into di p by dt and e s2 equal to M 2 into di p by dt, so e s1 minus e s2 M 1 into minus M 2 di p by dt. The net mutual inductance M 1 minus M 2 varies linearly with the core position.

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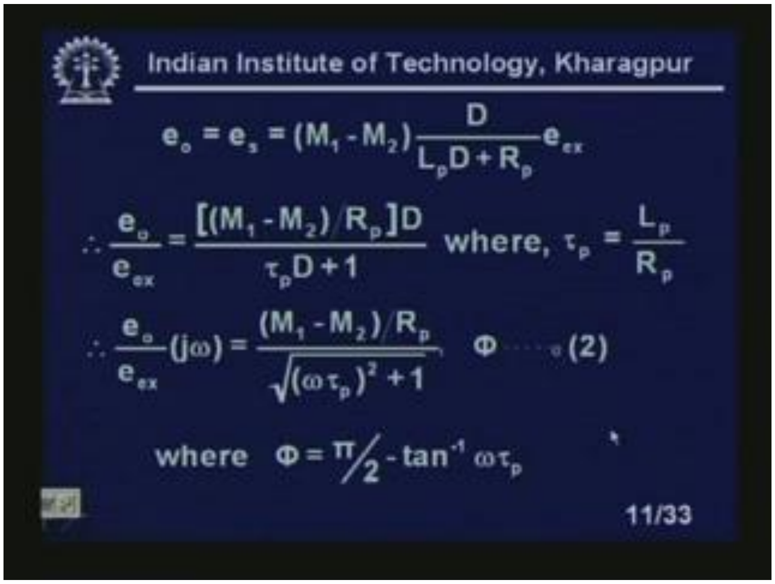

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$$e_o = e_s = (M_1 - M_2)\frac{D}{L_pD + R_p}e_{ex}$$

$$\therefore \frac{e_o}{e_{ex}} = \frac{[(M_1 - M_2)/R_p]D}{\tau_pD + 1} \quad \text{where, } \tau_p = \frac{L_p}{R_p}$$

$$\therefore \frac{e_o}{e_{ex}}(j\omega) = \frac{(M_1 - M_2)/R_p}{\sqrt{(\omega\tau_p)^2 + 1}} \quad \Phi \cdots (2)$$

$$\text{where} \quad \Phi = \pi/2 - \tan^{-1}\omega\tau_p$$

For a particular core position, e naught equal to e s equal to M 1 minus M 2 D operator L p D plus R p ex, right, excitation voltage. Now, you see, this e naught by ex I can write, excitation output voltage by, if I normalize the output, it will be M 1 minus M 2 by R p D operator tau p D plus 1, where tau p equal to L p by R p, right? Now, you see here that this is the time constant. So, this is the first order system, so it is a time constant of the system. Now, e naught by ex if I look at, now obviously what will happen? Where is the x, where is the position?

Position is here; in the inside there is, it is M 1 and M 2, because this is directly proportional to the position of the core, is not it? This M 1 and M 2, it, it directly depends on the position of the core. So, you see this output voltage also depends on this value of the M 1, so all other things will remain constant. M 1 will vary, M 2 also will vary, while the, if I move the core up, then what will happen? If they move the core up what will happen?

The M 1 will increase, M 2 will decrease. If I decrease the, if I make the core down, M 2 will increase and M 1 will decrease, is not it? So, there it is, this x is hidden within this M 1 and M 2. So, obviously, this output voltage will be proportional to the position of the core R x, right? So, if I write in the frequency domain, so it will be like this one, M 1 minus M 2 R p square under square root omega tau p square plus 1 with an angle phi. It is not come, so the angle will look like this, right? So, this is the magnitude, this is the magnitude part and this is the, your phase part. So, what is the phase, let us look at.

So you see, the phase is equal to pi by 2 minus tan inverse omega tau p, right? So, the phase also depends on the frequency, tau p is a constant. So, in fact, I can make omega tau p constant, because tau p does not depend on the position of the core, is not it? Tau p depends on L p and R p. You see, here this is constant for particular L p dt. Omega is the excitation frequency, if I keep constant, it will also remain constant. So, phi equal to pi by 2 minus tan inverse omega tau p, this will remain constant for a particular excitation frequency.

If ….. I can make it zero also. If I can cancel, if I make tan inverse omega tau p equal to, exactly equal to pi by 2, so this will be cancelled. There will be no more, but sometimes this is not be possible, so you will use some lag network or lead network to kill the phase, phase, I mean lag or lead, right? So, I can make the phase compensation with simple RC circuit. Let us look at that.

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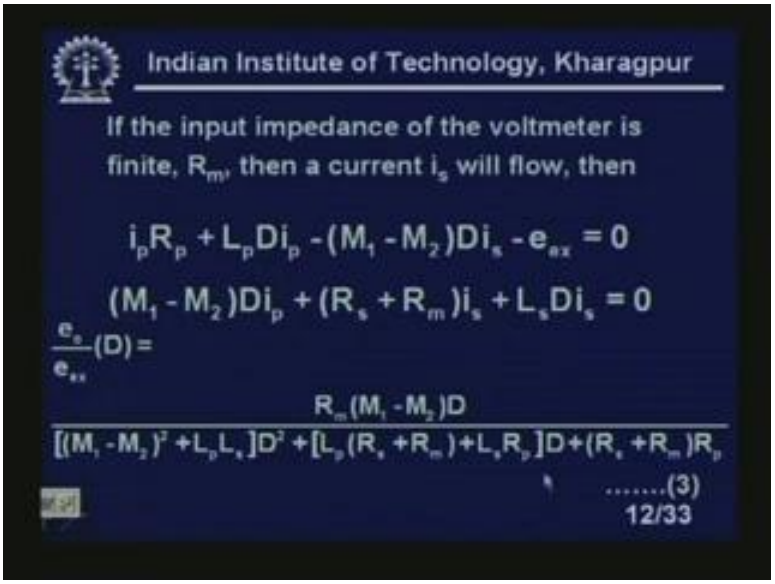

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If the input impedance of the voltmeter is finite, R_m, then a current i_s will flow, then

$$i_pR_p + L_pDi_p - (M_1 - M_2)Di_s - e_{ex} = 0$$

$$(M_1 - M_2)Di_p + (R_s + R_m)i_s + L_sDi_s = 0$$

$$\frac{e_o}{e_{ex}}(D) = \frac{R_m(M_1 - M_2)D}{[(M_1 - M_2)^2 + L_pL_s]D^2 + [L_p(R_s + R_m) + L_sR_p]D + (R_s + R_m)R_p} \quad \text{.......(3)}$$

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If the input impedance of the voltmeter, now you see the, all the analysis, so far whatever we have made, we are assuming that the, there is, no current is flowing through the secondary. Current is not flowing through the secondary, because we are assuming that the, we are measuring these impedances. We are connecting that secondaries open circuit, but most of the cases it is not true. Secondary we must, we will connect some, but you can say to some, I mean if I do some I mean approximation, this is also true, because we will connect a very high input impedance.

Suppose if I connect a CRO, cathode ray oscilloscope to measure the voltage output e naught, so obviously it has a very high input impedance. So, in that type of situation, so R i will be very high. So, I can assume almost that the, your secondary is open circuit. But if I assume, so i s will b e zero, but obviously if I take the finite case, if you take, assume that the, there is some current is flowing through the secondary. So, in that case we assume that the finite resistance R m, meter resistance is R m and a current i s is flowing through the secondary, because if you take a finite resistance R m, so obviously the current also will flow.

Previous analysis we have seen that there is, no current is flowing through the secondary. Only two voltages e s1 and e s2 was induced due the, due to the mutual inductance between the primary and the two secondaries, right? So, in that type of the situations my equation is, if you look at the digital board it will look like i p R p plus L p Di p minus M 1 minus M 2 Di s equal to minus e to the power e ex, subscript ex equal to zero. So, if I can write this equation, M 1 minus M 2 this will be equal to Di p plus R s plus R m i s plus L s Di s equal to zero. So, if I, I mean take all these, so I can write the simplified equations in order by e naught by, I mean e ex D M 1 minus M 2 whole square L p L s D square plus L p R s plus R m L s R p D plus R s plus R m R p, right? This is equation number 3.

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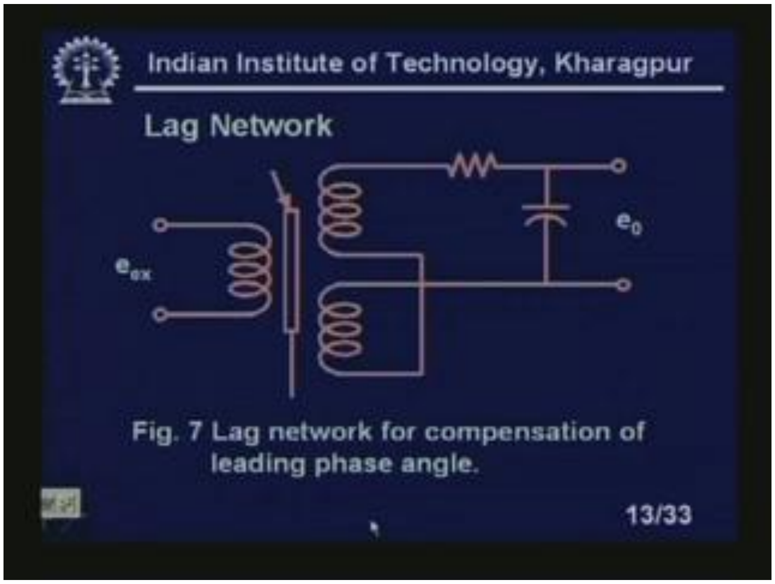
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Lag Network

Fig. 7 Lag network for compensation of leading phase angle.

So, lag network, as I told you, we need some lead and lag networks. So, lag network looks like this one. You see, this is a phase, this is a circuit. If there is a, there is a lagging phase angle, if there is a, phase angle is lagging, in that situation we will connect ….. This is our lag network. So, it will kill the lag and it will have, the output voltage will be in phase with the input voltage. It is not very important, in most of the case you will find, right? So, this is the lag network for compensation of the leading phase angle. If the phase angle is leading, you can use this lag network. Lead network, similarly if it is lagging phase angle I can use a lead network.

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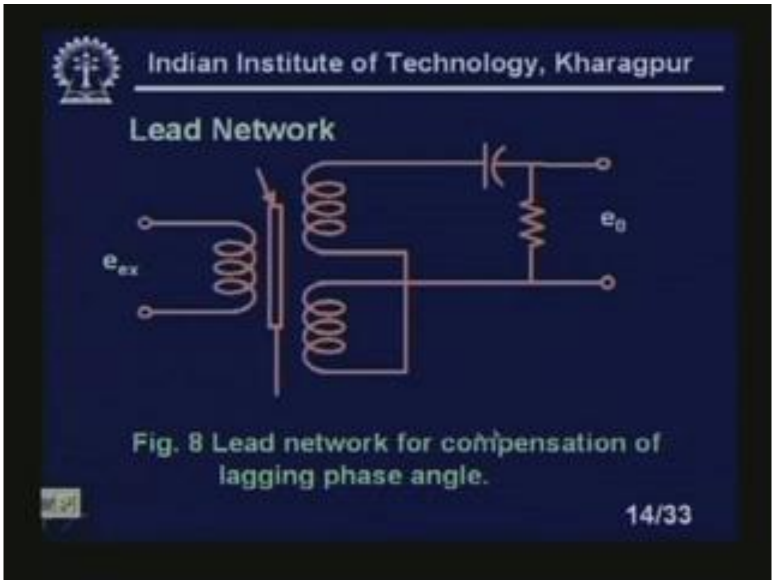
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Lead Network

Fig. 8 Lead network for compensation of lagging phase angle.

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So, lead network just interchange with capacitors and the, and capacitors and the resistance, I will get a lead network. So, it is a leading phase angle, it will look like this one.

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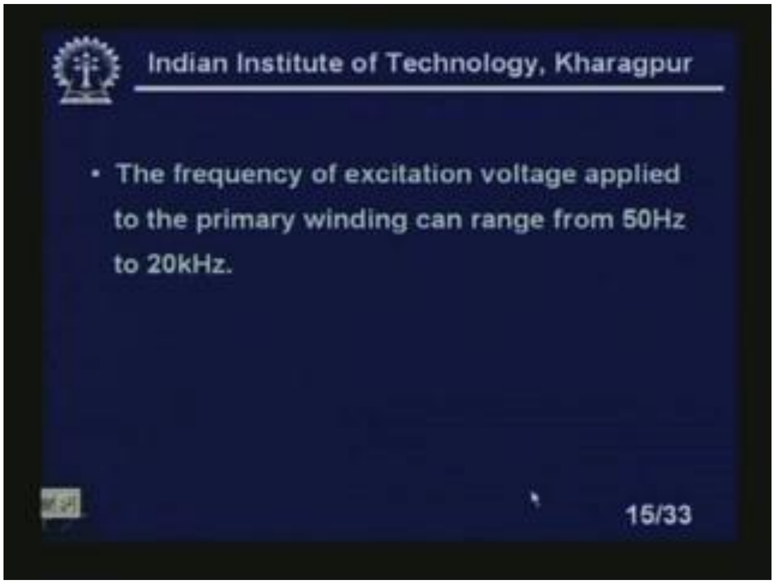
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- The frequency of excitation voltage applied to the primary winding can range from 50Hz to 20kHz.

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The frequency of excitation voltage applied to the primary winding can range from 50 hertz to 20 kilohertz.

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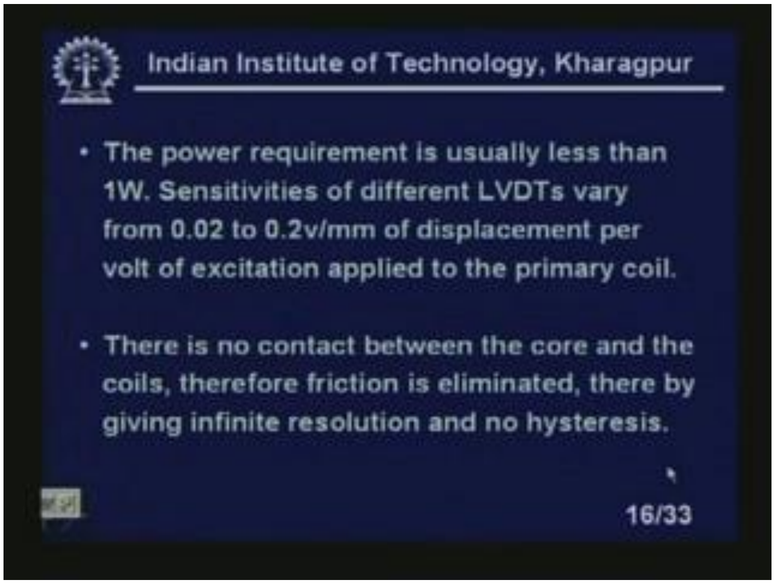

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- The power requirement is usually less than 1W. Sensitivities of different LVDTs vary from 0.02 to 0.2v/mm of displacement per volt of excitation applied to the primary coil.
- There is no contact between the core and the coils, therefore friction is eliminated, there by giving infinite resolution and no hysteresis.

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The power requirement is usually less than 1 watt and the sensitivities of different LVDT's vary from 0.02 to .2 volt per millimeter of displacement per volt of excitation applied to the primary coil, right? This is typical sensitivity, it is a very sensitive device. Now you see, most important thing of the LVDT is, you see it is a displacement sensor, as I told you. But, directly you can, displacement in the, in other case you can use it for, you can, so many you can use it for a load sensor, you can use it for pressure.

If you use in conjunction with a diaphragm you will find it is used as an, I mean as a pressure sensor. You can use it as a flow meter if you connect a, you will see that if you connect to the bob of a rotameter, you will find that this will be used as an, as a flow meter, as the indication of the flow. So, all these different, I mean applications are there, but directly it is actually measuring the displacement.

Now, other type of, simplest form of displacement measurement, it is a just potentiometer. A simple potentiometer if I look at, you will see if I connect like this one, suppose I have a like this one, so let me take another page that will be better or I will take a different colour. You see, what will happen, so I have, sorry let me write in a new page.

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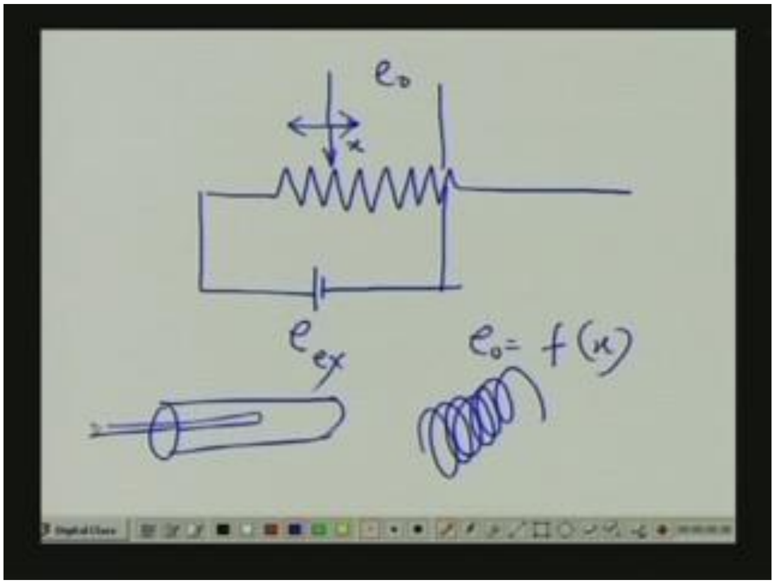

A simple resistance, a rheostat or a potentiometer, pot what we will call, suppose I have a wiper or jockey, in the case of potentiometer we will call it wiper, in the case of I mean rheostat we will call it jockey. So, if the jockey moves in this direction, then what will happen? I will give some excitation voltage, suppose and I am measuring the voltage on this one e naught suppose this excitation, so what will happen? This output voltage will be a function of this displacement, is not it? Suppose this is x, so this simple, a potentiometer can also be used as a, I mean as a, I mean displacement sensor.

However, the difference between the potentiometer and first of all the potentiometer and the LVDT, number 1 is the, its resolution. Resolution of LVDT is extremely good. Please note that resolution good means its numerical value will be less and another thing is you will find that sensitivity in the, both the cases I can change. I can change the excitation voltage, ex the excitation voltage of the, if I look at the digital class, I mean if I change the excitation voltage, my output voltage will also be increased or I can modify this thing. I am not ….. I am talking of the resolution. Resolution ….. you see that whenever a potentiometer if I look at the digital class you will find that the potentiometer here what will happen?

You see it will, even though I am showing here that it is getting contact only one, one, one turns, but you will see that practically potentiometer looks like this one, is not it? So, it will, always this wiper will contact more than one or two windings. So, resolution will basically depend how closely you make the windings. You are, it is, it is possible for you to make the windings as well as whether the, whether the, this wiper or jockey is getting connected to one winding or two windings, but that is not the case in the case of, I mean that is not the case for LVDT.

So, LVDT, what will happen? You see there is no contact between the, between the wiper which is basically a core, movable core and either primary or secondary. So, the resolution I could not, so it is, I mean, I mean it is first of all life will also increase. You will see here, in the case of, if you look at the digital class you see that what will happen that in this case that this core will, this wiper will move and after few use you will find there is wear and tear it is called, it is, this contact will be a, will become noisy because the contact also depends on how much pressures you are giving. That type of case does not arise in the case of, case of LVDT, because LVDT I have core, this bobbin and inside the bobbin this core is moving, is not it? So, there is no physical contact. So, life is almost infinity. You can say the mean time …. failure is very, very high.

Moreover, resolution is also high because resolution here is very, very small, I mean small means, I mean, I mean good, extremely high because in this case you see there is no, there is no question of even though whatever the windings we have on the outside that does not depend, that, that does not matter how fine and how close those windings, is not it, because the resolution here depends on the, the magnetic linkage between the two. It does not depend on the physical position or the physical number of coils which is getting touch with the wiper. So, that is the great advantage of the LVDT.

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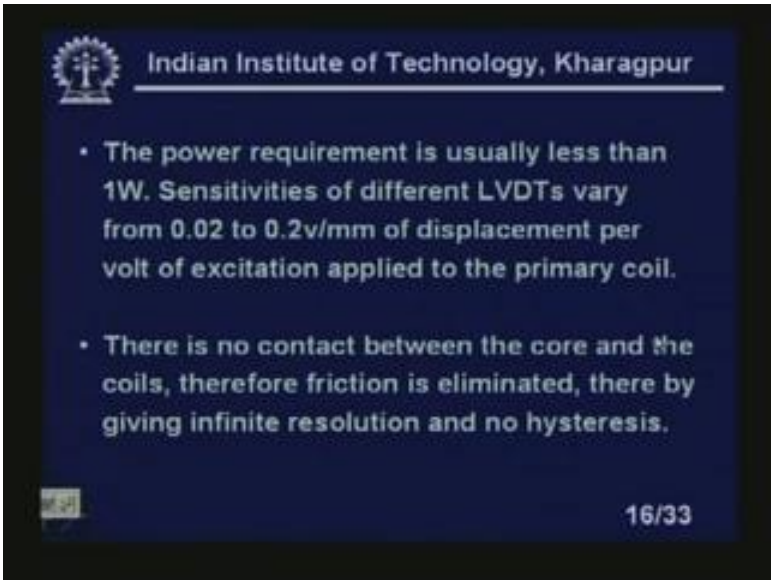

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- The power requirement is usually less than 1W. Sensitivities of different LVDTs vary from 0.02 to 0.2v/mm of displacement per volt of excitation applied to the primary coil.
- There is no contact between the core and the coils, therefore friction is eliminated, there by giving infinite resolution and no hysteresis.

So, that is we have seen, we have written, you see there is no contact between the core and the coils. Therefore, the friction is eliminated thereby giving infinite resolution and no hysteresis. This is another important, you see in the case of potentiometer there will be certain order of hysteresis you will find, but there is no hysteresis in this case.

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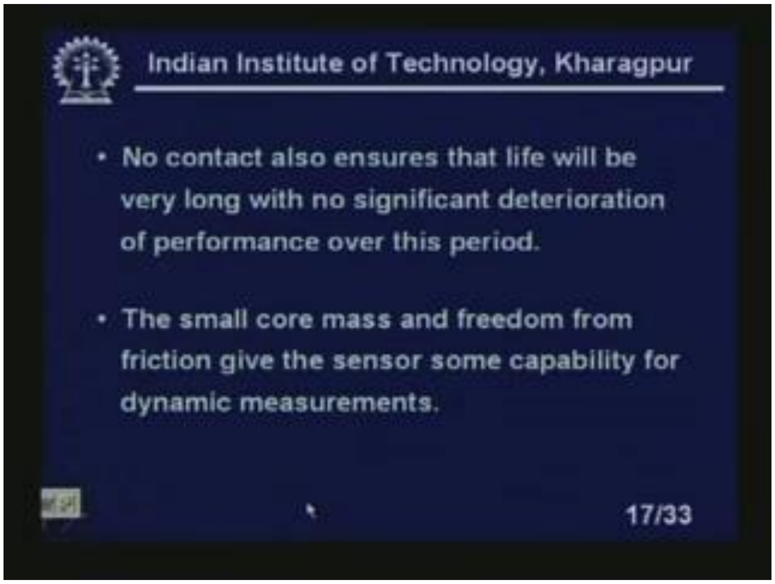

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- No contact also ensures that life will be very long with no significant deterioration of performance over this period.
- The small core mass and freedom from friction give the sensor some capability for dynamic measurements.

No contact also ensures that life will be very long with no significant deterioration of performance over this period. The small core mass and the freedom from the friction give the sensor, gives the sensor the some capability for dynamic measurements.

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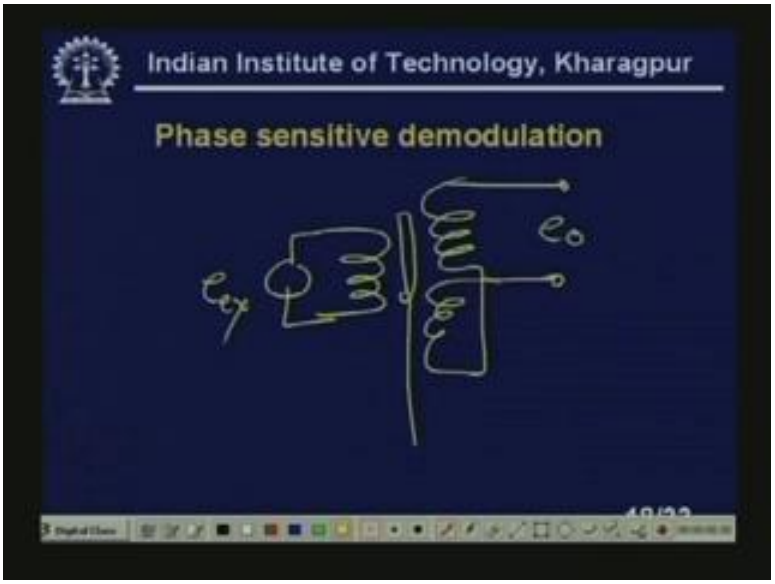

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Phase sensitive demodulation

Now, phase sensitive demodulation is very important in the case of LVDT, because LVDT we have seen that if the core moves up and down and I mean, if I look at, you see, if I, we have seen that I have a primary and two secondaries like this one. You see, this moves, so it moves up and down. What will happen? I will get a output now, is not it? So, if I move up, I will get some sinusoidal voltage, if I move down I will also get the same sinusoidal voltage. But how will I know on which side of this one, whether it is lying, sorry, whether it is lying up the meet position, null position or below the null positions?

For that reason, I have to make the phase sensitive demodulation of the circuit, I mean of the output. If I can make phase sensitive demodulation that means in that cases we will separately fully rectify the output to a secondary voltage, then make the algebraic sum of the two. So, one side I will get positive voltage, other side I will get a negative voltage, right?

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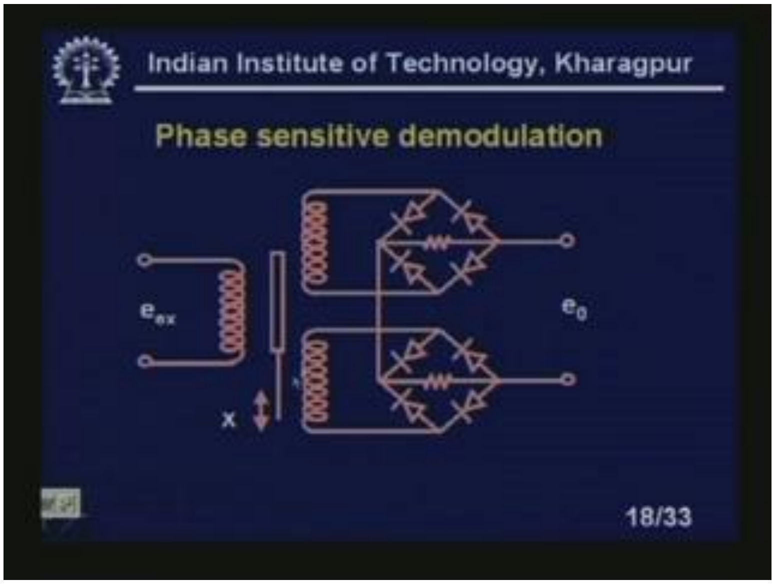
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Phase sensitive demodulation

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You see, this is the phase sensitive demodulation circuit. You see the, each half is actually rectified with a full wave rectifier. In all the cases, whether the, this is positive, this is negative we will find the current is flowing through this direction. If this side is more positive and this side is more negative, current is also flowing through the same direction through the resistance R. Similar is the case in the lower half that means in the other secondary. So, these two voltages, these two voltages we are making algebraic sum. If I can make this algebraic sum, then what will happen? You will find that the output voltage, polarity of the output voltage will depend on the position of the core that means whether the core is above the null or below null, right? If it is above null, it will be positive if we assume positive; if it is, this core is below null it will be negative, right? So, this is the phase sensitive demodulation circuit.

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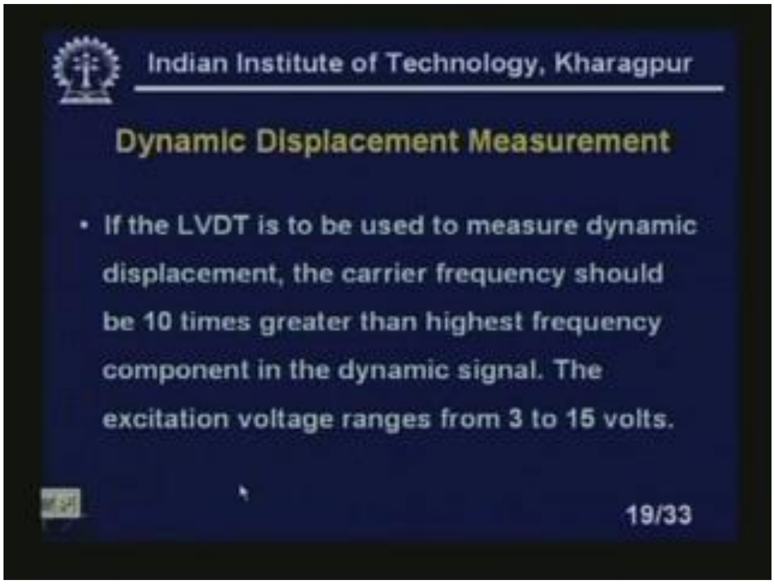

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Dynamic Displacement Measurement

- If the LVDT is to be used to measure dynamic displacement, the carrier frequency should be 10 times greater than highest frequency component in the dynamic signal. The excitation voltage ranges from 3 to 15 volts.

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Now you see the dynamic displacement measurements. If the LVDT is to be used to measure dynamic displacement, the carrier frequency should be 10 times greater than the highest frequency component in the dynamic signal. We will show the phase sensitive demodulation output after few slides. The excitation voltage ranges from 3 to 15 volts, right, because in some situations, I may need to make the dynamic measurements even though frequency should not be that high.

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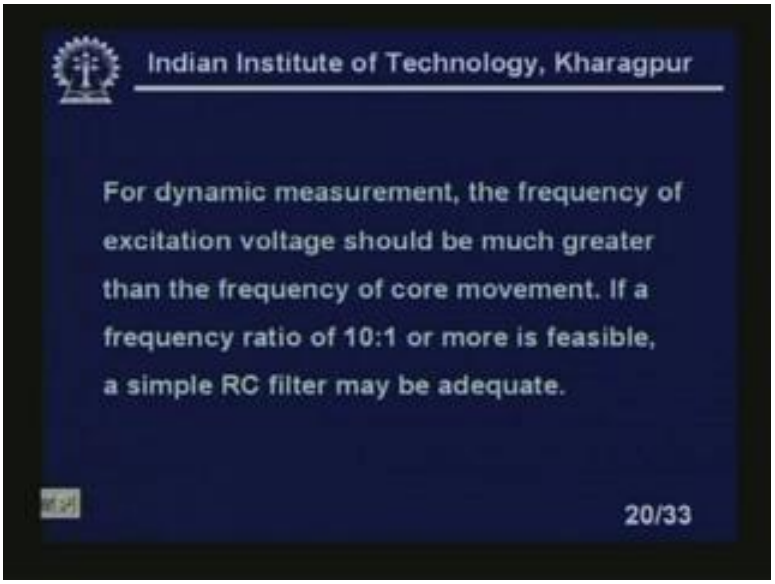

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For dynamic measurement, the frequency of excitation voltage should be much greater than the frequency of core movement. If a frequency ratio of 10:1 or more is feasible, a simple RC filter may be adequate.

So, for dynamic measurement, the frequency of excitation voltage should be much greater than the frequency of core movement. If a frequency ratio of 10 is to 1 or more is feasible, a simple RC filter may be adequate.

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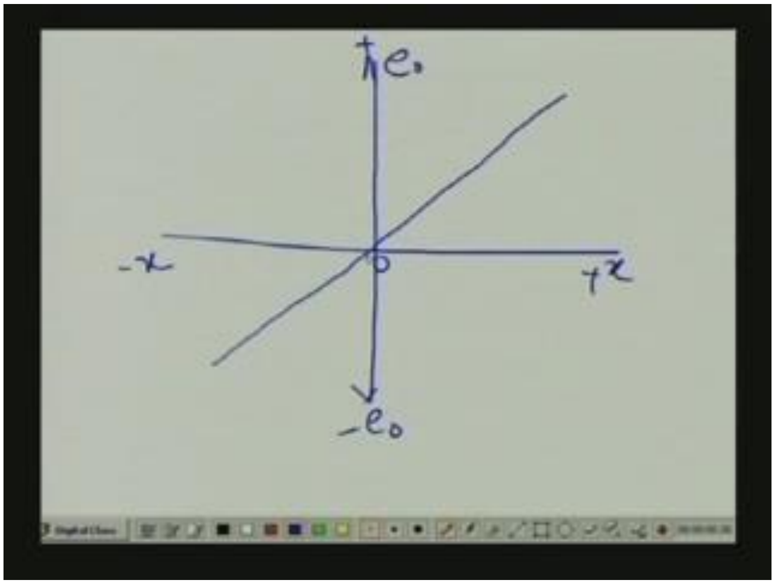

Now this is plus e, obviously this is … since it is fully rectified, so it is dc. Even though our excitation voltage is AC, now our output is DC because the, our two secondaries we have fully rectified and we are adding it algebraically, so the output voltage will look like this one. I am sorry, let me take another page. So, right, so this is our output voltage. This is positive, this is minus e naught, this is x, plus x, zero, this is minus x. As I told you, plus x, minus x is nothing but the above null or the one side of the null is positive. If one side of the core movement is positive, one side of the null, of the core movement is positive, other side of the, movement on the other side of the null is we are taking negative. So, you see we are, distinctly we are getting a linear relationship, but along with the change in the magnitude. This is …….

Now, I can tell it is above null or below null looking at the voltages; this is very important. Look at the digital class. If I look at, you will find that if the core below null, so obviously what will happen? So the, I will get a negative voltage.

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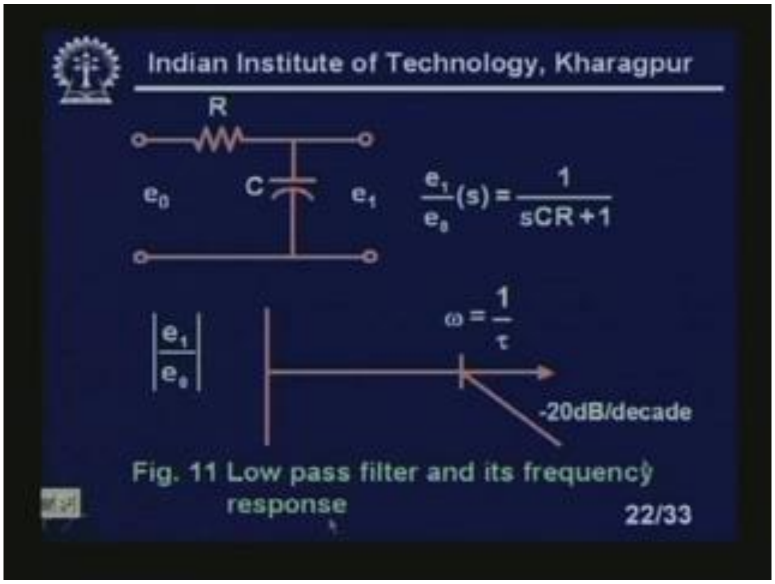
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$$\frac{e_1}{e_0}(s) = \frac{1}{sCR+1}$$

$$\omega = \frac{1}{\tau}$$

-20dB/decade

Fig. 11 Low pass filter and its frequency response

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Now, this is, you see the, again we are coming back to our RC circuits which is used for, I mean our simple RC circuits to make our, for dynamic measurements. In that case the carrier frequency should be much higher that means excitation frequency should be at least 10 times higher than the maximum expecting dynamic signal in the LVDT, right? That means what is dynamic signal here? Dynamic signal is the, movement of the core is the input, right?

Input is the movement of the, so that input component, frequency of that dynamic input component should be 10 times lower than the frequency of the excitations of the LVDT, clear? So, if I have that type of, I can have a simple RC filters. So, this is first order RC filter, so that will suffice that I can extract the original signal. So, the response will look like, you see, e 1 by e naught. This is the output voltage e 1 by e naught, so it is minus 20 dB per decade. So, it is a ….. frequency omega equal to 1 by tau, right? So, low pass filter and its frequency response.

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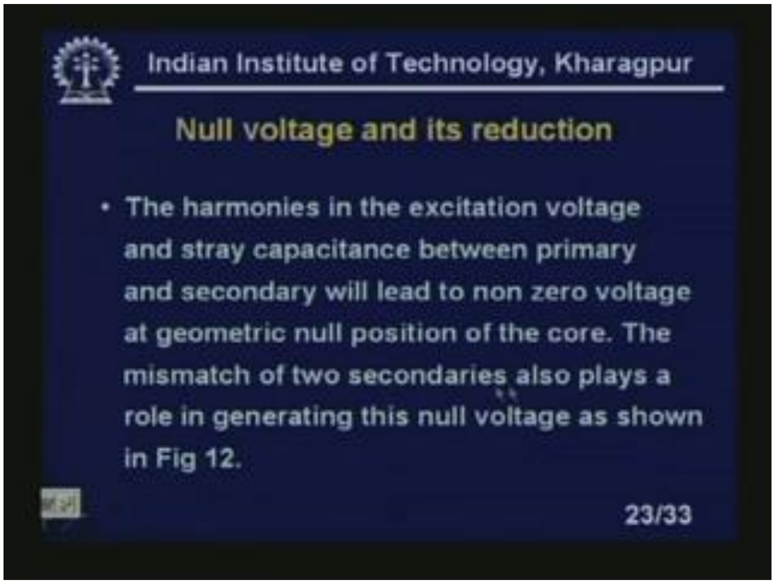

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Null voltage and its reduction

- The harmonics in the excitation voltage and stray capacitance between primary and secondary will lead to non zero voltage at geometric null position of the core. The mismatch of two secondaries also plays a role in generating this null voltage as shown in Fig 12.

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Now, another thing, even though I say it that in the case of LVDT you see that the two, two secondaries are exactly identical, but you know it is very difficult, absolutely difficult to make two, I mean secondaries exactly identical and the harmonics also will be present in the secondaries, right? So, this will create problem. That means this will make our, our circuit, this will make our circuit in such a way that I won't get zero voltage at geometric null position, right? That is the thing we have seen.

The harmonics in the excitation voltage if I look at and stray capacitance between the primary and secondary will lead to non zero voltage at geometric null position of the core. The mismatch of the two secondaries plays, also plays a role in generating this null voltage as shown in the figure 12, sorry.

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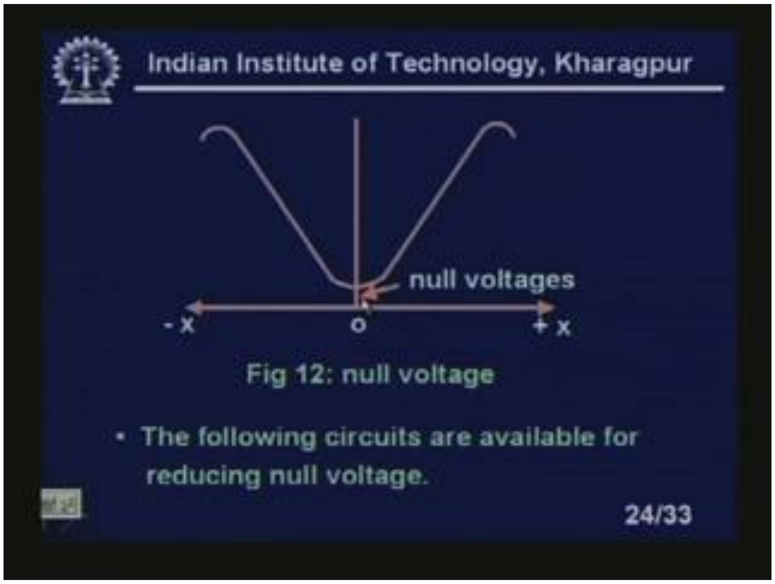

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Fig 12: null voltage

- The following circuits are available for reducing null voltage.

You see, this is a null voltage. It is supposed to be zero, but there is an, so the figure 2 is the null voltage. So, this you see here, the null voltage it is the voltage non zero, I mean voltage I am getting at the geometric null position, right, because making two identical secondary is almost impossible, right? So, what will happen that will be, some non zero voltage will remain. Actually what will happen if I look at the, I mean vector diagram it looks like this.

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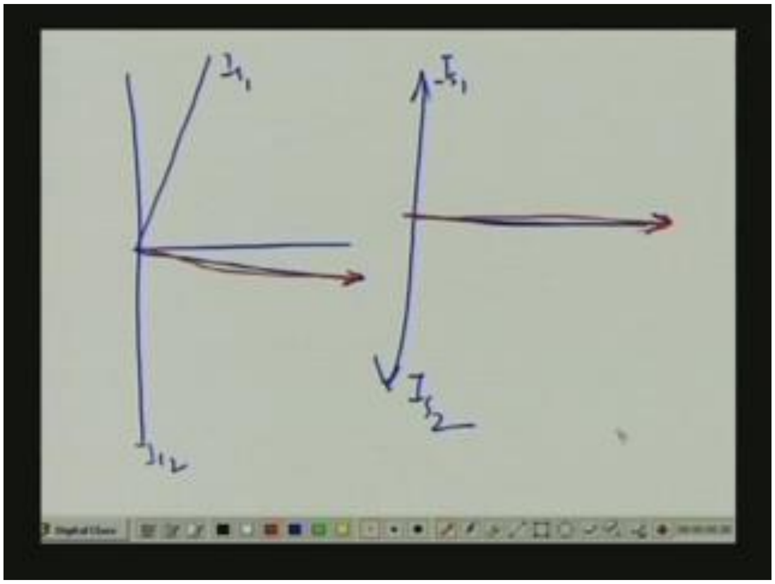

So, the two secondaries should be like this one. You see the, this is, if the secondary current I s1, this is I s2. If these two cancels it will look like, but actually what will I have? Due to mismatch, you will find one will be like this one, other will be like, this is I s1, I s2. So, the resultant will go like this one. In this case the resultant will go like this, right? If I take a different colour, so the resultant will go like this, whereas in this case the resultant will go like this. So, clearly I am getting non zero voltages, right?

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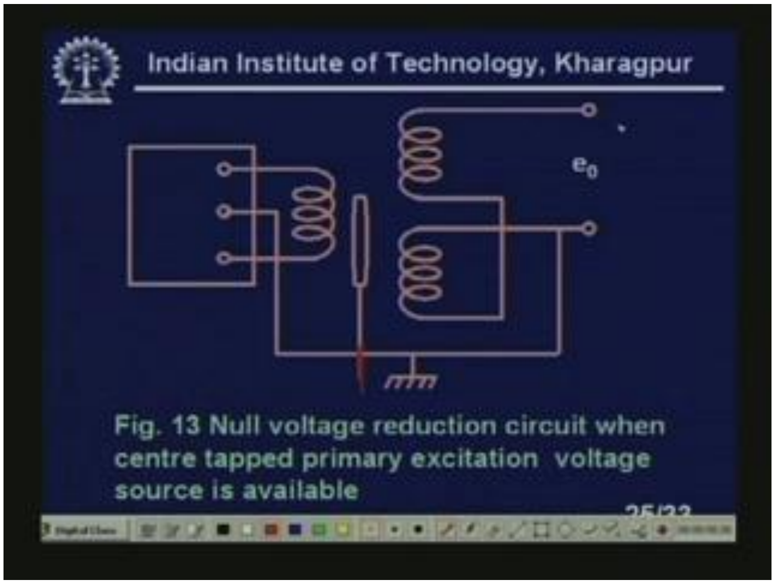

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Fig. 13 Null voltage reduction circuit when centre tapped primary excitation voltage source is available

Now, this null voltage is a nuisance, we must kill it. So, there are various circuits available to kill this null voltage. One of the voltages, you see the null voltage reduction circuit when the centre tapped primary excitation voltage source is available. If you have the centre tapped primary excitation voltage source, I can use this type of circuits, where you have seen that this centre tap is grounded, sorry this is not grounded. Actually this is the core motion, so it will come like this one, it will come out like this one, right and you see here, so I have a, centre tapped primary source is available. So, this is, the centre tapped is grounded with the ground of the one of the output terminals and I am getting outputs. In this case, case we will find the output voltage will be, the null voltage will be zero, right?

Now, figure 13, in next figure we will show that the, if the centre tapped excitation voltage is not available, how it we can kill this null voltage? It will look like this one.

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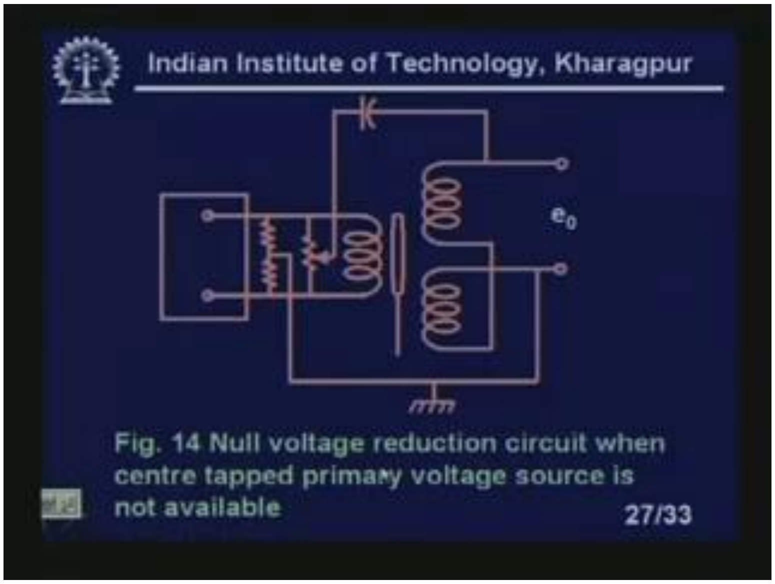

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Fig. 14 Null voltage reduction circuit when centre tapped primary voltage source is not available

You see the figure 14, the null voltage reduction circuit, when the centre tapped primary voltage source is not available. You see here this will vary this position. You see centre tapped is not available, two potentiometers it is dropped. This is grounded, this again in the previous case it is grounded, so this will vary. We will vary the position on the, this is potentiometer. It is all the, I mean voltages has come across the potentiometer. We will change the position on the core, position of the wiper, so that the output voltage will become zero.

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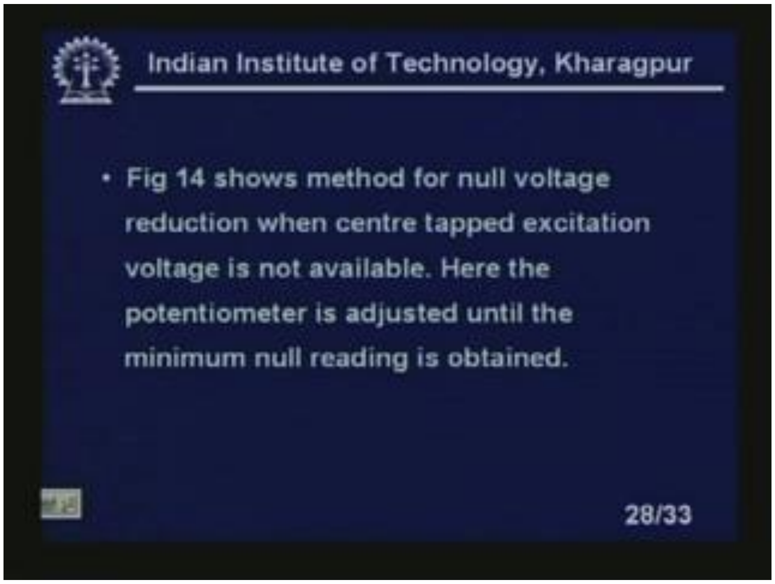

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- Fig 14 shows method for null voltage reduction when centre tapped excitation voltage is not available. Here the potentiometer is adjusted until the minimum null reading is obtained.

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So, figure 14 shows actually method for null voltage reduction when centre tapped excitation voltage is not available. Here, the potentiometer is adjusted until the minimum null voltage reading is obtained. If it cannot be zero, we can make, we cannot make it zero, make it minimum, so that that will be that means at zero null position, that some minimum voltage is, we will get. That will suffice in most of the cases.

Now, how will you design this LVDT? So, this thing must, you must see.

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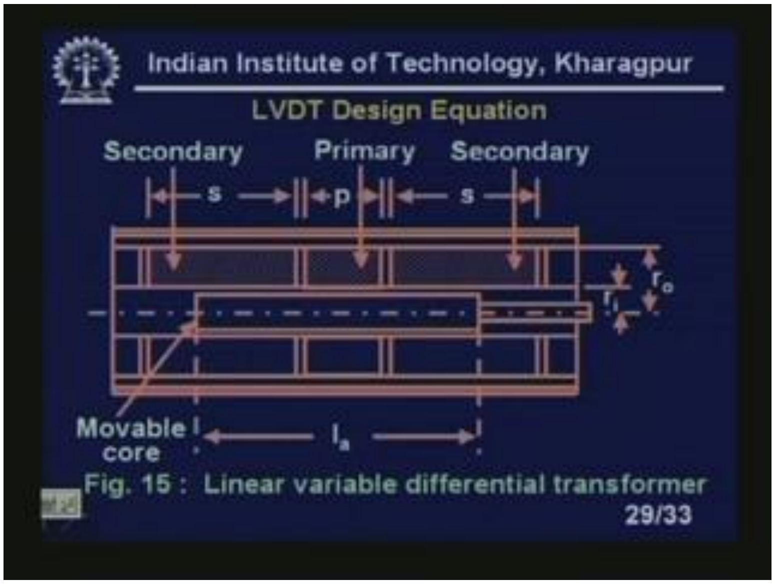

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LVDT Design Equation

Fig. 15 : Linear variable differential transformer

This is our, see schematic of our LVDT. Even though you see that these are the two primary windings, this is a primary winding, because you see this is basically a cylinder sought of thing, right? It is cylinder, I mean here we have the, this core, you see this iron core, so this is our primary. This is the coil, like this one; it is a primary and two secondary, identical secondaries. Now you see, this length of the secondary we have given S, this is length of the primary we have given P.

Secondary, two identical secondary of equal length and r i and r zero is the, this r i is the inner radii and inner, r i and r zero are the inner and outer radii of the LVDT or assembly I should say and l a is the length of the armature or length of the core, right? This is our movable core, please note.

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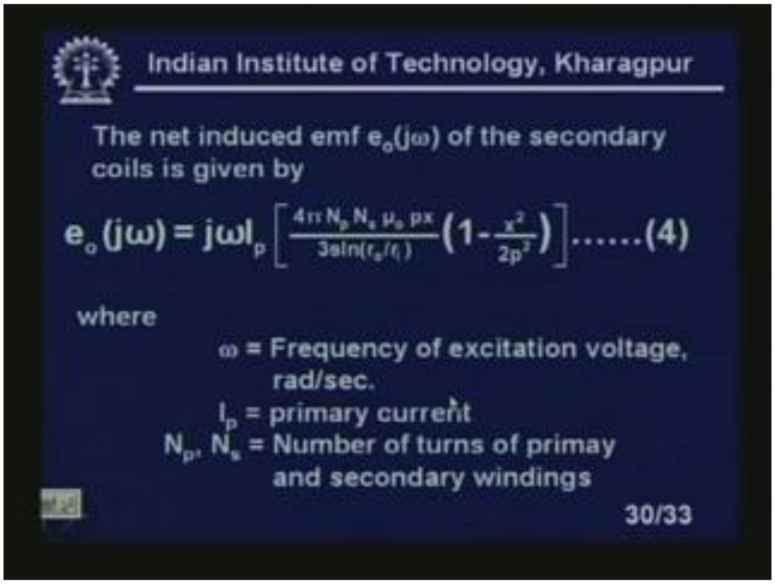

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The net induced emf $e_o(j\omega)$ of the secondary coils is given by

$$e_o(j\omega) = j\omega I_p \left[\frac{4\pi N_p N_s \mu_o p x}{3 s \ln(r_o/r_i)} \left(1 - \frac{x^2}{2p^2}\right) \right] \ldots\ldots(4)$$

where

ω = Frequency of excitation voltage, rad/sec.

I_p = primary current

N_p, N_s = Number of turns of primay and secondary windings

Now, net induced emf of the secondary coil is, will be given by this. You see here,
so this is our net induced emf in the output: e j omega j omega I p 4 pi N p N s mu naught px upon 3 s natural log of r o by r i 1 minus x square by 2 p square - equation number 4, where omega is the frequency of excitation voltage in radians per second and I p is the primary current, N p, N s are the number of turns of primary and secondary windings.

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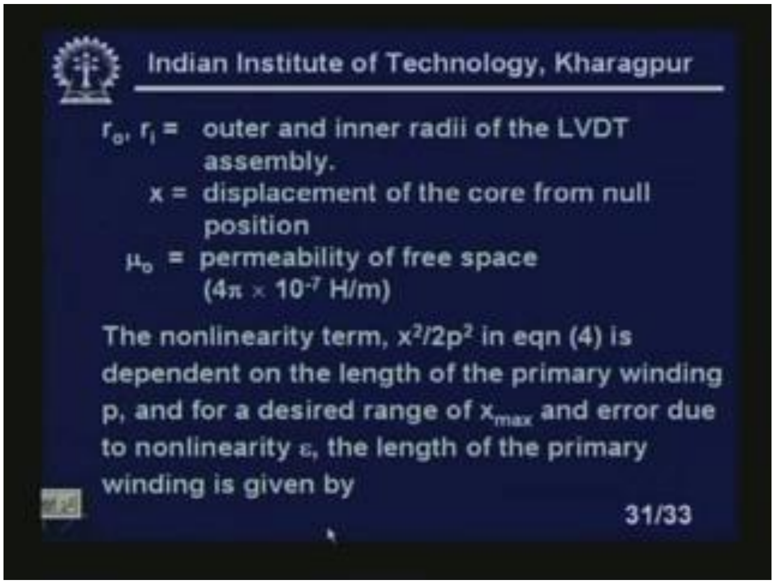

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r_o, r_i = outer and inner radii of the LVDT assembly.

x = displacement of the core from null position

μ_o = permeability of free space ($4\pi \times 10^{-7}$ H/m)

The nonlinearity term, $x^2/2p^2$ in eqn (4) is dependent on the length of the primary winding p, and for a desired range of x_{max} and error due to nonlinearity ε, the length of the primary winding is given by r naught and r i is the outer and inner radii of the LVDT assembly, I should say and displacement of the core from the, x is the displacement of the core from null position, from the, right from the beginning we have used that one and mu naught is the permeability of free space - 4 pi 10 to the power of minus 7.

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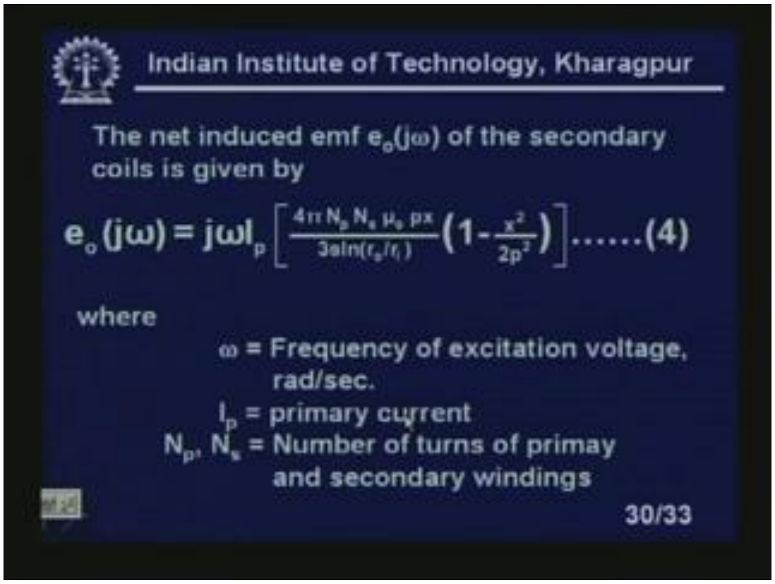

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The net induced emf $e_o(j\omega)$ of the secondary coils is given by

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where

ω = Frequency of excitation voltage, rad/sec.

I_p = primary current

N_p, N_s = Number of turns of primay and secondary windings

Now, if you look at the nonlinearity term, this is our non linearity term. You look at, this is our nonlinearity term, is not it? x square minus upon 2 p square this is the nonlinearity term in the LVDT, right?

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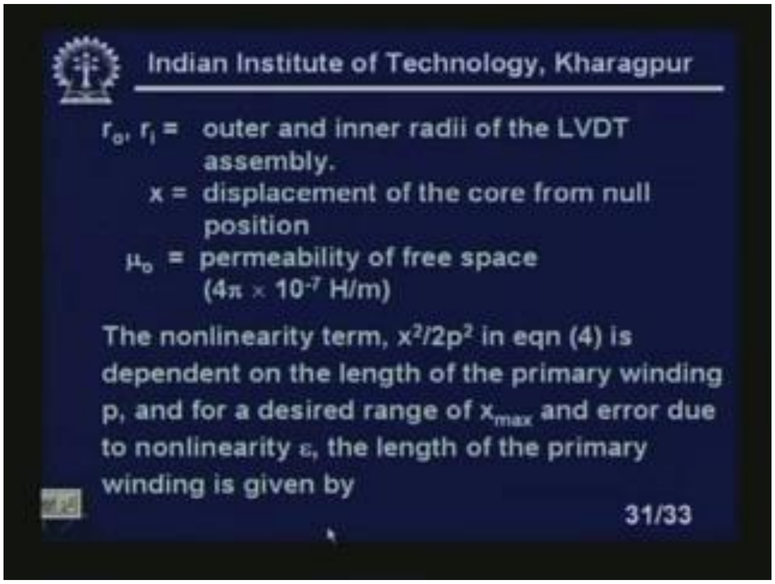

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μ_o = permeability of free space ($4\pi \times 10^{-7}$ H/m)

The nonlinearity term, $x^2/2p^2$ in eqn (4) is dependent on the length of the primary winding p, and for a desired range of x_{max} and error due to nonlinearity ε, the length of the primary winding is given by

So, the non linearity term x square minus by 2 p square in the equation 4 is dependent on the length of primary winding P for a desired range of X max and the error due to nonlinearity, I mean epsilon, the length of the primary winding is given by this.

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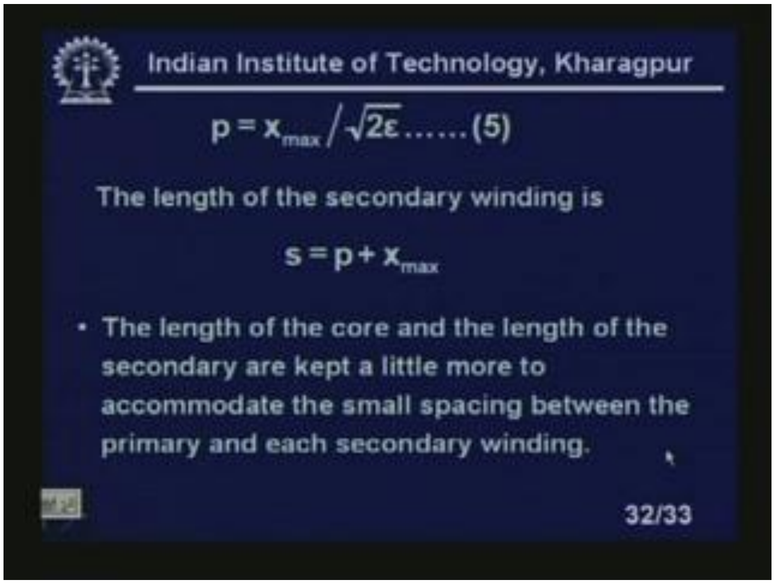

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$$p = x_{max} / \sqrt{2\varepsilon} \ldots\ldots (5)$$

The length of the secondary winding is

$$s = p + x_{max}$$

- The length of the core and the length of the secondary are kept a little more to accommodate the small spacing between the primary and each secondary winding.

P equal to X max upon root 2 into epsilon. So, this is actually the length of the primary. So, we will get from this expressions ……. The length of the secondary winding is also given by this expression: s equal to P plus X max. The length of the core and the length of the secondary are kept little more to accommodate the small spacing between the primary and each secondary windings, right?

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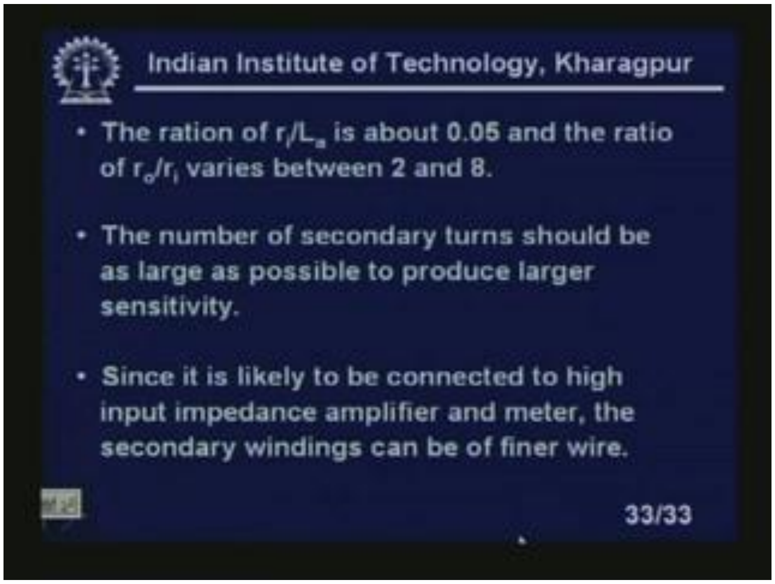

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- The ration of r_i/L_a is about 0.05 and the ratio of r_o/r_i varies between 2 and 8.
- The number of secondary turns should be as large as possible to produce larger sensitivity.
- Since it is likely to be connected to high input impedance amplifier and meter, the secondary windings can be of finer wire.

This is necessary and you see, if you look at, so this ratio, in fact this will be ratio, the ratio of r i by L a is about 0.05 and the ratio of r o by r i varies between 2 and 8. The number of secondary turns should be as large as possible to produce larger sensitivity and since it is likely to be connected to high input impedance amplifier, quite obviously and the meter, the secondary windings can be of finer wire, right?

Now, you see that in practical cases we will find it is very difficult to actually commercially if you are not available, I mean LVDTs are not available, you can make your own LVDT. Even though, we have made it in our laboratory also according to your need, but it is an excellent and it is, it is an application, even though I said that the, it has applications in the measurement of, I mean process parameters measurement, that means it is usually used for the measurement of displacement and along with the, sorry along with the displacement, with the, it is used for the measurements of the pressure if I use a diaphragm gauge and it can be used for the measurement of, in the measurement of I mean flow. So, in the case of diaphragm you see how it is used. If I look at, you will see, here you see, fine?

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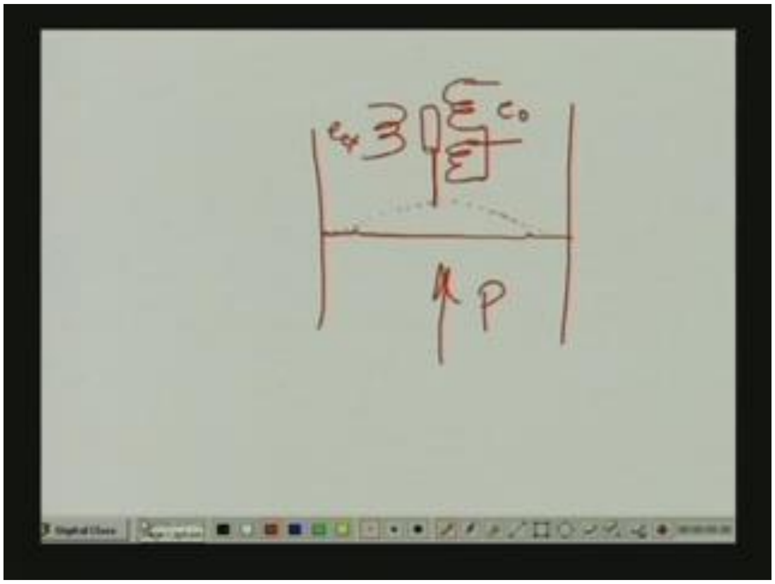

What they do? If I look at the digital class, so I have a stretch diaphragm, right? So, if I increase the pressure on this side, you see this diaphragm will be stretched like this. We will study this diaphragm ……. Now you see, this interesting thing is that that the linearity of the diaphragm depends on the how much is the displacement. Less is the displacement we will have the better linearity that in pressure versus … If I now connect a core of LVDT like this one primary to secondary, right, output voltage I will be getting excitation ex. Now you see, what will happen? As the pressure increases I will get the, this core will move from the null position. I will get a non zero output voltage e naught. I won't need any phase changing demodulations of that type of thing.

This is not necessary because in the case, in these cases diaphragm will move only in one direction; it will never move in this direction, clear? So, this will give you the output voltage, the non zero output voltage, right? Now, this is the one applications of LVDT.

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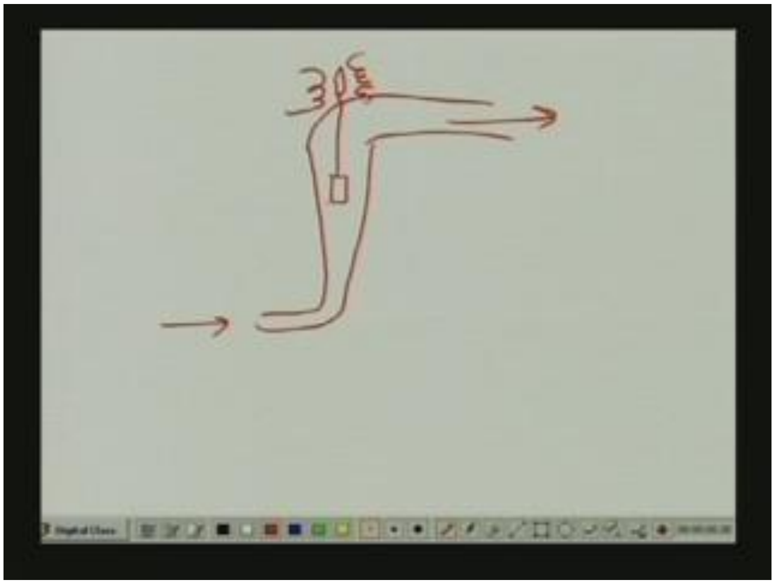

Other applications of LVDT if I look at, you said that we have seen that the rotameter in many places, so we have a core and a channel like this one. So, the float is here, so the flow is in this direction, it is coming out in this direction. So, what they do? With a …… ceiling they connect a core here, same similar two secondaries in opposition. So, if I draw it nicely, it looks like this.

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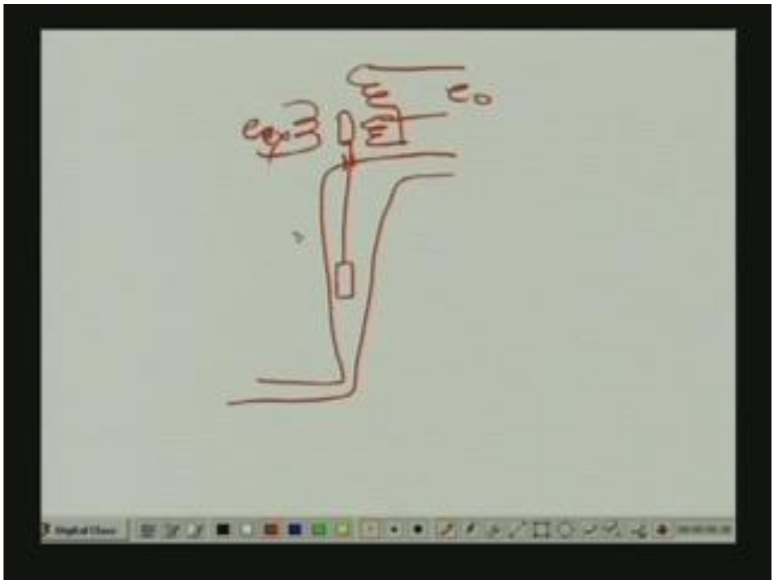

You see, so I have a, so I have a bob here and it is flowing like this one, the ceiling is there, so output voltage now e naught, sorry e x. So, what will happen if the bob moves? This float moves, I will get a non zero output voltage. So, the voltage will increase and the output …. quiet obvious. In the case of rotameter also as the flow increases, this float will go up and up. It is another example of an LVDT. I can put some more examples.

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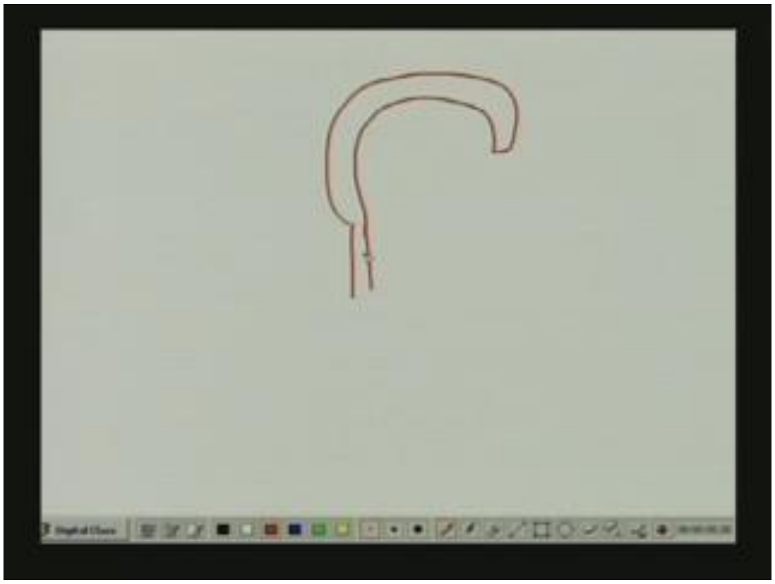

One of the examples of the, another I mean, sorry pressure sensor we will find that, you know that our …… gauges basically depends on a this type of pressure measurements, a C tube, okay let me draw it nicely.

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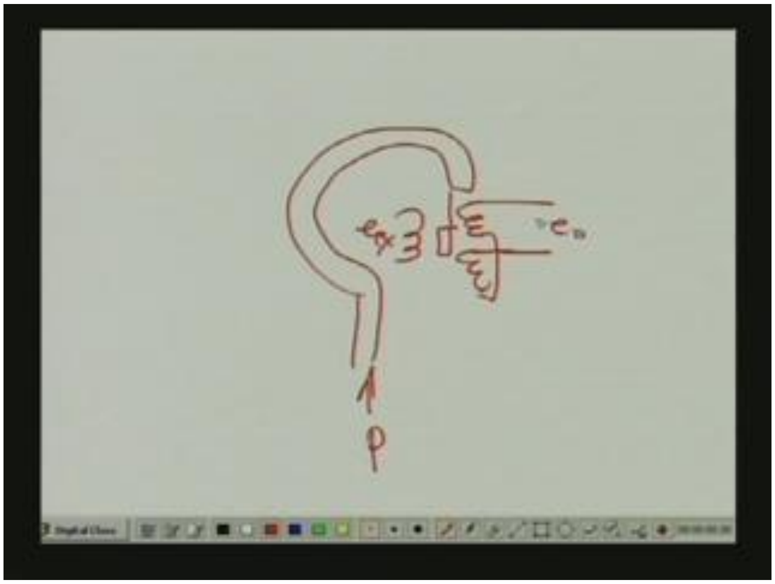

We have a C tube like this one. So, this tube movement I can, this tip I can connect an, a, if I connect a core of the LVDT here, again this will come here and this will go here, e naught this is the excitation. What will happen? You see, if the core moves then what will happen? If the, if the pressure increases, as you know this tip will try to move out. If it moves out, so within the, what will happen? So, this position of the core will move out, move from the, change from the null position. So, I will get a output voltage. So, even though measuring pressures, I am getting electrical output. Even though, I told on previously in the case of …. gauges, it is very difficult to get the electrical output. But here you can see, I can get the electrical output here by using an LVDT. So, this is the several application of the LVDT, even though it is basically used for the measurement of displacement.

Moreover it is, as a biomedical applications even when the child is, when it, it is, I mean it is in mother womb, so the, its respiratory signals also can be collected by the, using LVDT, right? So, these are the different applications of an LVDT. Now LVDT, as I told you, basic I mean the advantage of this type of devices is, its sensitivity is also there. I can increase the sensitivity increasing the excitation voltages and I can increase the resolution obviously, which is much higher than the conventional, our other displacement sensor. So, whenever I need a better resolution, I need a better sensitivity, we have to use LVDT instead of, I mean instead of simple potentiometers or linear potentiometers, which is used for measurement of displacements.

With this, I come to the end of this lecture of LVDT.

Preview of next lecture

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

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Contents

- Capacitance transducers
- Displacement transducers
- Level gauge
- Differential pressure transducers
- Pressure pick up.

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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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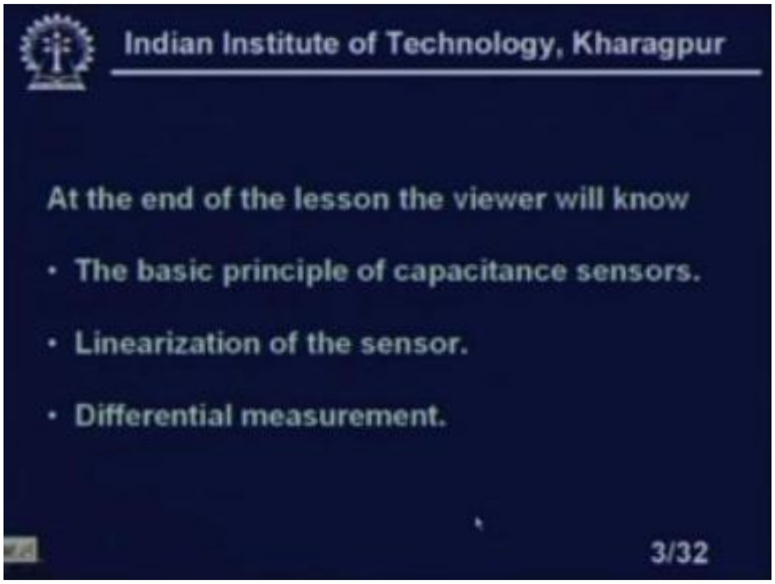

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At the end of the lesson the viewer will know

- 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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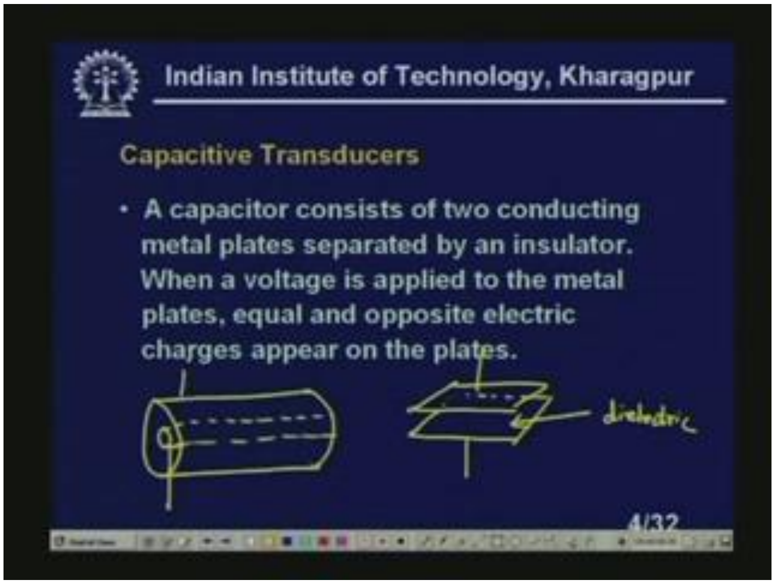

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Capacitive Transducers

- 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.

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 metals 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.

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

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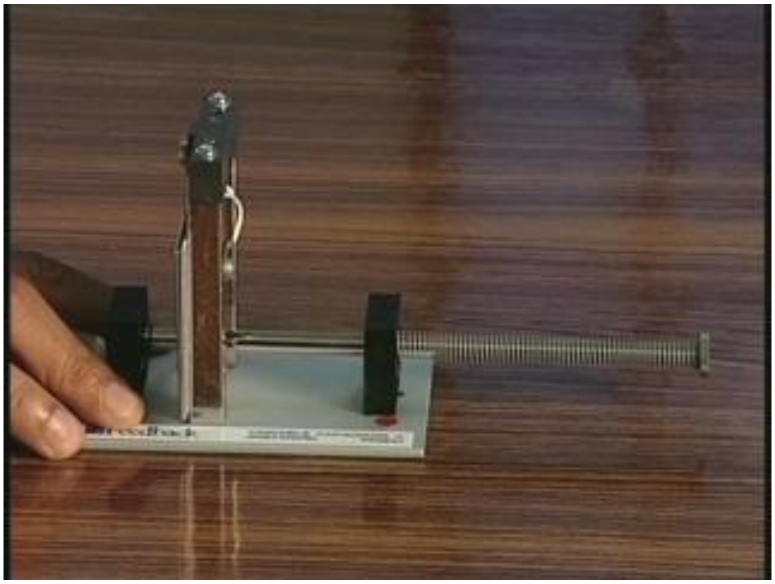

This is another application of the capacitance sensor which can be utilized to measure the displacement. Usually capacitance sensors are based on the three different criteria. One you can vary the area of the plates, you can vary the displacement between the plates that means separation of the plates 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.

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. 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 sensor. Thank you!