Industrial Instrumentation
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Lecture - 24
Piezoelectric Sensors

Welcome to the lesson 24 of Industrial Instrumentation. In this lesson we will consider piezoelectric sensors. Now, as you know piezoelectric sensors is based on piezoelectric crystals, right? So the, it has a property that if you apply a force across the surface of this piezoelectric crystals I will get a voltage and this process is reversible. That means if I apply the voltage I will get the force also. So, utilizing these principles obviously I can make the sensors which can measure force and piezoelectric crystals is extensively used for, as I told you that is reversible that is it is extensively used for generations of the ultrasonic waves.

As you know that the ultrasonic sensors are, are, is used, ultrasonic sensors are used extensively in the case of flow measurements and all these things like ultrasonic flow meters are there. So the, you have seen that actually there we are using the, to launch the ultrasonic signals, I, we want that ultrasonics, I mean piezoelectric sensors, piezoelectric crystals actually we have used there, so it is another use. Also, the piezoelectric crystals as you know it is used for measurements of, for the generation of the very stabilized frequency, because it is, piezoelectric crystal if you, we will see later on that it has, if you draw the equivalent circuit that you will find that it has a very high selectivity.

It helps to make the, make the oscillator which is very stable in frequency. These are the all different applications of the piezoelectric sensors. So, we will discuss one by one what are that and piezoelectric crystals we will find that I, I need a, a special type of amplifier to those, to amplify the charge generated across the plates of the piezoelectric crystals. So, let us look at the piezoelectric sensors and principle of operations.

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So, contents is not there. Contents as I told you, we will have, we will discuss basically the piezoelectric, piezoelectric sensors, its principle and charge amplifier and the crystals, piezoelectric crystals as it is used in making, making the sinusoidal oscillators, right? So, principle of operations are piezoelectric crystals, let us took at. The piezoelectric sensors are based on the principles of electromechanical energy conversion. The mechanical input is converted to the electrical output and that is the basis of this transducers and this transducer shows piezoelectric effect. Actually, this is actually piezoelectric effect. That means if I apply some force, I will get some voltages. This particular effect is called the piezoelectric effect. Not all the material has some, this effect we will see that there are some synthetic material which has this property. Also, there are the, there are some natural materials which has this property.

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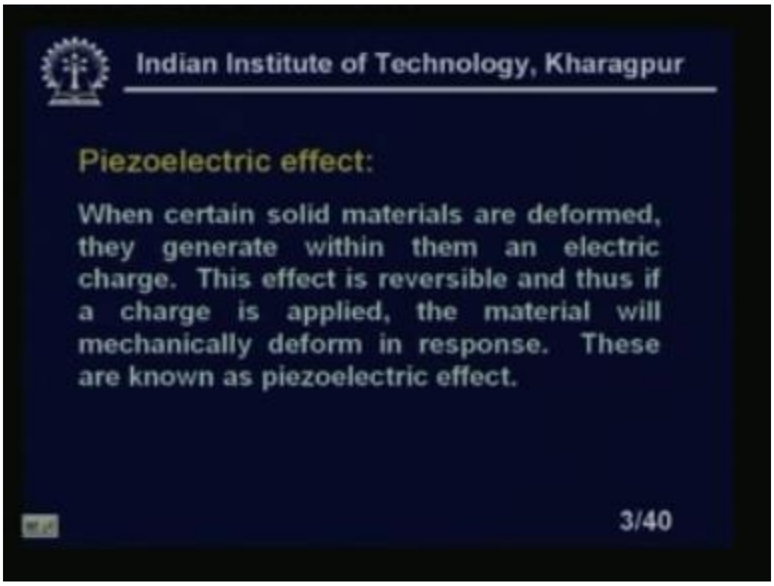

Piezoelectric effect - what is the piezoelectric effect? When certain solid materials are deformed they generate within them an electric charge. This effect is reversible and thus if a charge is applied the material will mechanically deform in response. These are known as piezoelectric effect. Exactly this thing we did while we are making the ultrasonic sensors. Instead of steady voltages what we are giving? We are giving a time varying voltages across ……. Quite obviously the force which we will get that is also time varying signals and that can be, I mean that can be order of mega hertz range, right, so that we can get the ultrasonic signals from the piezoelectric, I mean sensors.

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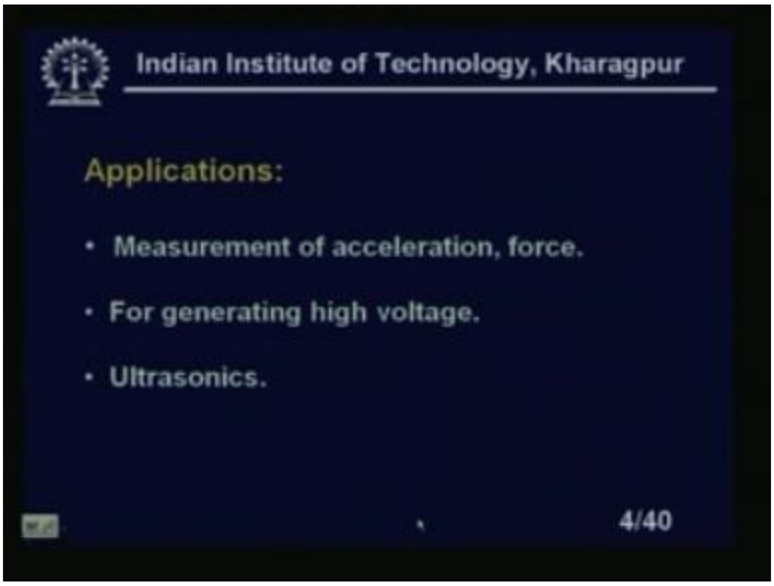

Applications - measurement of acceleration, force; also, it is extensively used in the vibration analysis. That is the only sensor which is used for vibrations, for crack detection, for thickness measurements, all those things you will find that it is used.

For generating high voltage, because momentarily it will make a very high voltage even though, I mean, is the current capability is very small but I can generate a very high voltage. If I apply sudden high pressures or impacts on the piezoelectric crystals, obviously the high voltage will be generated; then ultrasonics, right? These are the different, also we have not mentioned, it is also extensively used as I told you earlier at the beginning of the lesson, for making the crystal oscillator. A piezoelectric phenomenon, let us look at historic background of these particular sensors.

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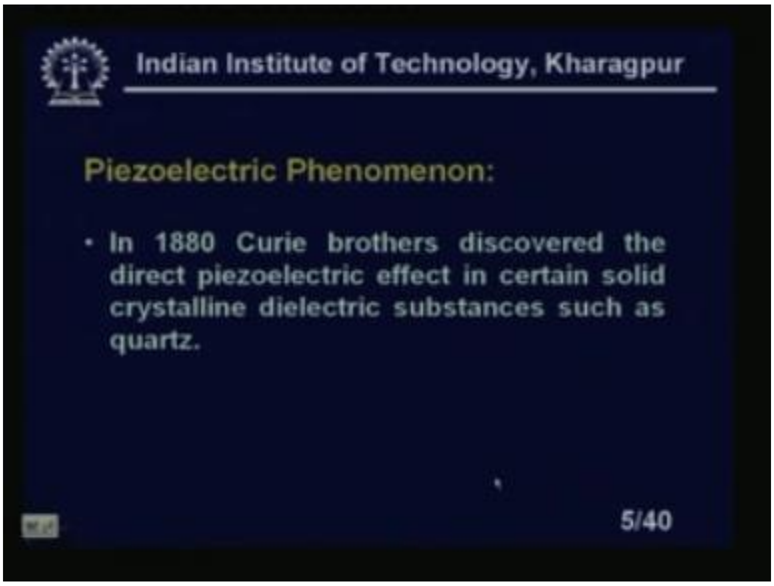

In 1880, Curie brothers discovered the direct piezoelectric effect in certain solid crystalline dielectric substances such as quartz. Quartz is a natural substance. We will see that quartz is not only the material which has a piezoelectric effect, there are many synthetic materials I mean which found later on, I mean or the scientists have developed. We will see that in those piezoelectric materials, in those materials you have, you can get the piezoelectric effect, right?

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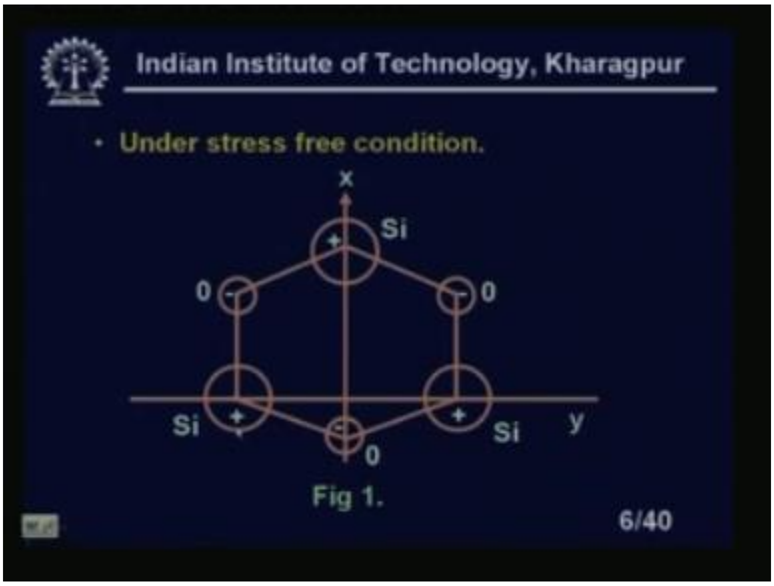

Now, under stress free condition what will happen? What is under stress free? Let us look at the diagram. Under the stress, stress free condition what will happen to these piezoelectric sensors.

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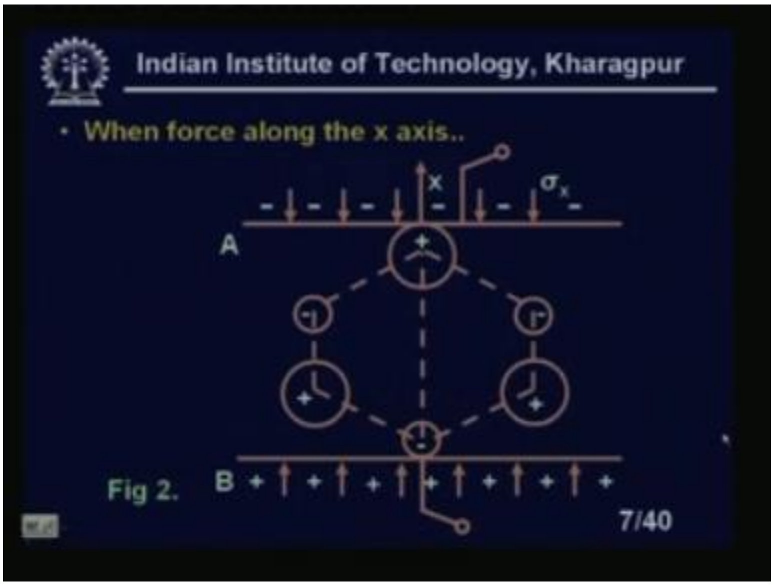

You see, this is a total, I mean this is silicon dioxide crystals. You see what will happen here? I have silicon. This is positive and this x-axis and this, I mean this is the silicon ion, this is the oxygen ion. So, under stress free condition it will look like this, right? Now, what will happen? Now, if a stress is applied on these particular crystals, let us look at? When the force along the x-axis is applied, so I will get a response like this one. If I take this is your x-axis, this is as y-axis you see that if I apply some force what will happen let me see.

Yes, you see, I am applying a force here, force here ……. I am applying force here, force here also that obviously if I put on a, obviously it will, on the both sides that means on both sides I am putting a pressure. So, what will happen you see that this positive and negative ions will be distributed like this, right? This is along that x-axis if I apply the pressure. Now what will happen if I apply the force in the y-axis? You see this is the y-axis and this is the x-axis. These are two plates A and B.

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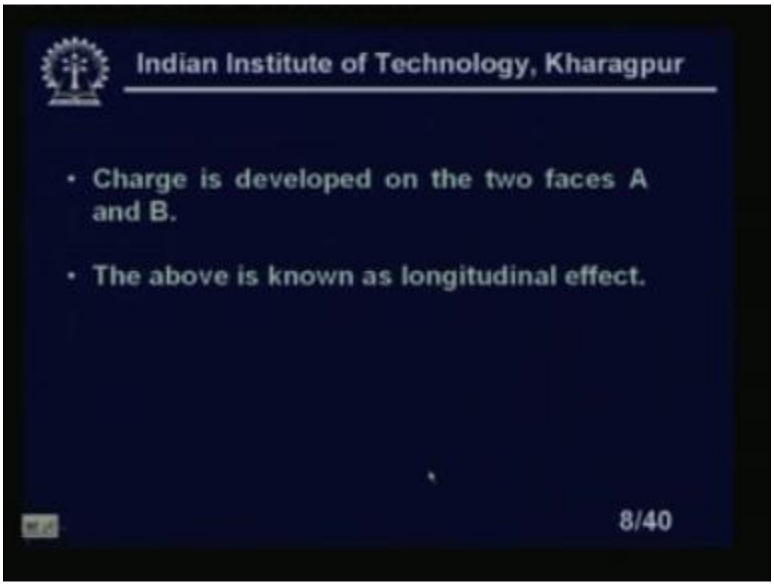

Charge is developed on the two faces A and B, right? You can see that charges have been developed, charges have been developed across plates A and B, right? Positive charge will be developed here, negative charge will be developed here, right? The above is known as longitudinal effect. This is called the longitudinal effect. We have also transverse effect. Let us look at that.

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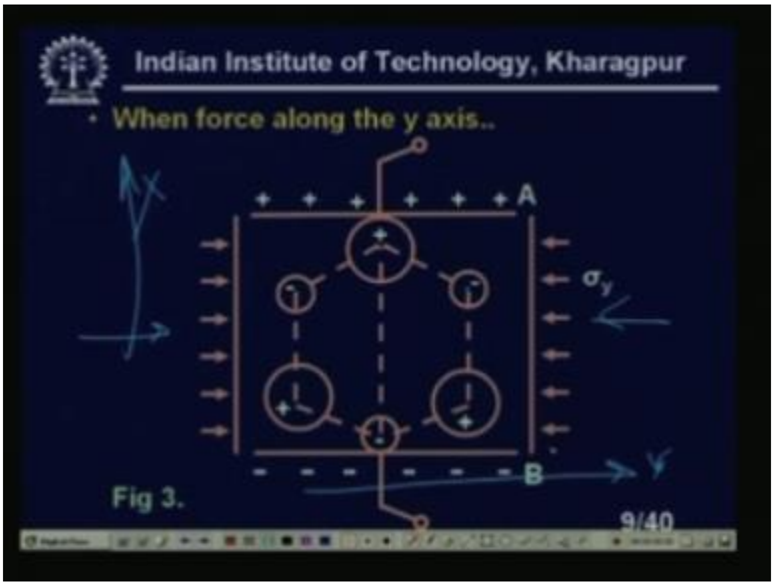

When the force along the y-axis, if now, suppose if we apply the force along the y-axis, then what will happen? If I apply the force along the y-axis let us look at, so I am applying force in this direction, in this direction. So, this is my y-axis and this is x-axis, right? But my plates are, I mean I am collecting the charge from the, from the plates which is placed on the x-axis, right? So, what will happen you see the positive charge will move in this direction and the negative charge will move in this direction. So, this will be the positive plate and this will be the negative plate, right? So the, the stress which I am applying this is sigma y, because the sigma x if we can look at, this is sigma x, because this is applied here, right, applied here, applied in this x direction and since it is in y direction we are applying, this stress is sigma y, clear?

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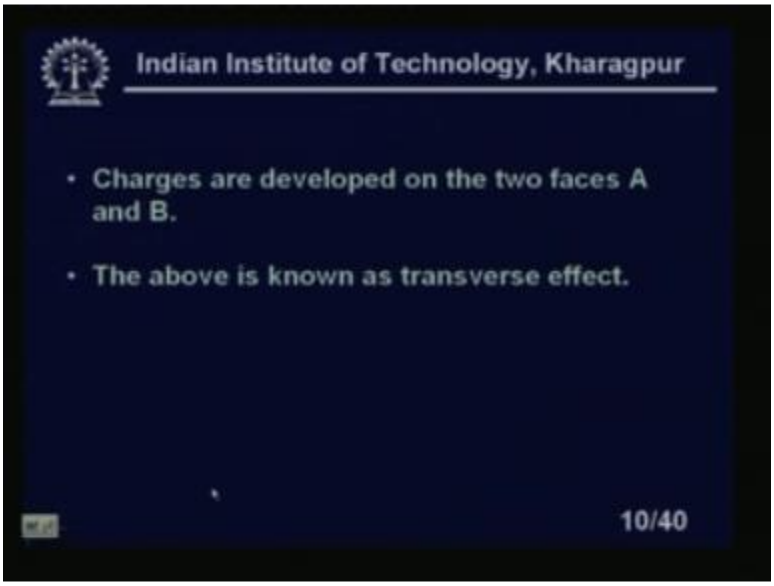

Now, charges are developed on the two faces A and B; same the charges in the previous case when we apply the x-axis, along the x-axis or across the x-axis the charges will be developed is across A and B and when we apply the stress in the y-axis, the charges developed will also be on the, across the plates A and B. The above is known as transverse effect. One is the longitudinal effect, transverse effect. You all familiar with this longitudinal and transverse, because we have extensively, these points have been discussed while we have, we have, while in the, we have, we have studied in the lesson on the stress, on the strain gauges, right?

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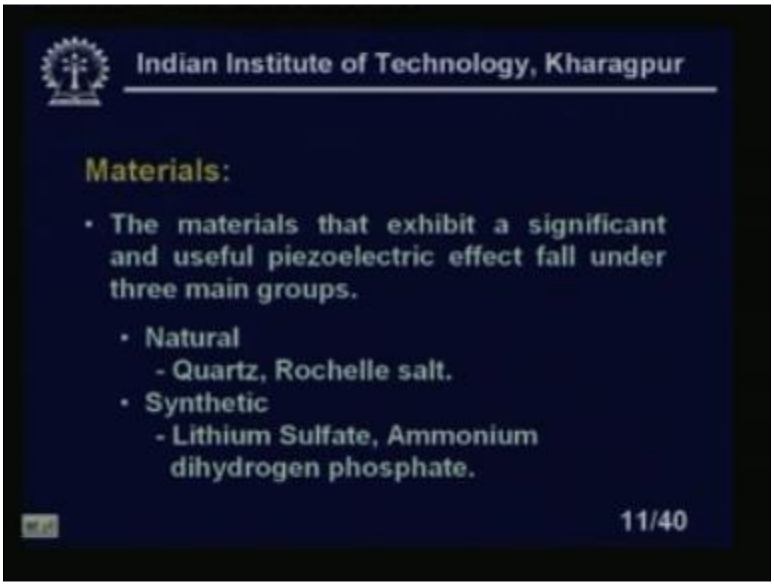

Now, materials - what are the different materials which is used, I mean for the piezoelectric crystals, because you know the, previously the, I mean this only quartz people thought of that is only have the property. Quartz is quite expensive also. Quartz has piezoelectric, I mean property. So, but later on we found that there are some synthetic materials also which has piezoelectric property. Let us look at that. The materials that exhibit or that show a significant and useful piezoelectric effect fall under three main groups.

There are three main groups we can categorize. One is the natural quartz and Rochelle salt are the two. Quartz is very commonly used and Rochelle salt is also used. Then we have synthetic lithium sulphate, ammonium dihydrogen phosphate. These are the two different synthetic materials. It has also, these, these two materials also have the property of the piezoelectric effect. That means if I apply pressures, voltages will be developed and if we apply the voltage, pressure will be developed or force will be developed across the plates.

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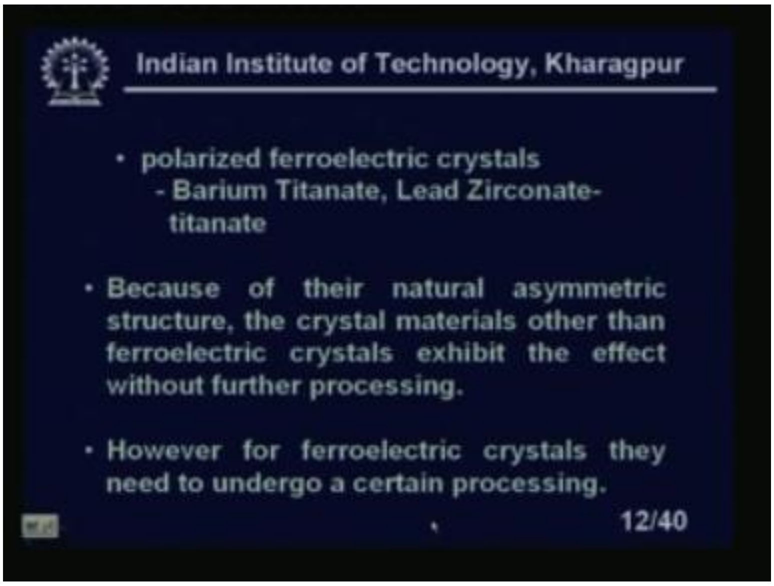

Also we have polarized ferroelectric crystals - these are the barium titanate and lead zirconate-titanate. These are also coming under the synthetic, but the property is something different that is we have put under different categories, right? Because of their natural asymmetric structure, the crystal materials other than the ferroelectric crystals, ferroelectric crystals, it show the effect without further processing. We do not need any further processing. We will see that if I have natural asymmetric structure, then the crystal material other than the ferroelectric crystals show the effect without further processing. However for ferroelectric crystals they need to undergo certain processing. What are those?

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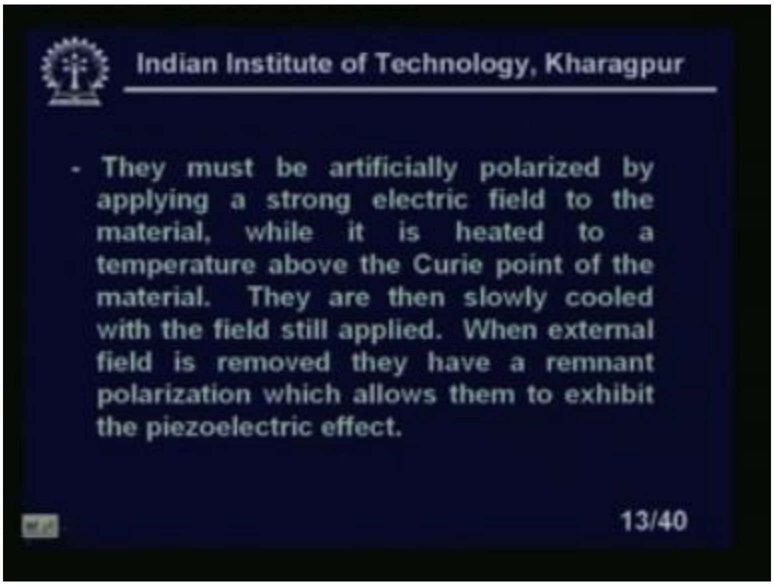

They must be artificially polarized by applying a strong electric field to the material, while it is heated to the temperature above the Curie point of the material. They are then slowly cooled with the field still applied. When external field is removed they have a remnant polarization which allows them to show the piezoelectric effect or exhibit the piezoelectric effect. This is the thing we will have.

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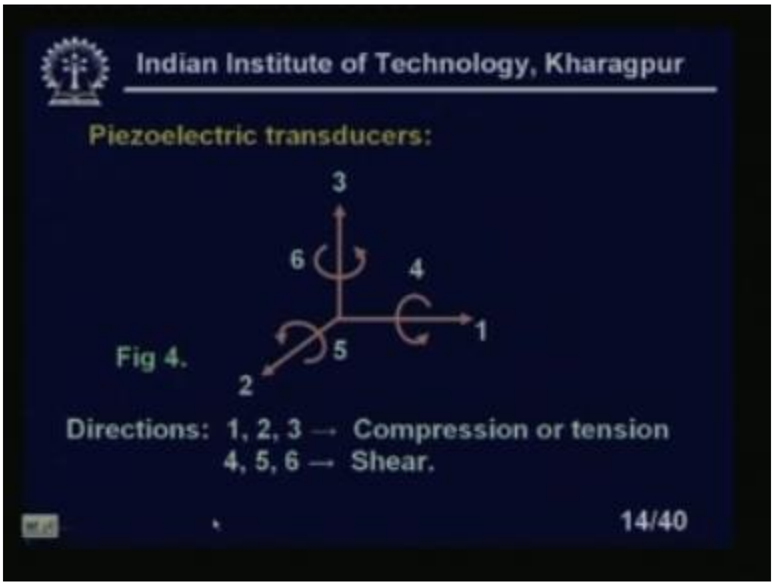

Now, the piezoelectric transducer if I look at, actually is naturally available transducer. You see that how the, its, what are different axis? We are taking one you see these are all, I mean in this direction three, I mean this, all this, this arrow is actually the shear stress which is developed across the different axis of the piezoelectric crystals. These are the force typical tensile or compressive. These are the shears. So, direction 1, 2, 3 are the compression or tension either compressive force, can be tension or tensile force; both cases you will get the piezoelectric effect and 4, 5, 6 are the shear stress on the piezoelectric crystals, right?

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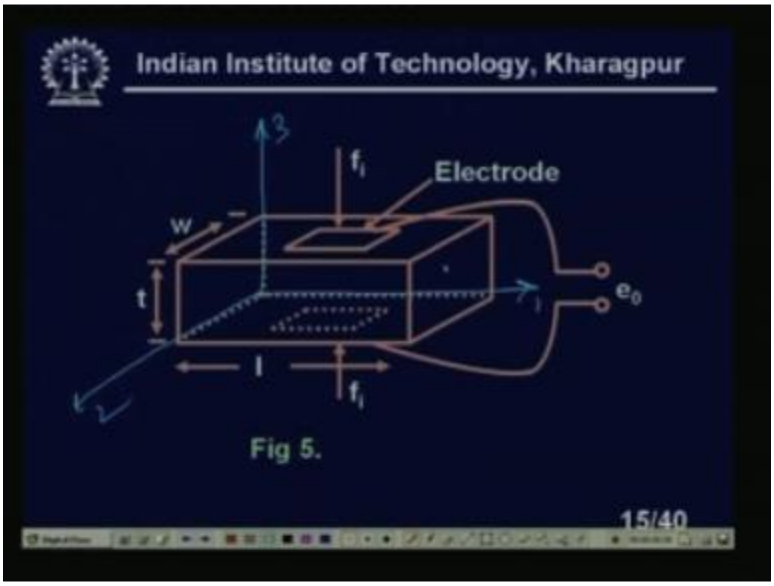

Now, see this is the typical piezoelectric, I mean I should say the schematic of the piezoelectric crystals. As it looks like, I can take the axis like this is x-axis, this is y-axis, this is z-axis or this is 1, 2 as it happened here let us see, so 1, 2, 3. In this case also I can show that this is 1, this is 2 and this is 3, right, like this one. So, this is 1, this is 2 and this is 3. So, we have a shear also, right? So, the dimensions you see, the width of the crystals is w, thickness is t and its length is l, right? So, we have two electrodes. We have seen the two electrodes, one in this and another one this. We are taking the voltage e 0, right? We apply the force fi across these plates, right?

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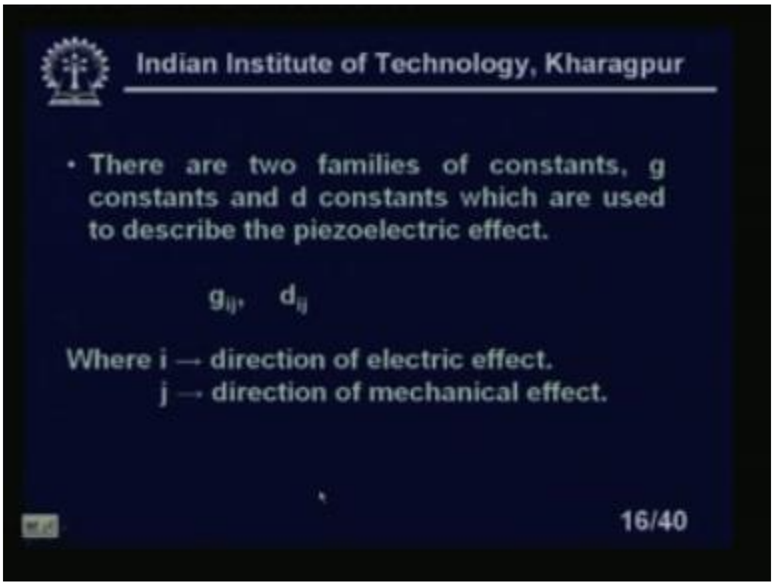

Now, there are two families of constants - g constants and d constants which are used to describe the piezoelectric effect, right? We will discuss two constants. These are necessary or I should say the parameters of the piezoelectric crystals by which we can define the piezoelectric crystals. So, that is the reason I am telling there are two families of constants, g constants and d constants which are used to describe the piezoelectric effect. So, g ij and d ij what are these? Where i is the direction of electric effect and j is the direction of mechanical effect, fine.

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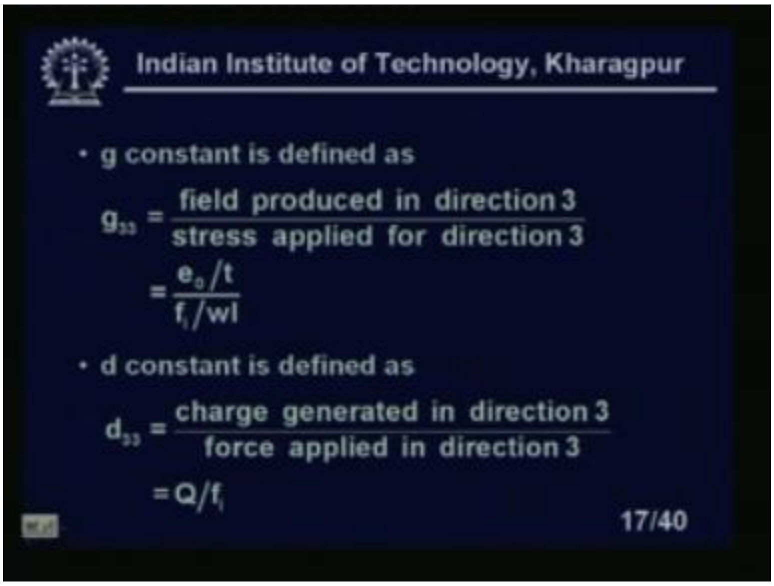

So, g constant is defined as g 33 field produced in the direction 3 divided by stress produced, stress applied for direction 3, right? So field produced that is I mean voltage e naught divided by t thickness and stress means force applied f i across that divided by area, is not it? You see, the force applied is f i and what is the width? w into l that is the area of cross section. So, if I divide f i by, so I will get a stress f i divided by w into l, I will get stress and e naught divided by t, so I will get the field, is not it? So, e naught by t upon f i by w l.

Now, d constant is defined as d 33, charge generated in direction 3 divided by force applied in direction 3 which can be written as Q divided by f i, right? That means charge developed divided by the force applied.

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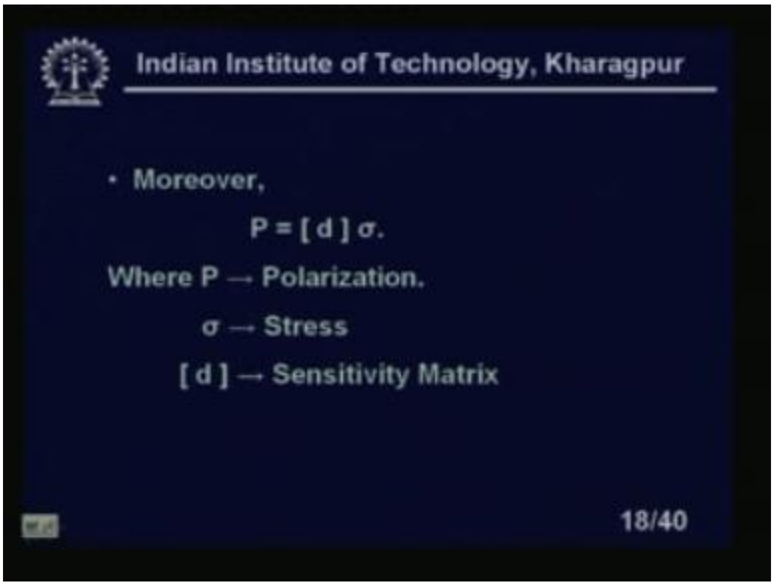

Moreover, P is equal to d multiplied by sigma, right, where P is the polarization and sigma is stress and d is called the sensitivity matrix of the piezoelectric crystals, right?

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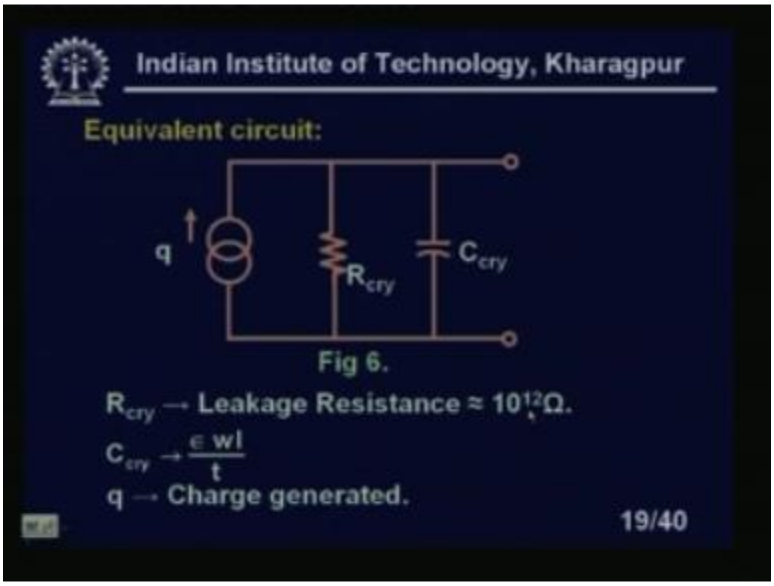

Equivalent circuits of piezoelectric, I mean for this one you see like this one, so we have a crystals. Then we have a, you see that this R crystal, this is the charge, I mean equivalent circuit in not that sense, I mean if I replace this, I mean piezoelectric crystals by a signal generator, the, the circuit will look like this one. So, I have a signal generator, voltage source of q, I mean charge source. Then we have the resistance R crystals in parallel with the capacitance that means C crystal or C.

So, crystals we are taking the first, I mean three letters, crystal, so I am taking first three letters cry, clear? Now, cry is the leakage resistance which is extremely high. It is 10 to the power 12 ohm, 1000 giga ohm I should say and C crystals is equal to epsilon into w l by t. Typically, I mean dimensions of a, of a expression of a capacitance, right? W l is the area of cross section of the capacitance. If I consider it as a parallel plate capacitor, t is the thickness and epsilon is the permittivity of the medium, right or dielectric constant of the medium and q is the charge generated, right? So, the q charge generated, R crystals - leakage resistance, which is around 1000 giga ohm and C crystal equivalent, I mean capacitance of the crystals is equal to epsilon w l divided by t and q is the charge generated.

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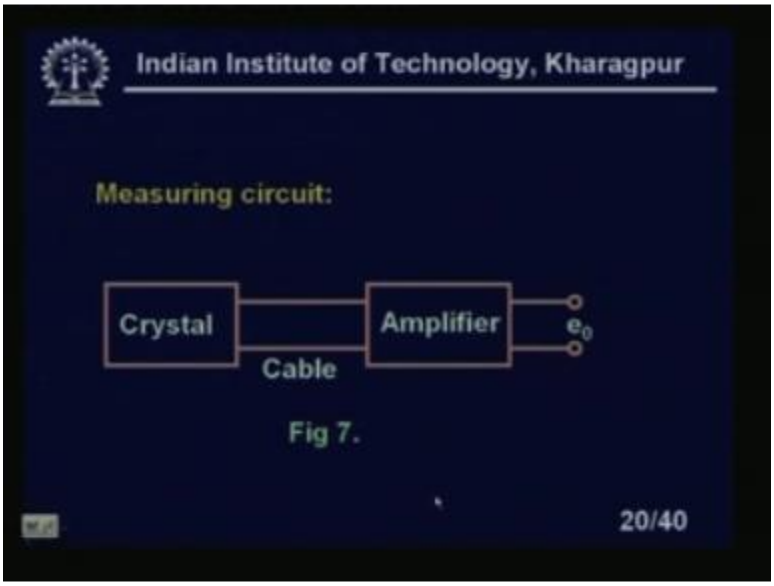

Measuring circuit loop we have like this one. We have a crystal, we have a cable, but there must be some cable, some wire is to be connected and it is connected to the amplifier, so that I will get the output e naught.

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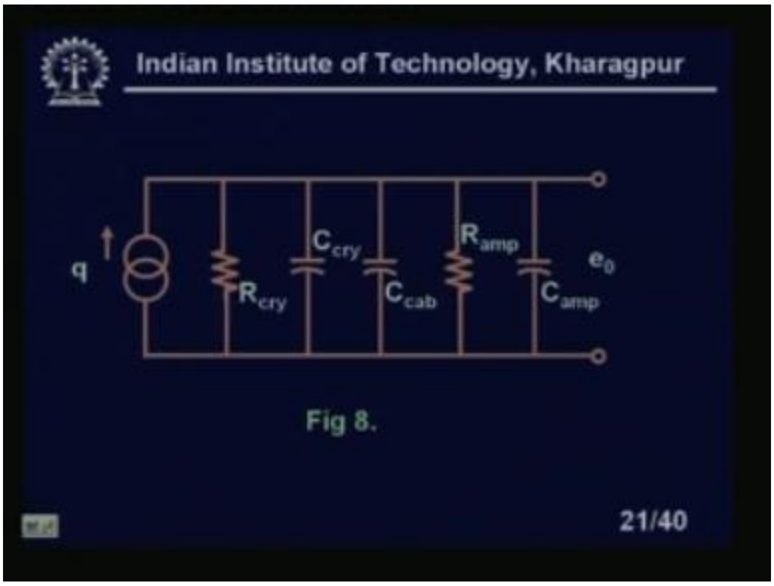

Now, this is the complete circuit of the piezoelectric crystals along with the, if we use, if you think of the charge generated along with an amplifier. So, all the impedance of the amplifier also should come in the picture of the equivalent circuit, right? So, here you will see, we have q, R crystals that means leakage resistance of the crystals, C cry capacitance, C is the cable capacitance which is coming across, R is the, is the amplifier impedance and is the input impedance, capacitance of the, because as you know in, any amplifier has capacitive range at which actually you will get the that particular input impedance. So, that impedance, capacitance must be mentioned also in the equivalent circuit.

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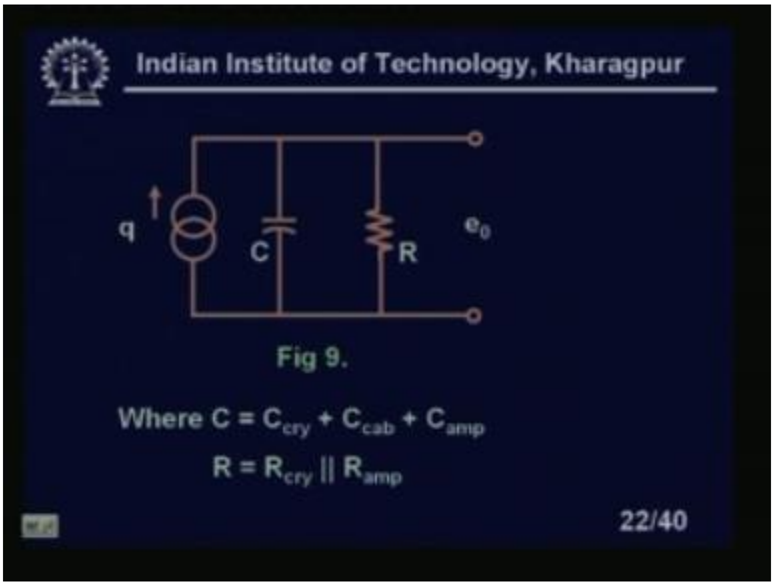

Now, you see we have, we have simplified the circuit. What we have you see here we have two capacitance, three capacitances and two resistances. This we have combined to an equivalent capacitance. We are writing C and R and what is C and R let us look at. So, this is C, all the capacitance are combined here and all the resistance are combined here. We are getting the output voltage e 0 and charge generated q, right? Let us look at. So, charge generated will be q. So, C equal to C crystals plus C cable capacitance plus C amplifier, all will come in parallel. Then, since it is in parallel, all will be added, all the capacitance value will be added and R is the, R crystal resistance in parallel with the amplifier resistance.

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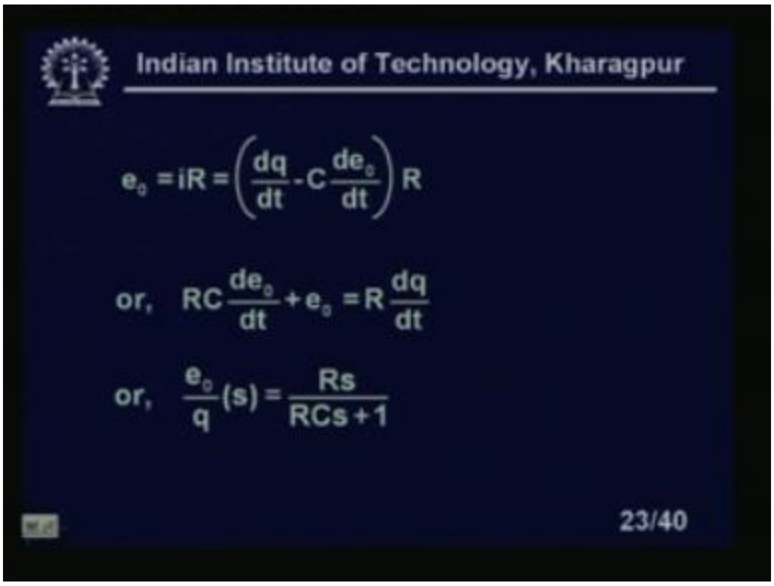

So, e naught I can obviously write small i into R equal to dq by dt minus C into de naught by dt whole multiplied into R or RC equal to RC multiplied by de naught by dt plus e naught equal to R dq by dt. So, e naught by q because q is the input, I mean we assume that q is the generated and what is the output let us look at. So, the sensitivity will be e naught by q s in s domain R into s divided by RC s plus 1, right?

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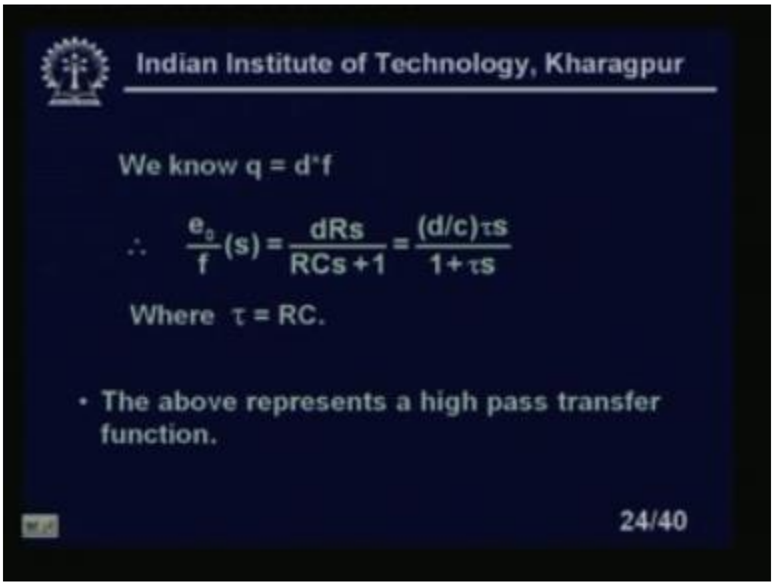

This, where q equal to d into f, where e naught by f s that is e naught because as you know q is equal to d multiplied by f, where e naught is equal to e naught divided by f that is actually, this should be, that should be the sensitivity, because actually we are applying the force, force is generating the charge, right? So, but so actual sensitivity if we want to find we have to find e naught by e naught by q, we have to find e naught by f actually the output voltage divided by the force which we have applied equal to d into R into s divided by RC s plus 1. This we can write d by c into tau s by 1 plus tau into s, where tau equal to R into C, clear? The above represents a high pass transfer function of this.

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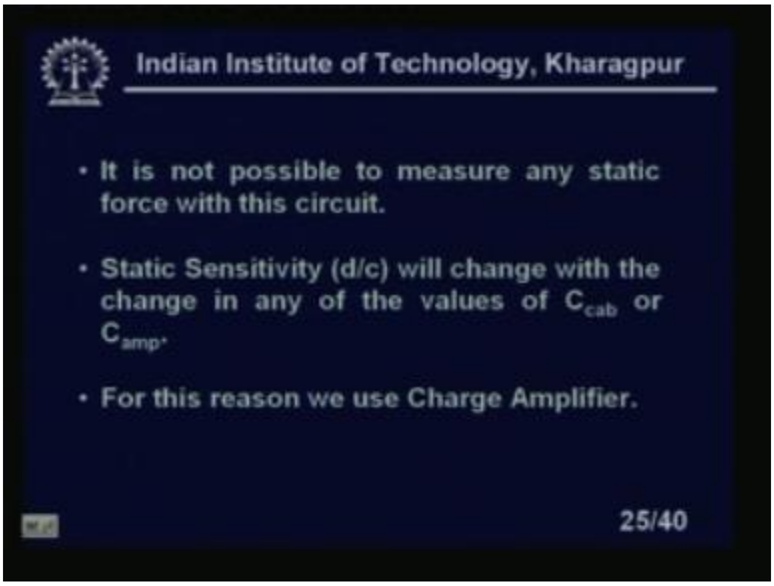

So it looks like, it is not possible to measure any static force with this circuit. Please note the static is not possible. So, in dynamic whenever there is a change in the force, then only I can measure, I will get the output. Otherwise we will not get any output. Static sensitivity d by c will change with the change in any of the values of the C cable capacitance, I mean cable capacitance and C amplifier. So, it is sensitive to this, so this must be constant. For this reason we use a charge amplifier. So you see, it is not possible to keep all these things constant. So, it is better if we use a charge amplifier.

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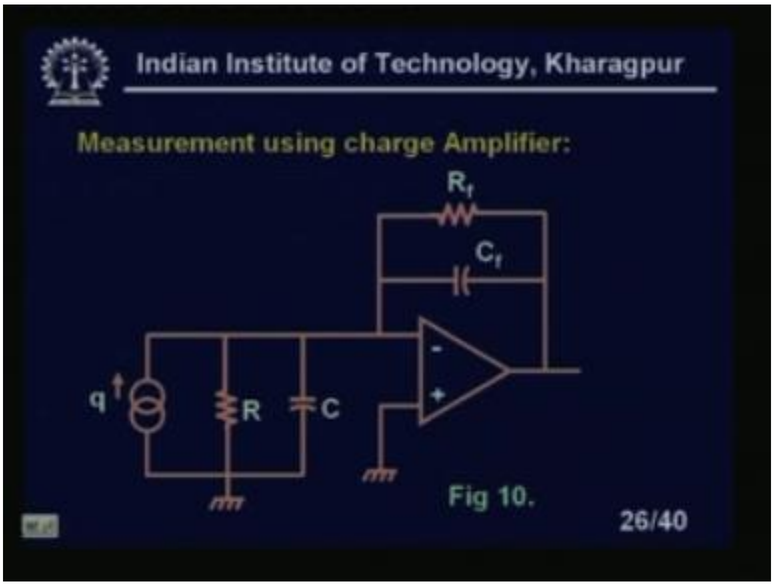

Measurement using the charge amplifier, the charge amplifier looks like this. We have a q and we have a R and C at the input side. On the feedback side we have feedback resistance R f and the feedback capacitance C f and we are using the operational amplifier, right? So, this is the basic charge amplifier.

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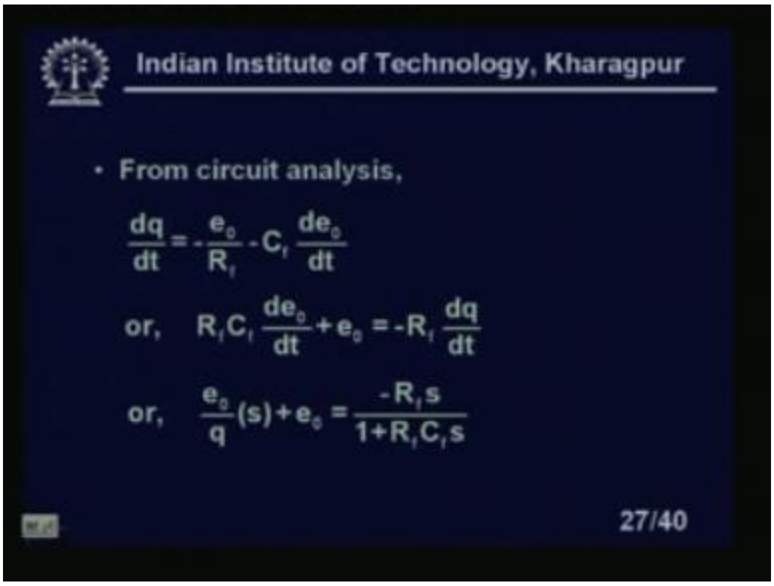

Now, from circuit analysis we can say that the dq by dt equal to minus e naught by R f minus C f into de naught by dt. So, this will give you R f into C f into de naught by dt plus e naught minus R f into dq by dt. Just algebraic manipulations we are doing or we can write e q by, e naught by q in s domain plus e naught equal to minus R f s upon 1 plus R f C f into s.

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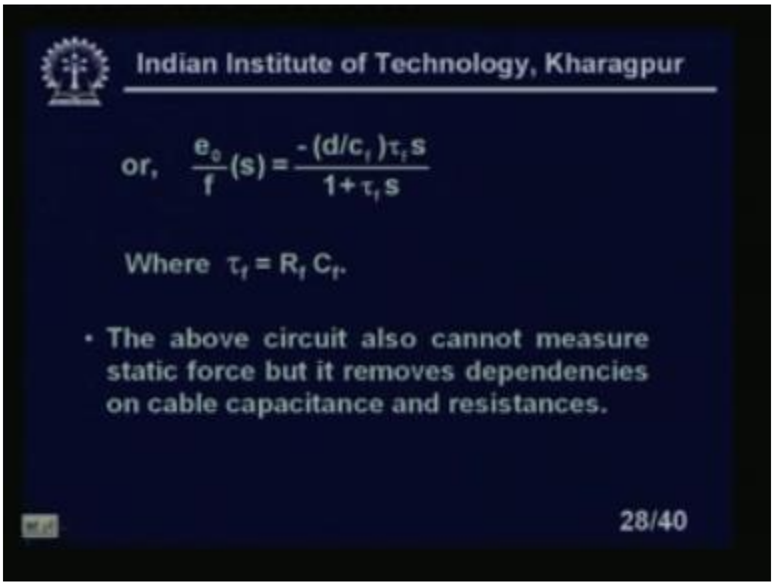

And e naught by f s equal to minus d by C f tau f s 1plus tau f s, where tau f equal to R f into C f. The above circuit also cannot measure static force, but it removes the dependencies on the cable capacitance and the resistance, right? So, what is the cable capacitance all these things will come in the picture.

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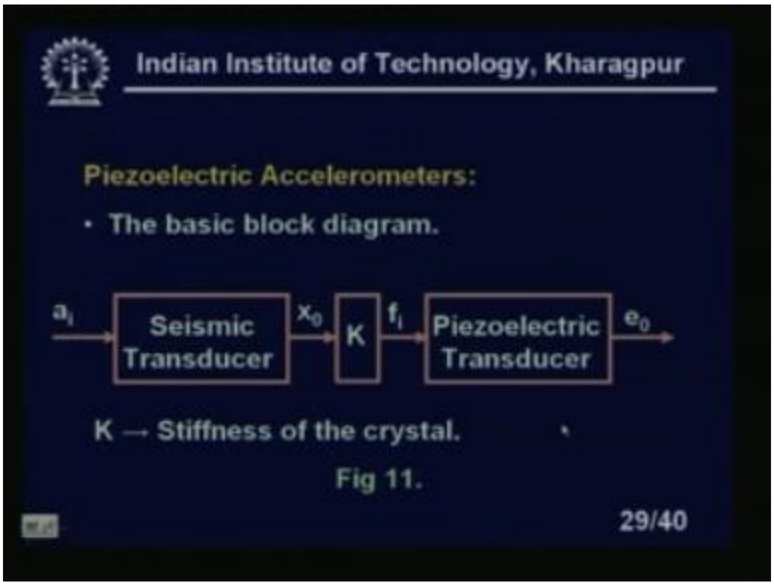

Now, the piezoelectric accelerometers if you look at, so the basic block diagrams of the piezoelectric, because piezoelectric, I mean crystals are used as accelerometers, so we can make integration of that we will get velocity, if we make another integration, so I get the displacement, right? In vibration analysis as you know, it is extensively used as piezoelectric sensors to pick up the vibrations. So, the basic block diagram, because I have a seismic transducer, K stiffness of the crystal, piezoelectric transducer this is the output voltage we are getting e naught.

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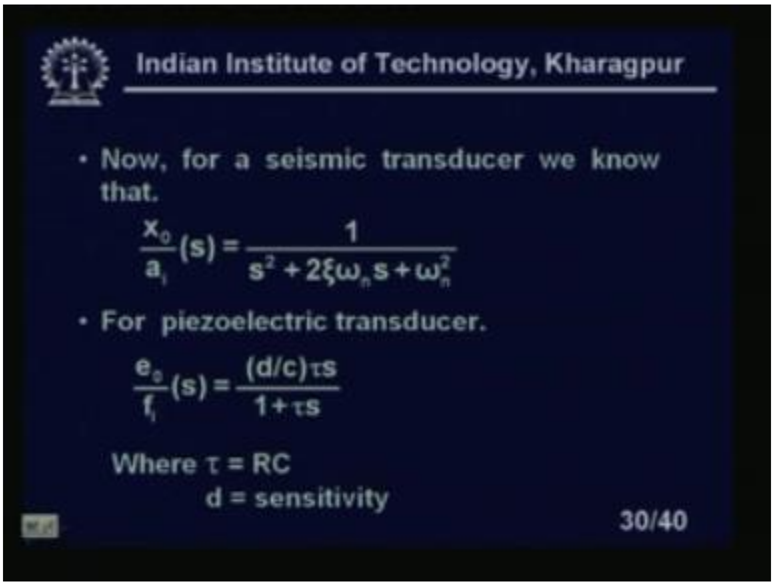

Now, for a seismic transducer we know that that x naught by a i s equal to 1 upon S square plus 2 xi omega n S plus omega n square, right? For piezoelectric transducers we have e naught upon f i S into d by c tau S 1 plus tau S, where tau equal to RC and d is the sensitivity.

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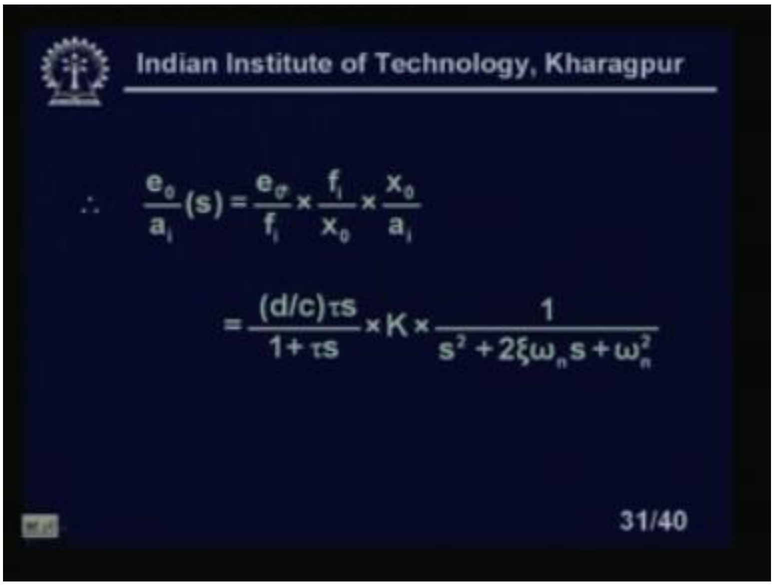

Now I can write, I just make little manipulations e naught by a i S, S domain, e naught by f i into f i by x naught into x naught by a i. Ultimately I am interested in e naught; this will all cancel out; e naught, this will cancel out, this and this will cancel out. So, only e naught by a i will remain. So this I, if I substitute separately e naught by f i, f i by x naught and x naught by a i, I will get this whole expression you see; I will get this whole expression, clear? d by c tau S 1 plus tau S into K into 1 plus S square plus 2 xi omega n S plus omega n square.

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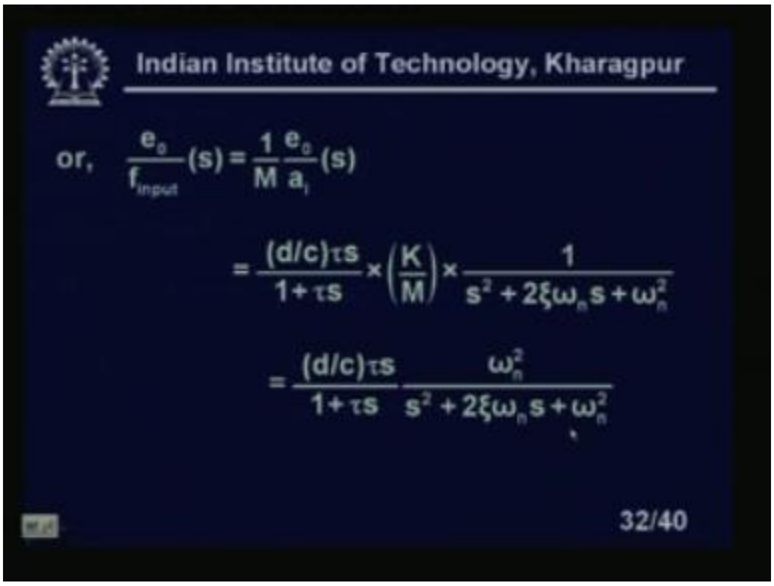

Now, e naught by f input S equal to 1 by M e naught by a i into S. This I can write d by c into tau S 1 plus tau S multiplied by K by M into 1 upon S square plus 2 xi omega n S plus omega n square equal to d by c tau S 1 plus tau S omega n square S square plus 2 xi omega n S plus omega n square, right?

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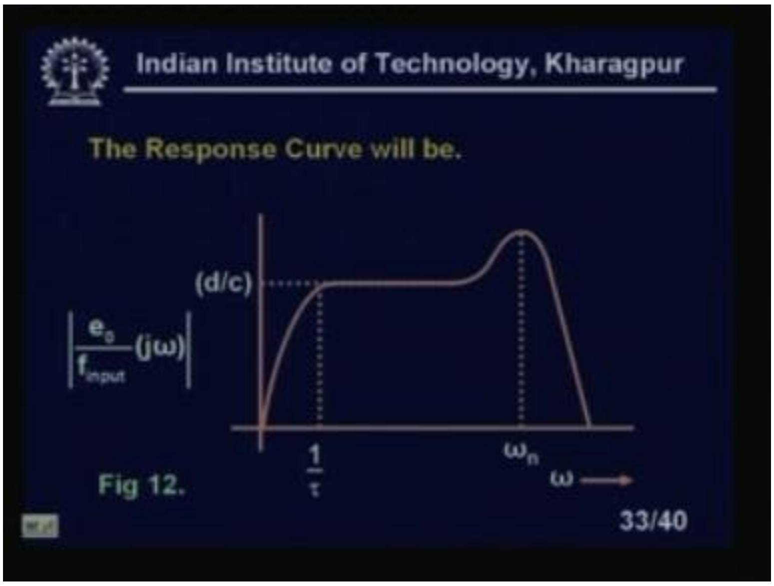

The response curve will look like, like this one. That means that the output voltage divided by f input that means force it will look like this. This is highest point d by c, we are plotting omega here. So, it is, it is almost as a band pass characteristics you can say, with a certain hump So, after that natural frequency, because of the natural frequency there will some hump at resonance, so after that it is falling down, right? That 1 by tau, so I am getting the output, the mod of e naught, output voltage divided by the force in j omega domains will be d by c, right? So, this is the response of the piezoelectric crystals.

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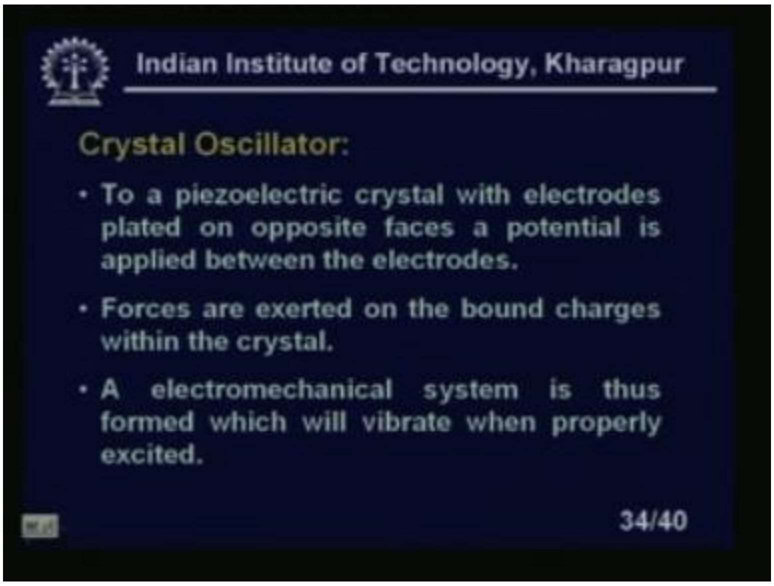

Now, as I told you that oscillators are different types. Now, piezoelectric crystals also has a tremendous applications in making oscillators. We are not discussing about the piezoelectric crystals as it is used as a generation of ultrasonic waves. When we have discussed the ultrasonics we have seen that what are the different, how can we generate all these things ultrasonic waves and but crystal oscillator is very one of the common, almost all of you are using some quartz watch.

What is the quartz it is written? You see it is written quartz. It is not that just to attract the, I mean customers and increase the price of the watch. Actually this is used for watch or wall clock. Everywhere you will find it is written quartz. It means that they are using some oscillators, because ultimately in all electronic, I mean watch or clock we need some basic oscillators, right, so that will drive some stable motors, so that will be incremented, I mean it will step change; for each signal it will change like this one, so that the seconds arm will move. Subsequently it will move the minutes arm and for the hour arm, right with the gear arrangement.

Now, but basically we see, I need an oscillator. Now if I use, what is the problem if I use, suppose if you use a oscillator based on 555 or any other you can use two transistors also to make an ……. oscillator or you can make an op amp to use or you can make ……… oscillator; not necessarily I need sinusoidal oscillations there, right? But the thing is there you know that if you make that type of oscillator, it heavily depends on the, not only depends on the, on the type of the resistance and capacitance, it depends on the, on the absolute value of the resistance and capacitance and as you know that as the time goes by, so this may change, right?

This value of R and C may change, so that will change the, ultimate the clock that the period of the clock. So, if it changes, obviously your watch or the clock will no more remain accurate. So, for that reason people use a crystal, because as you know the crystal has the property if you draw the equivalent circuit of the crystals you will find this is a very high value of inductance, we know. As you know the inductance if you have any coil, it has large inductance, obviously its q will be, I mean quotient point will be very, very high, right?

So, if the q is high, obviously if I use some oscillator circuit, some oscillator circuit based on this particular crystals, obviously what will be, that time you should not use crystals. You will say the, you should, you should look at a, I mean a passive circuit which has high value of inductance. If the inductance is very high, obviously what will happen you know that I will get the large value of the q. So, this large value of the q means I will get a tremendous amount of frequency stability of the circuit, right? So, let us look at that.

You see to a piezoelectric, piezoelectric crystals with electrodes plated on the opposite faces a potential applied between the electrodes you know forces are exerted on the bound charges within the crystal. An electromechanical system is thus formed which will vibrate when properly excited, right? A electromechanical system is thus formed which will vibrate when properly excited.

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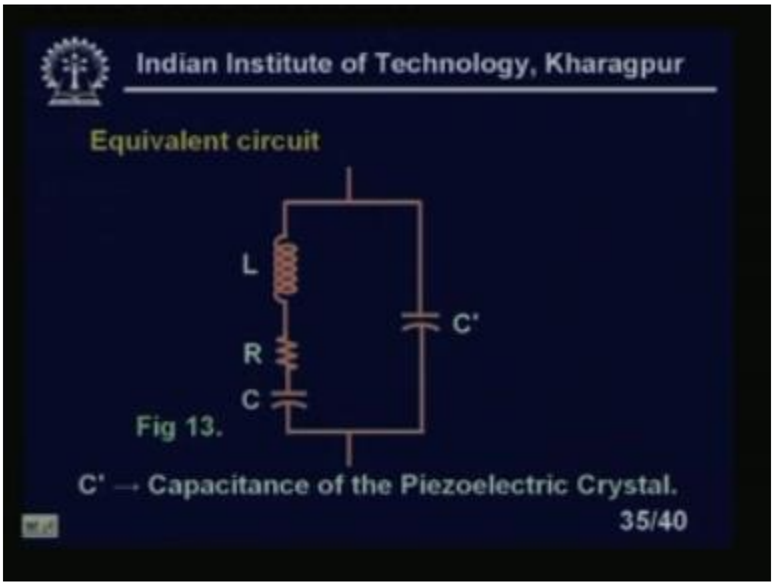

The equivalent circuit is like this one. You see, I have a inductance. Let us look at, I have an inductance L. Then I have an inductance L, I have a resistance R, C and also a parallel capacitance C dash. This value of L is very, very high in the case of piezoelectric crystals. That makes the frequency stability excellent otherwise nobody should care for these quartz crystals, right?

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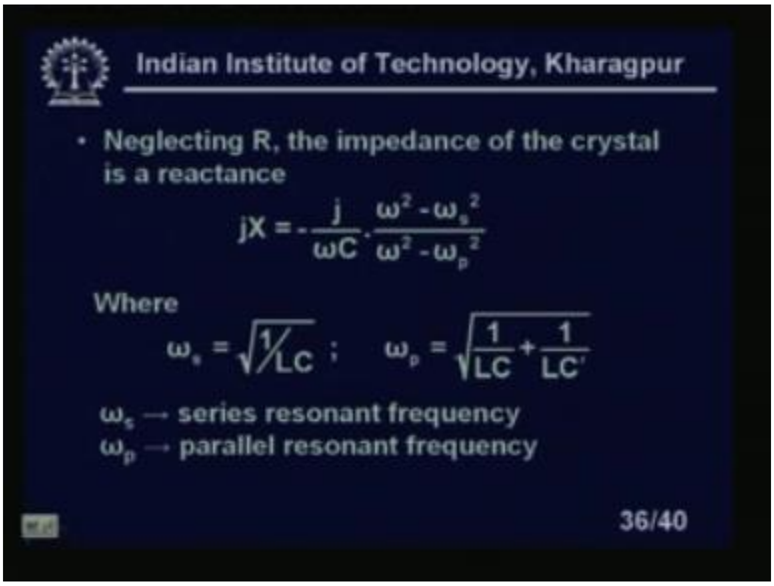

Neglecting R, if I neglect R, the impedance of the crystal is the reactance, which can be given as j by omega C into omega square minus omega s square upon omega square minus omega p square, where omega s and omega p are the series and th parallel resonance of the circuit, where omega s, 1 by LC and omega p equal to 1 by LC plus 1 by LC dash, right? Omega s, as I just right now told, series resonance frequency and omega p is the parallel resonance frequency. These are, one is series resonance and parallel resonance frequency. So, what will happen actually?

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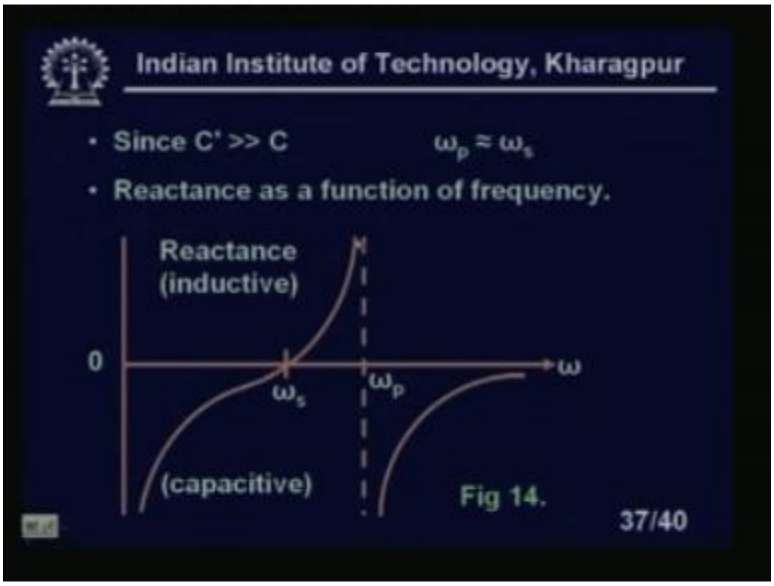

Since the C dash is much, much greater than C, omega p is almost equal to omega s, right? So, if it is omega p omega s, reactance as a function of frequency, you see, if I plot this one, it will look like this one. This is inductive here and here you see it is capacitive. Omega s is series resonance and omega p is parallel resonance. So, this is the, if I plot the reactance of the piezoelectric crystals versus frequency I will get a response like this one, right?

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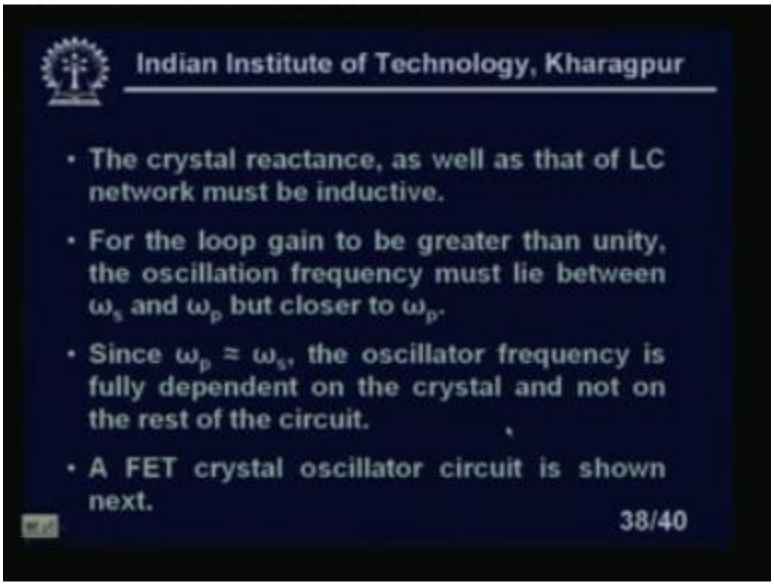

Now, the crystal reactance as well as that of the LC network must be inductive, quite obviously. Basically this, I mean, I mean your piezoelectric crystals you can see, if you look at from the basic point of view it is nothing but an LC oscillator. We have studied the LC oscillators in our analog electronics. You see, simply the LC oscillators, only thing that L is replaced by piezoelectric crystals. For the loop gain to be greater than unity, the oscillation frequency must lie between omega s and omega p, but closer to omega p. So, the loop gain we have seen, you see that it should lie between omega s and omega p, but closer to omega p. If it is there, so no problem, I can purposefully, can choose that thing.

Since omega p is almost equal to omega s, the oscillator frequency is fully dependent on the crystals and not on the rest of the circuit. This is the most important point of the piezoelectric crystals. See here, since omega p is equal to omega s, the oscillator frequency is fully dependent on the crystals and not on the rest of the circuit. Because you need rest of the circuit we will find that we have the other elements in the circuit, but the frequency will not depend, the frequency of the crystal, the frequency of oscillation of the oscillator will not depend on the rest of the circuit. It will depend only on the crystal itself and it is highly stabilized. It hardly changes with time or anything, so that is the reason I am getting a very stable frequency there. So, all these properties happens because of, because of large inductance.

Now let us look at a FET crystal oscillator shown in the next, I mean we will see that the how using a FET it is basically a Colpit oscillator.

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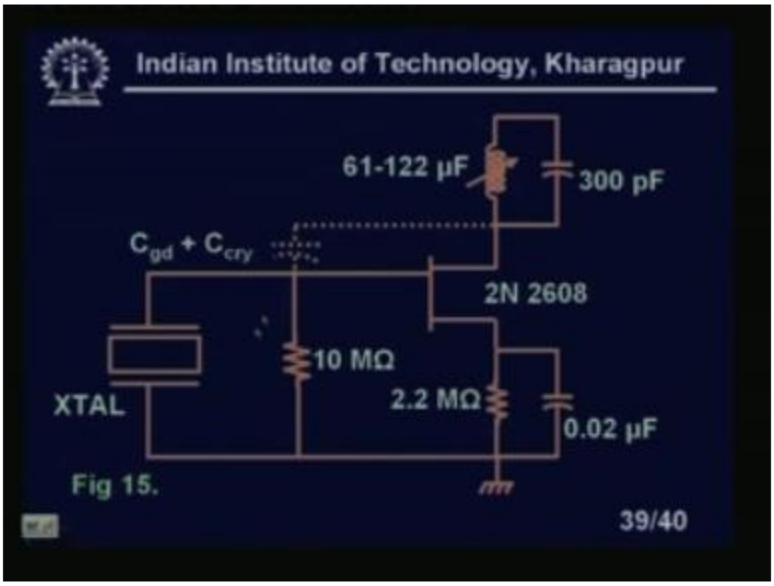

We can see this is the typical Colpits oscillator. You can see here, so I have a crystal here, I have a 10 mega ohm resistance and I am using a transistor 2N 2608 and this is a tank circuit which values 61.122 micro farads with 300 Pico farad capacitances, emitter bypass capacitor .02 micro farads, a resistance, emitter resistance 2.2 mega ohm. So this, but please note that the piezoelectric crystal does not necessarily mean that it will have totally independent of temperature; it has temperature dependency.

But you see the advantage of this one, this 10 mega ohm, 2.2 mega ohm capacitances, all these things, whatever the things you see the inductance here, it is very small. One or two turns of coil can generate this type of, this type of inductance. So, what will happen you know that in these cases, in this entire thing what will happen? This oscillation frequencies does not depend on the resistance, capacitance and all those things. It will depend totally on the crystals and crystals that parameters does not change, right?

So, obviously by this I can get a very, very stable signal from the circuit. We know, as you know there are many other oscillators. We have sinusoidal, we have a, we have a

Wien bridge oscillator, because basic in all oscillator, as you know the basic mother of the, all the function generation is a sine wave. Because, once you get the sine wave I can …….. a Schmitt triggers. So, I can, I can make a square wave. If you differentiate a square wave I will get a pulse. If you integrate a square wave I will get a, I mean it looks like this.

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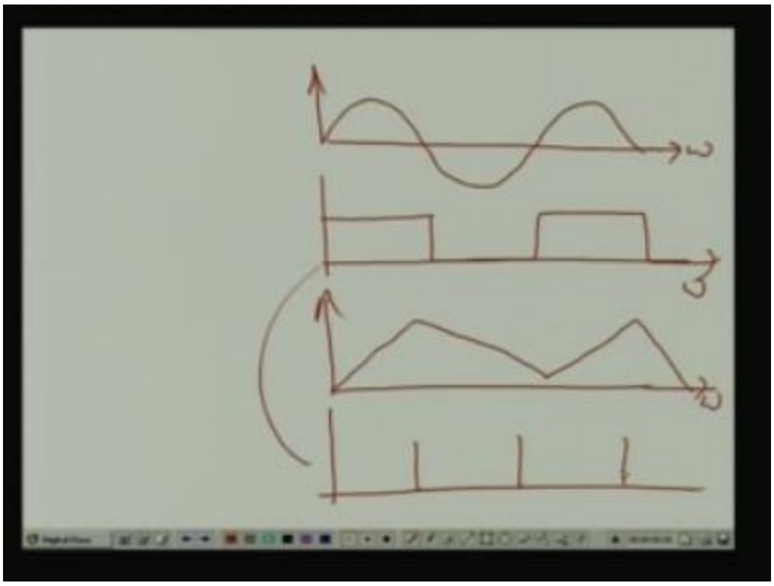

You see that if I have a sinusoidal wave, I should take some other colour, so I will get a square wave like this, sinusoidal wave. There are various types of oscillators. We know Wien bridge oscillators, then phase shift oscillators, Colpits oscillators, so these are the different types of oscillators available. Now, these signals, sinusoidal signals if I pass through a Schmitt trigger, I will get a signal like this one, right? If I chop the other parts I will get a signal like this one – lower part, right? If it do not have a dual supply, so I will get … If it is zero, so it will not.

Now, if I integrate this signal how I will get the signal? I will get the signal like this, is not it? So, I get a triangular wave. Now, if I differentiate this signal omega, what I will get? I will get a pulse like this one, is not it? So this will, I mean this is the basic, so basic of the, all the signals generator is basically a sinusoidal wave that we have seen, right? But as you know that in the crystals oscillator also we are basically generating sinusoidal wave. Then, we are passing through a Schmitt trigger, we are making a square wave. So, there are many, I mean Wien bridge oscillators. Why, you should ask, why should you go for crystal oscillator as a piezoelectric based sensors, piezoelectric based oscillator, because of the frequency stability. In Wien bridge oscillator or a phase shift oscillator you won't get that type of good stability, right?

So, as you can see in this particular lesson we have discussed the, the basic piezoelectric sensors, its structure, crystal structures, how I can apply the force, how will you get the signals, what is the charge amplifiers that we have discussed and what is the problem with the simple amplifiers that it is heavily dependent on the cable capacitance, cable resistance that can be avoided if I use a charge amplifier. So, those type of things we have discussed in this particular lesson. Also we have discussed that piezoelectric sensors, I am not going into the vibration analysis, all those things. But, piezoelectric crystals are also used for vibration analysis, crack detection and all those things.

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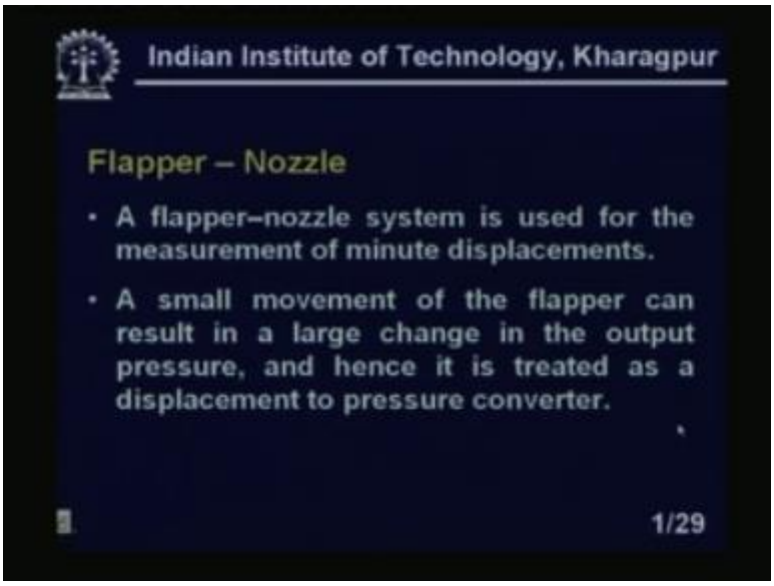

In continuation of the lesson 24, we will discuss now the flapper-nozzle systems. As you know, flapper-nozzle is a pneumatic system. It is extensively used in the pneumatic transmitter and all these types of things. Actually you will get a small displacement, can be converted into a large pressure change, right and as you know that in some industries it is still forbidden to use, use the electrical systems. Though the transmitters are electrical, but the large torque which are necessary for controlling the valve and all those things cannot be provided by the electrical system of supply of 40 volt or something and you cannot use more than 40 volt there. So that is a problem. So, what happens there? They still use those pneumatic systems, so flapper-nozzle is a part of that. So, I will discuss what is the flapper-nozzle systems.

A flapper-nozzle system is used for the measurement of minute displacements. A small movement of the flapper can result in a large change in the output pressure and hence it is treated as a displacement to pressure converter. That means displacement can be converted to the pneumatic pressure, right? So, it is total pneumatic systems we can see here.

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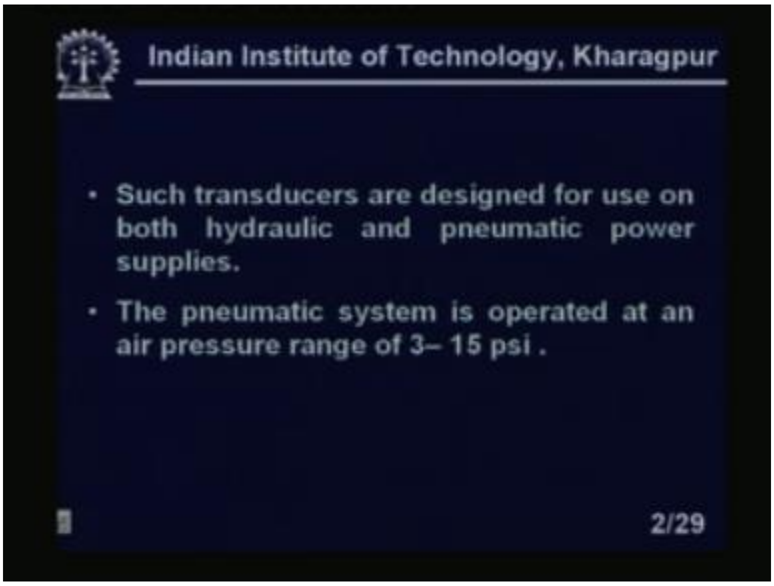

Such transducers are designed for use in both hydraulic and pneumatic power supplies. As you know, the pneumatic system is operated at an air pressure range of 3 to 15 psi, as you know that though we use SI systems in academics, still in industry they use those terms like 3 to 15 psi. As you know that 3 to 15 psi is a standard for pneumatic systems which corresponds to 4 to 20 milli ampere of current in the electrical domain.

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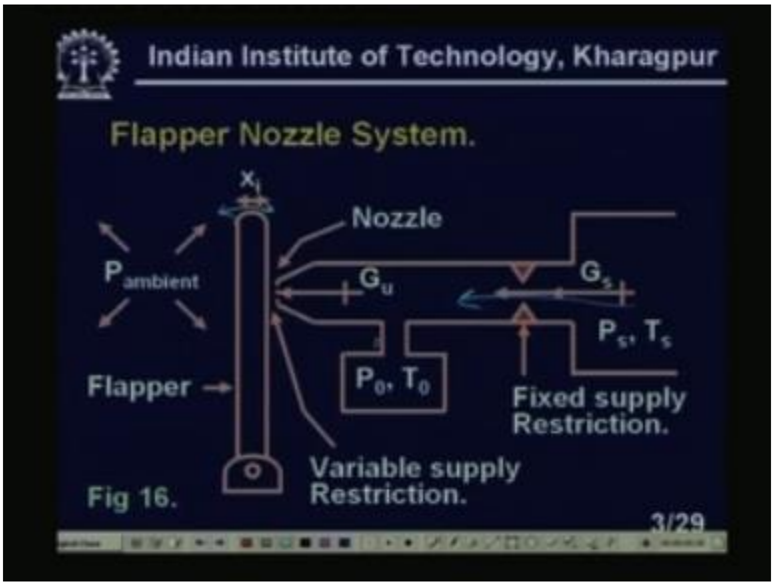

Now flapper nozzle system let us look at. You see, this is our flapper nozzle system. We have a flapper. You see this is, even though we have shown it is, it is usually very thin, right and there is a nozzle; nozzle also diameter is very, very small, right? Now, what will happen you know that if this flapper, if this flapper goes like this, if this flapper goes like this or this, so large pressures will be developed in this systems, right, at here. Here we are giving some continuous supply of pressures. Now, if it moves away what will happen? If it moves away the pressure will be less. So, this displacement, small displacement can measure, can be measured by the pressure, measuring the pressure at this point, right and also we can see, you can use a feedback control systems with the flapper-nozzle, because it can have a automatic feedback systems. That means you have, if I use a, if I, suppose if this nozzles is coming very close to this one, automatically the pressure will increase and it will give the back pressures here. So, it will put the nozzles in a particular position that is the feedback systems, anyway let us look at.

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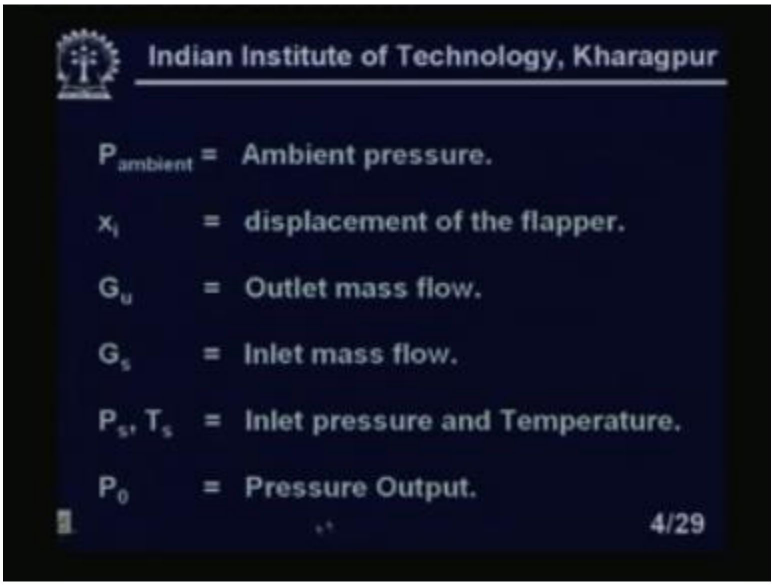

Now you see this is our, this is the P ambient pressure, I have a flapper. This, I have already told you this is very thin actually though it is shown, so it can move like this.
It can move like this that means flapper can move like this. So, it is very thin, so flapper can move like this. So like this one, so it is like this one flapper, so it will move like this. I have a hinge here, so nozzle here. It will move like this. If the flapper comes very close to the nozzle the pressure will increase, P o will increase. If it goes away P o will decrease. That is the basic principle of the flapper-nozzle systems and we have also, at the end of the nozzle a fixed, I mean pressure supply or air supply, right?

P is the ambient pressure, then x i is the displacement of the flapper, G u is the outlet mass flow, G s is the inlet mass flow and P s, T s is inlet pressure and temperature, P o is the pressure output at temperature T naught, obviously.

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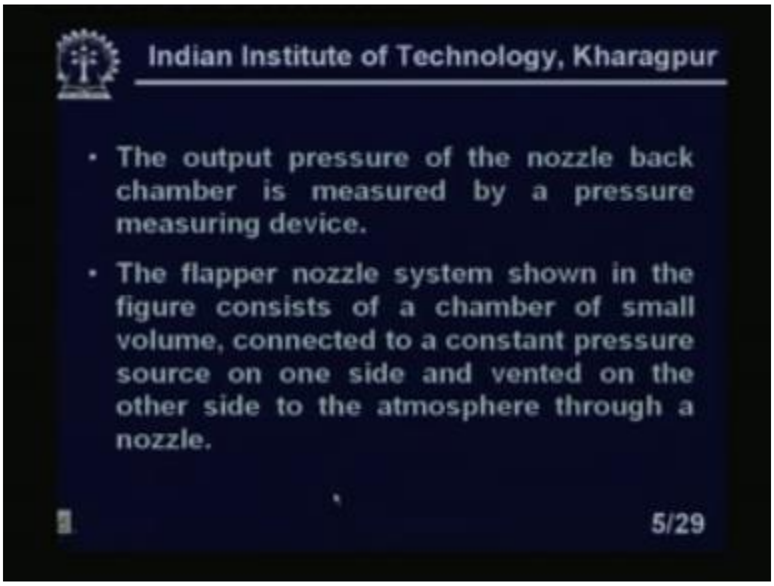

The output pressure of the nozzle back chamber is measured by a pressure measuring device. As you know that you can measure by some, there are so many gauges we have studied so far with bellow gauges or with Bordeaux gauges, by the diaphragm gauges we can measure and that pressure can be calibrated in terms of displacement of the flapper, right? The flapper nozzle system shown in the figure consists of a chamber of small volume connected to a constant pressure source on one side and vented on the other side to the atmosphere through the nozzle. Let us look at again.

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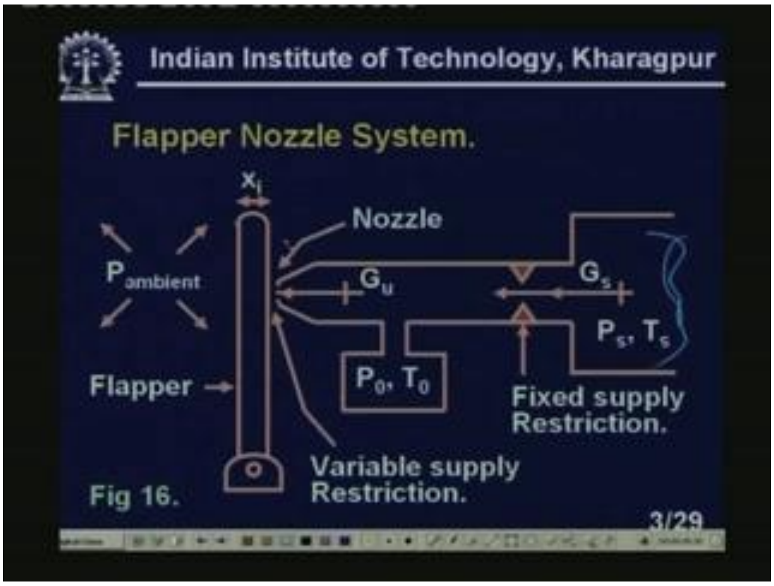

You see, so constant pressure source is this one G s and P s, this is our constant pressure source. Right here you see, this is our constant pressure source, this part. It is connected to, you see this is nozzle. This is a one part of the, one part of nozzle is free. Continuous air is leaking through this one and this is a continuous supply and this is actually measuring the pressure which corresponds to the, this corresponds to the position of the flapper, right? So, the output pressure of the nozzle back chamber is measured by a pressure measuring device, as I told you. The flapper-nozzle system shown in the figure consists of a chamber of small volume connected to a constant pressure source on one side and vented on the other side to the atmosphere through a nozzle.

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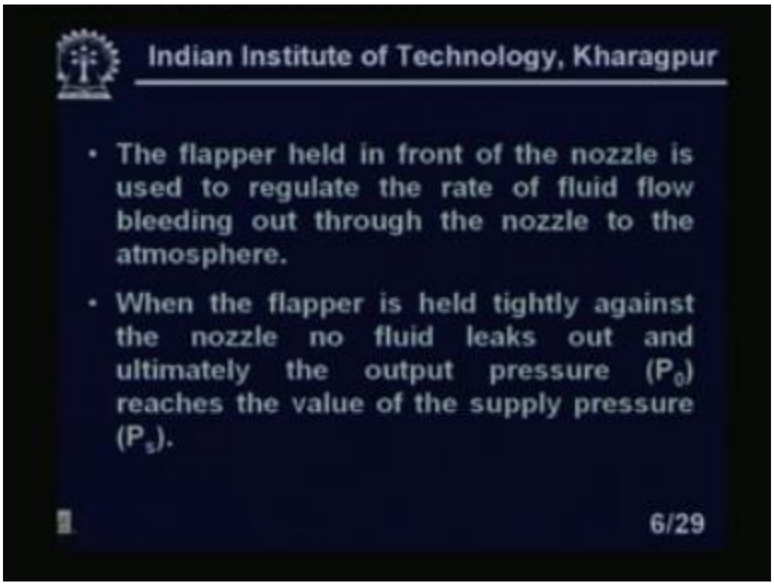

The flapper held in front of the nozzle is used to regulate the rate of fluid flow bleeding out through the nozzle to the atmosphere, right? There is a continuous leak of air or bleeding of air through the nozzle, right? That is actually we are telling here the flapper held in front of the nozzle is used to regulate the rate of fluid flow bleeding out through the nozzle to the atmosphere. When the flapper is held tightly against the nozzle no fluid leaks out and ultimately the output pressure P o reaches the value of the supply pressure P s, is not it?

Let us look at what is that? What I am saying that when these flappers, when this flapper, you see when this flapper comes very close to the nozzle, when this flapper very comes close, this pressures and this P s will remain same. P s and P o will be same at that point, right, if it is coming. But if it goes away it will not be the same. When the flapper is held tightly against the nozzle no fluid leaks out and ultimately the output pressure P o reaches the value of the supply pressure P s, right?

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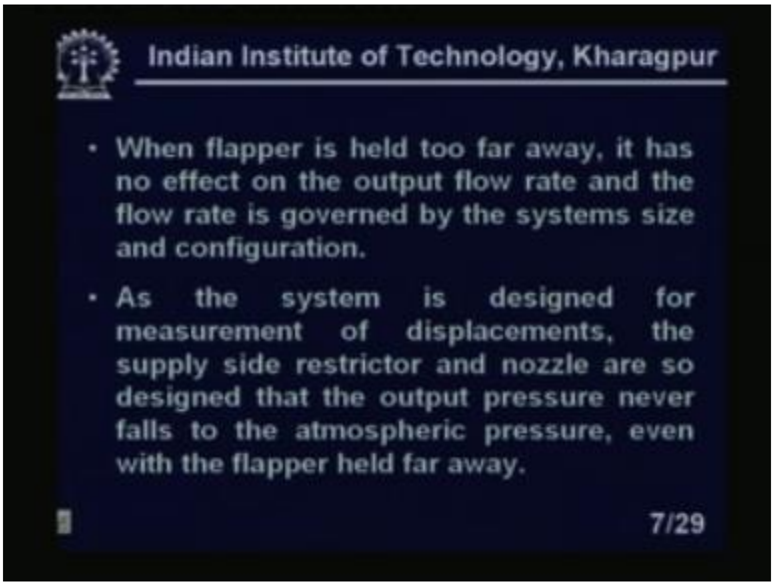

Now, when flapper is held too far away, it has no effect on the output flow rate and the flow rate is governed by the systems size and configuration. Quite obviously at the same time there is no control and as the system is designed for the measurement of displacements the supply side restrictor and the nozzle are so designed that the output pressure never falls to the atmospheric pressure even with the flapper held far away, right? That is the way we have to do, otherwise there will be a problem.

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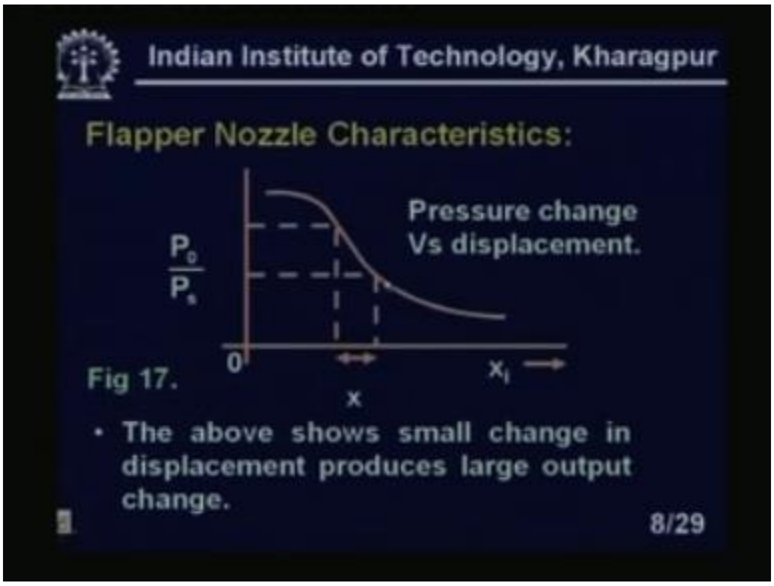

Now, flapper nozzle characteristics: you see, this is our flapper nozzle characteristics. This is the output pressure divided by the supply pressures, in the x-axis is displacement. What is the displacement, displacement of the flapper? So, pressure change versus displacement. This is a normalized so P o by P s. The above show a small change in the displacement produces large output change. You see that in this region you see for a small change in output, for small change in displacement I am getting a large change in the ratio of the output pressures and the supply pressure, right?

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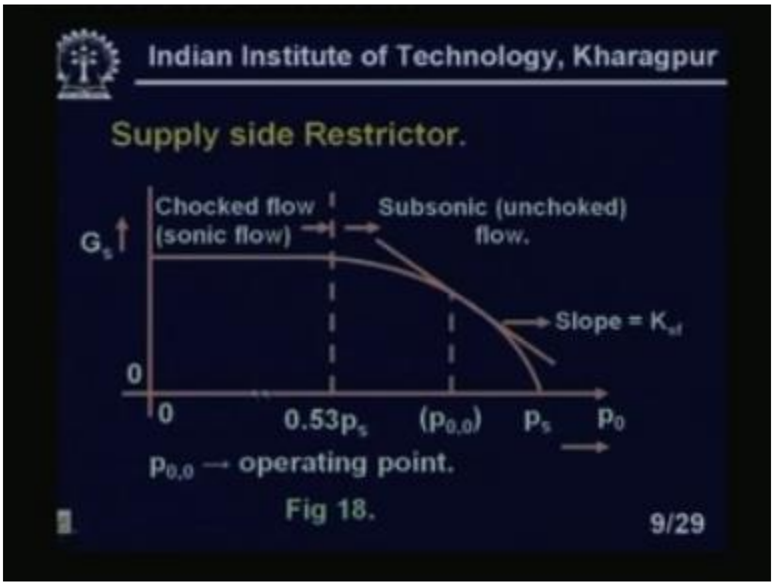

Now, supply side restrictor, we have a supply side restrictor also. You see here the chocked flow it is the actually operating point of our, this is our operating point where the slope of K sf and this is subsonic, is unchoked flow and we have a chocked flow which is sonic flow, right? So, here we are plotting P o or output pressure.

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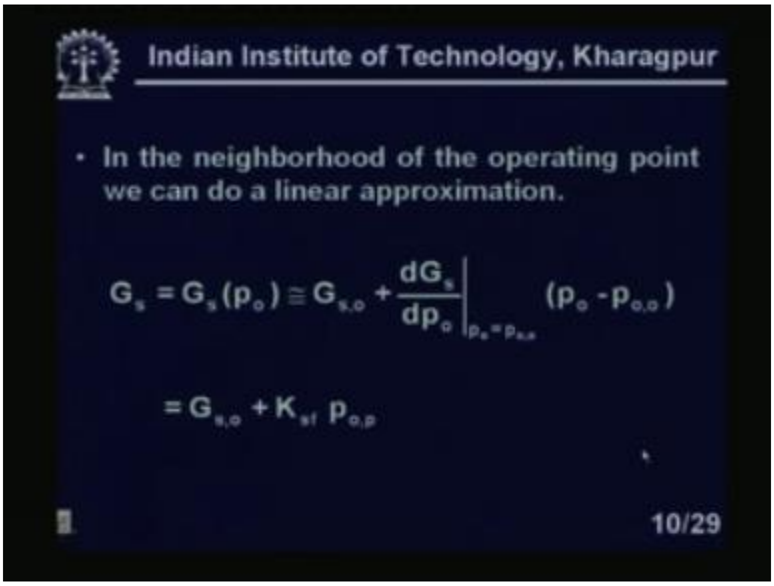

In the neighbourhood of the operating point we can do a linear approximation, otherwise it is non-linear, as we can see. But, at the, at the neighbourhood of the operating point of our flapper-nozzle system we can consider this as a linear sensor. So, G s equal to G s p o which can be almost approximated G so plus derivative of G s by dp o at the point p o equal to p oo and p o minus p oo equal to G so plus K sf plus p o into P of op.

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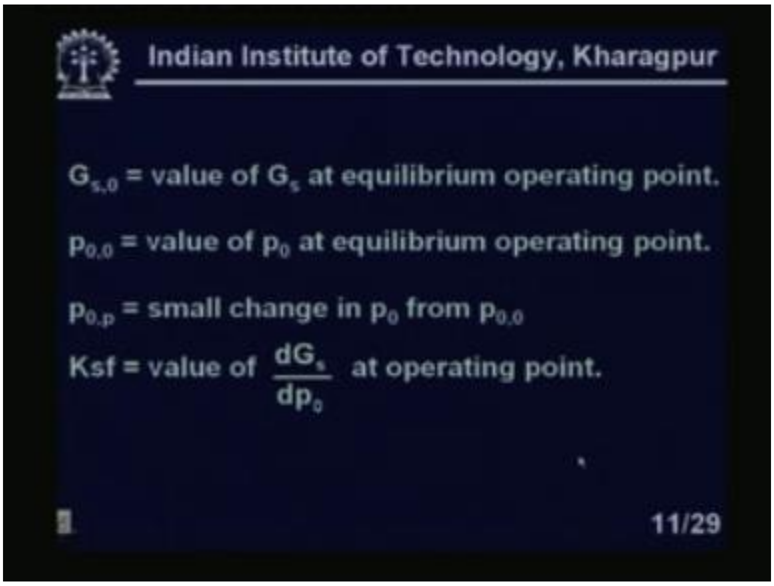

G s o is the value of G s at equilibrium operating point, p o o is the value of p o at equilibrium operating point and p op is the small change in p o from p oo, right and K sf value of derivative of G s with respect to p o at operating point.

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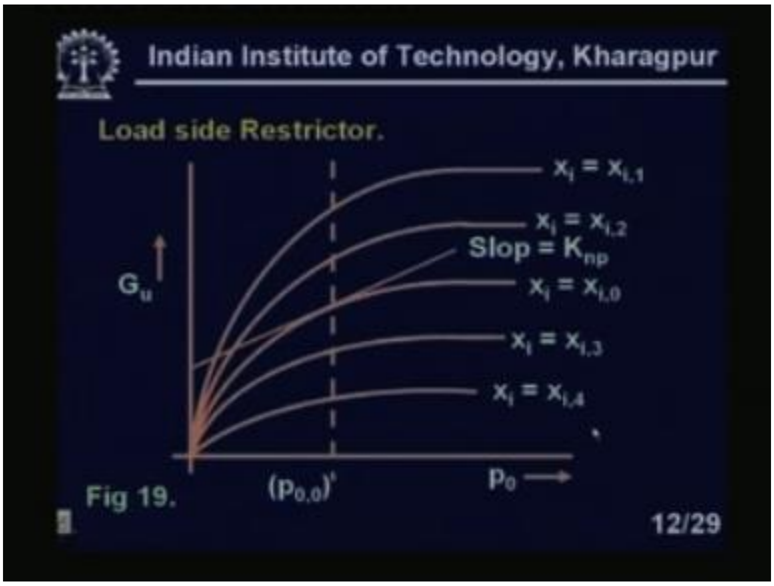

Load side restrictor let us look at. So, this is the load side restrictor graph. So, we have G u here and we have plotted p o here for different values of x i, right? So, we can also …… for a small region we can linearize, this operating point we can linearize across this, right?

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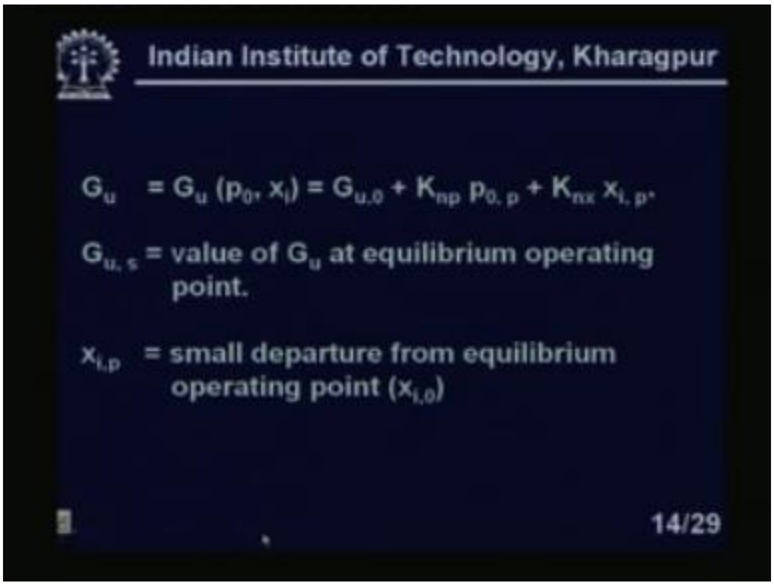

Here G u equal to G u p o, x i equal to G uo plus K np p op plus K nx x ip, right, where G us is the value of G u at equilibrium operating point and x ip is the small departure from the equilibrium operating point x i 0.

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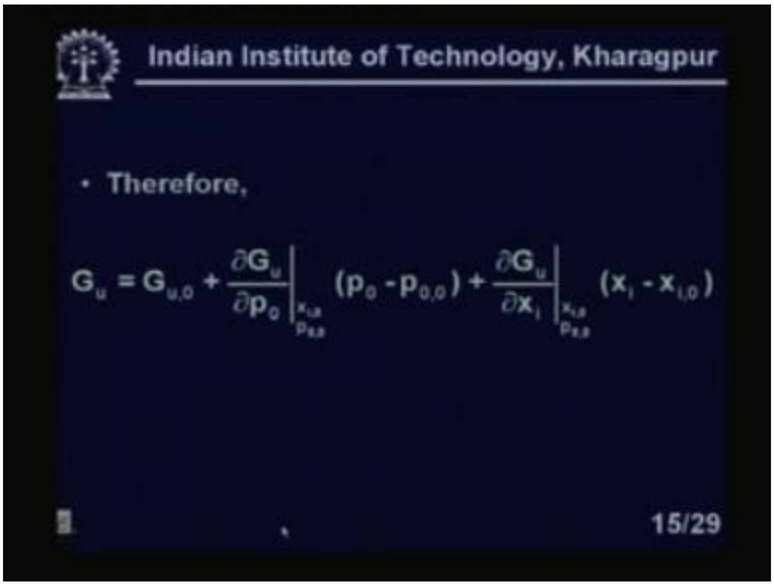

Therefore, I can write G u equal to G u naught, G u 0 plus delta G u with respect to delta G u by delta p o at x i at x equal to i 0 p oo multiplied by p 0 minus p 0 0 plus delta G u by delta x i x i,0 p 0,0 x i minus x i 0.

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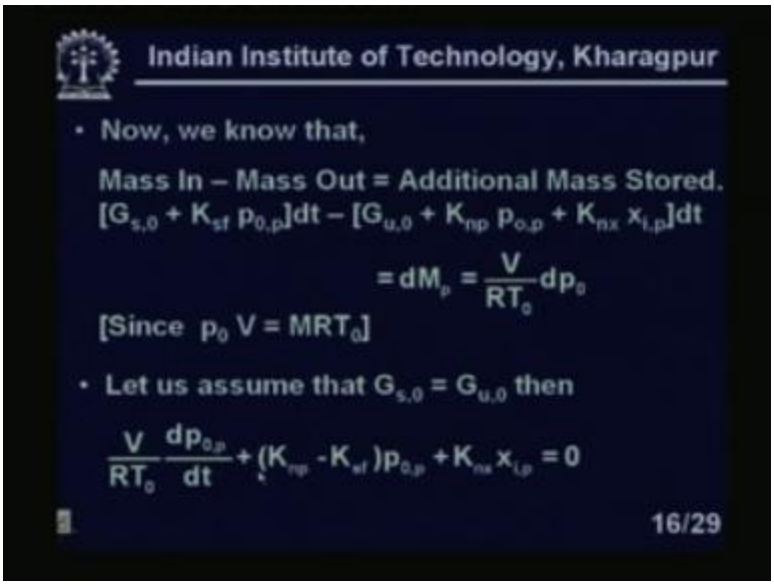

Now, we know that that mass in equal to mass out. Mass in minus mass out is the additional mass stored, right? So, G s o plus K sf multiplied by p o p dt minus G uo plus K np p op plus K nx x ip dt, which I can write dM p equal to V RT o multiplied by dp o, since p 0 V equal to MRT 0. Let us assume that G so equal to G subscript o, then I can write V by RT o dp 0 p by dt plus K np minus K sf p 0 p plus K nx x ip equal to, equal to zero.

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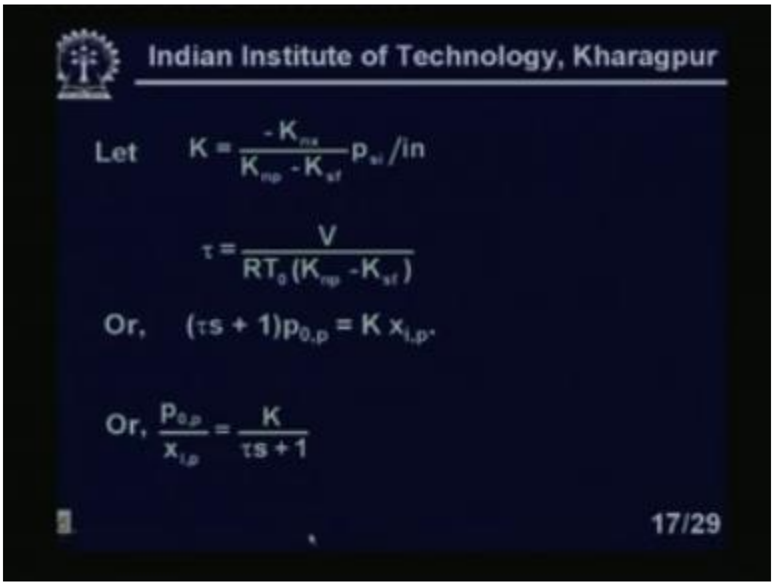

Let K equal to minus K nx upon K np minus K sf psi per inch, where tau equal to V by RT K np minus K sf. Then I can write, tau s plus 1 p 0 p equal to K x i p or p 0 p upon K x ip equal to capital K by tau s plus 1.

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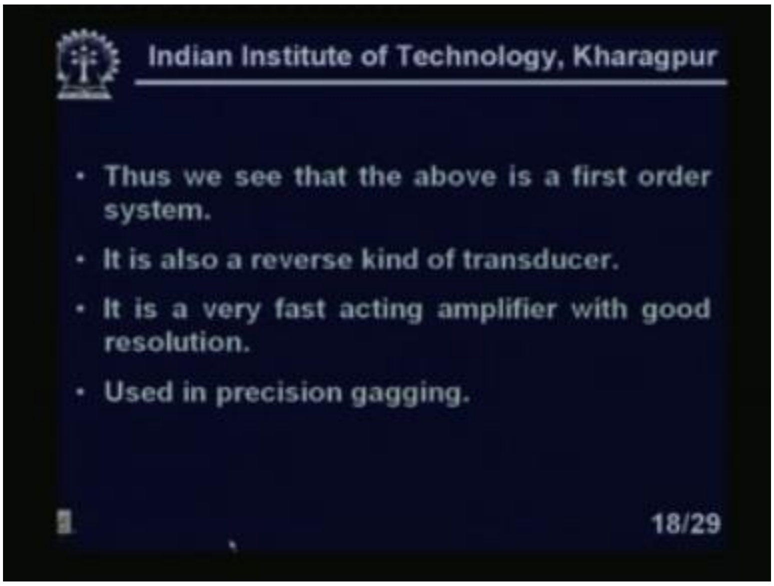

Thus we see that the above is a first order system. So, flapper-nozzle system is a first order system. So, it is also a reverse kind of transducer, right? So, process is reversible. That means if the flapper comes very close automatically the pressure will increase or if the pressure increases the flapper will go away it is I mean from the nozzle, sorry. It is a very fast acting amplifier with good resolution that is most important thing. It is very fast acting. Even though it is pneumatic system, it is quite fast. Used in precision gagging that means for a small displacement, I can use this method.

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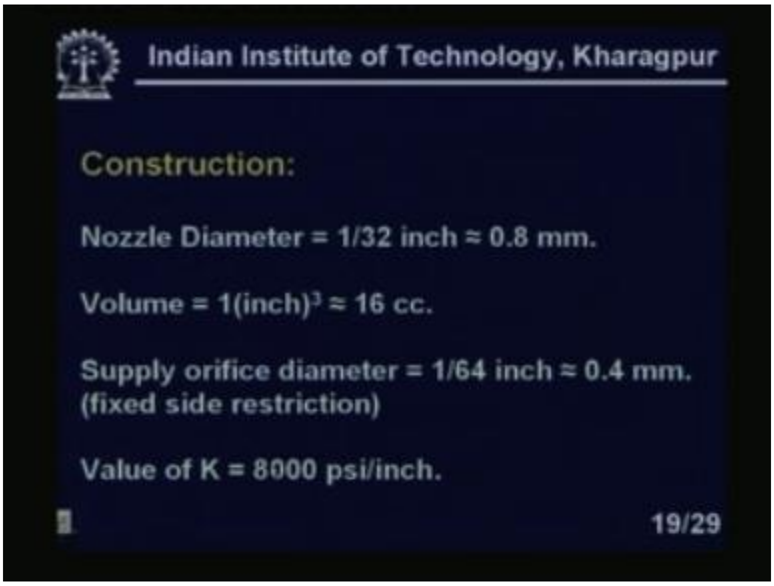

Construction, let us look at. Nozzle diameter is usually 0.8 millimeter, the volume is 16 cc, supply orifice diameter is .4 millimeter and fixed side restrictions, value of cap K equal to 8000 psi per inch.

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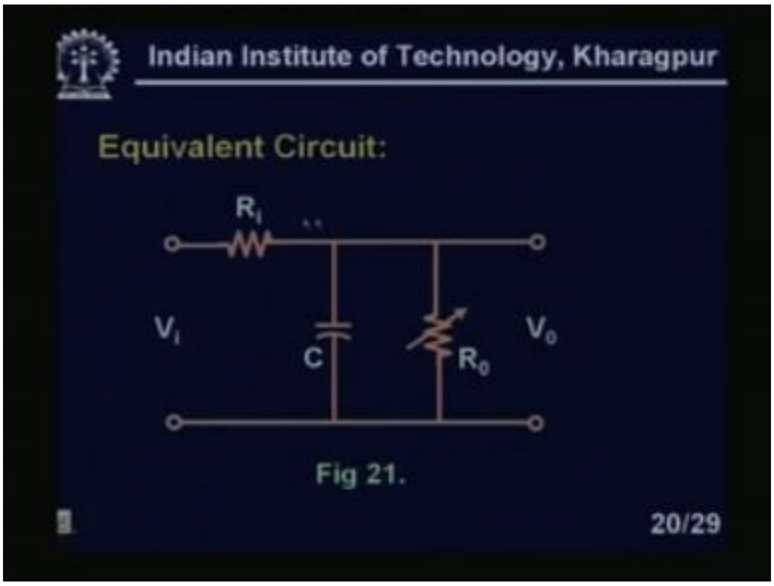

See, equivalent circuit if I look at, if I draw the equivalent circuit it is R i parallel with C with parallel R i in series with C parallel with R o. This is variable, this is output. So, this is input, this is output.

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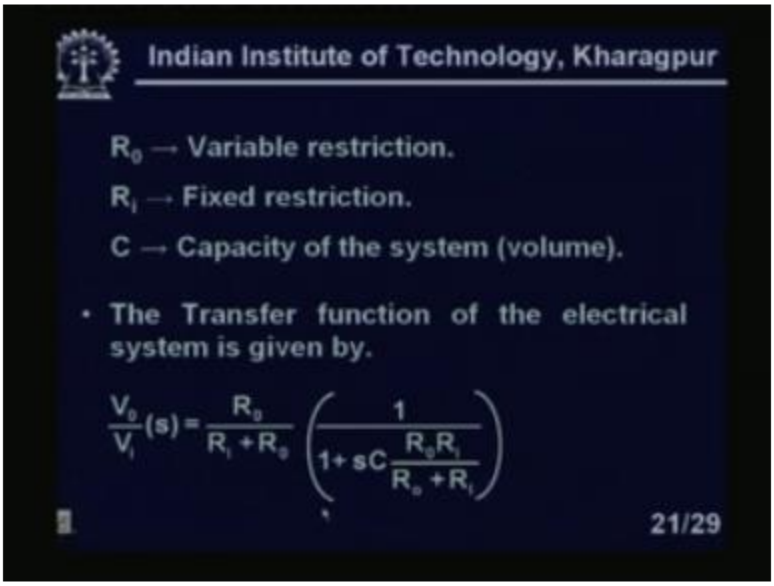

So, R o is the variable restriction, R i is fixed restriction, C is the capacity of the system or volume and the transfer function of the electrical system is given by V o by V i (s) R o upon R i plus R o multiplied by 1 upon 1 plus s C R o R i upon R o plus R i, right?

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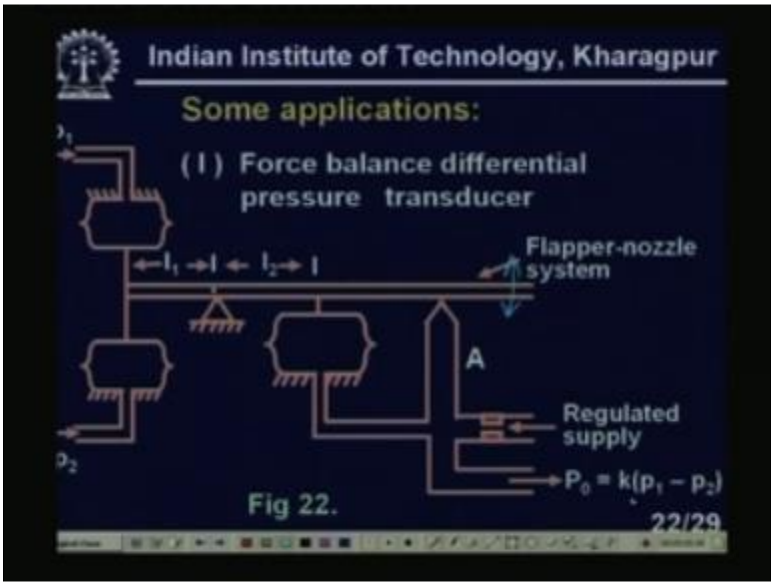

Some applications let us look at. Force balance differential pressure transducer it is extensively used. You see, this is the force balance. We have two bellows here, you see here two bellows. Pressure p 1 and pressure p 2 we are giving and this is the pivot and there is another bellow here and this is my flapper-nozzle system here. You see that this is flapper. So, across this pivot, across this pivot, so this can move. So, hinge here, so this can, flapper can move in this and this direction, right? So, bringing this, this flapper very close to the nozzle or going far off the nozzle, right?

You see, it cannot go very far. What is the, what will happen you see if it go far? So, you see if it comes very close it cannot close it. If it come, it cannot restrict this one, because there is a feedback bellow. So, it will push this upward, because if you put, comes automatically the pressure here will increase. So, it will go to the feedback bellow, so it will increase, right? Now if it, what will happen you see that if it goes far away, it cannot go far away also because in that case it will also, this pressure will increase. So it will, stabilization will come. So, regulated supply is coming p 0 equal to K p 1 minus p 2. So you see, this is the p 1 and this is p 2 coming through two differential pressures, right?

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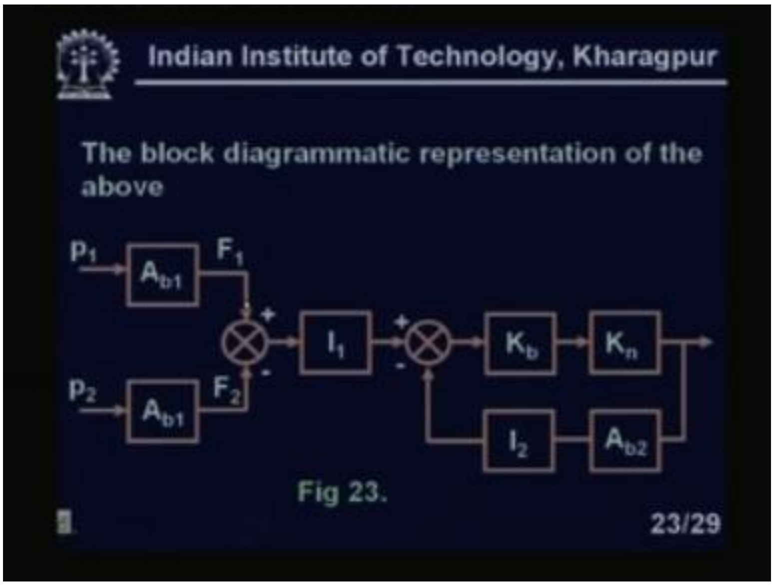

The block diagrammatic representations of the above you see like this one p 1 p 2 A b1 A b2, like this one K b, I 1, I 2.

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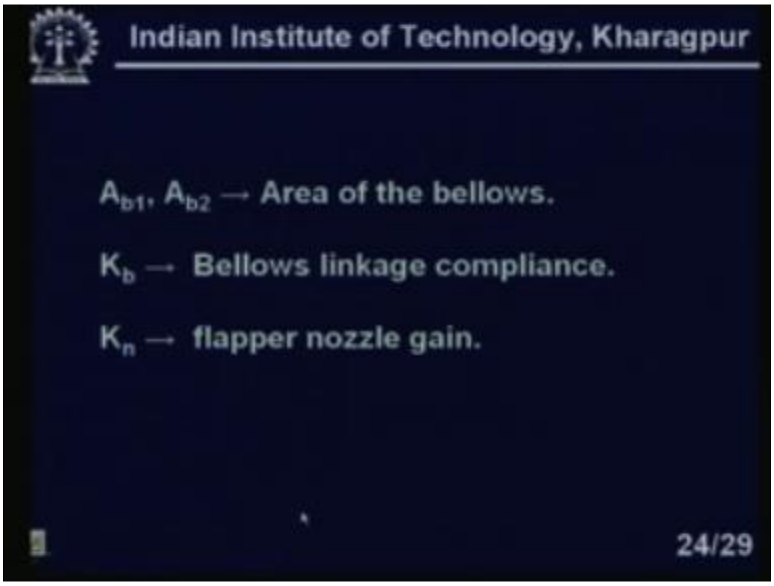

So, A b1, A b2 area of the bellows, K b is the bellows linkage compliance, K n is the flapper nozzle gain.

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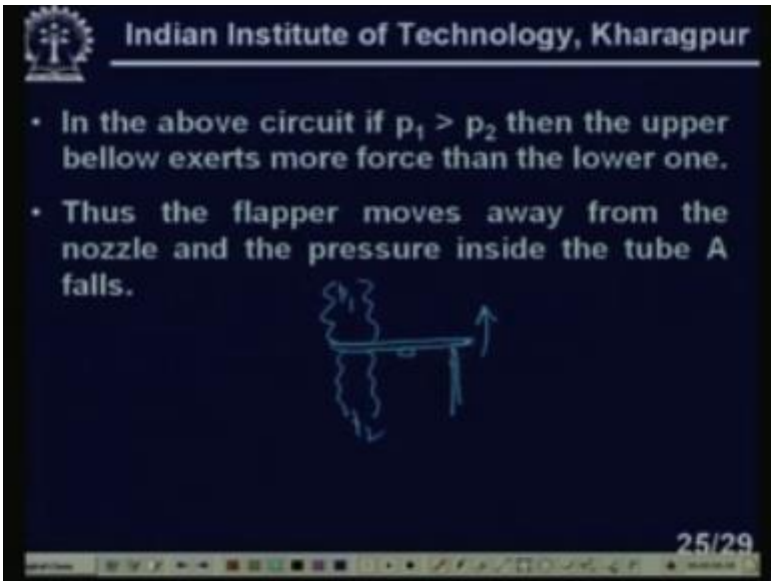

In the above circuits, if p 1 greater than p 2, then the upper bellow it exerts more force than the lower one. Thus the flapper moves away from the nozzle, right, because since we have a right side we have a bellow. You see, it looks like this, is not it? I have a bellow here, I have a bellow here. There is a flapper. I have a bellow here, I have here, so this is p 1, this is p 2 and I have a nozzle here, sorry, is not it? So, what will happen if this, thus the flapper moves away from the nozzle and pressure inside the tube A falls. Suppose if this is comes then what will happen? Pressure, this, this bellows will, because this is pivot, so this will, the bellow will, this the flapper will move in this direction. So, the pressure will fall, inside pressure of the orifice will, this nozzle will fall, is not it?

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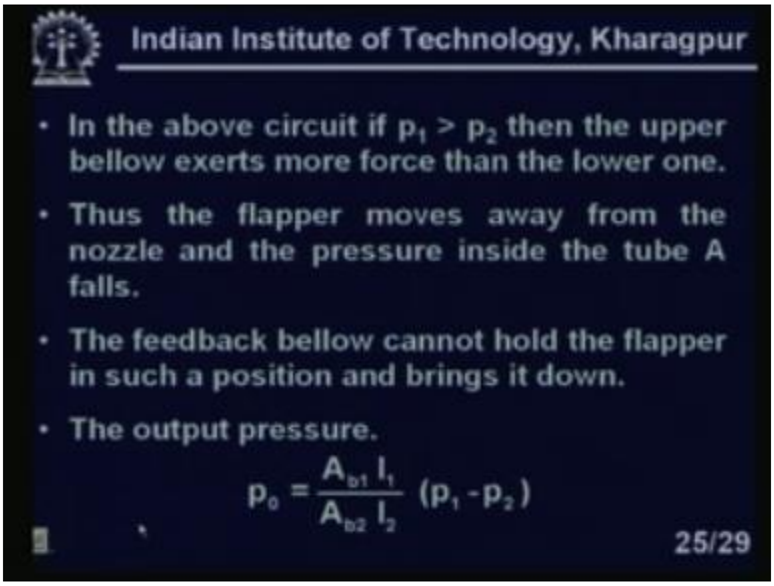

The feedback bellow cannot hold the flapper in such a position and brings it down. The output pressures p naught equal to A b1 l 1 by l 2 by A b2 p 1 minus p 2.

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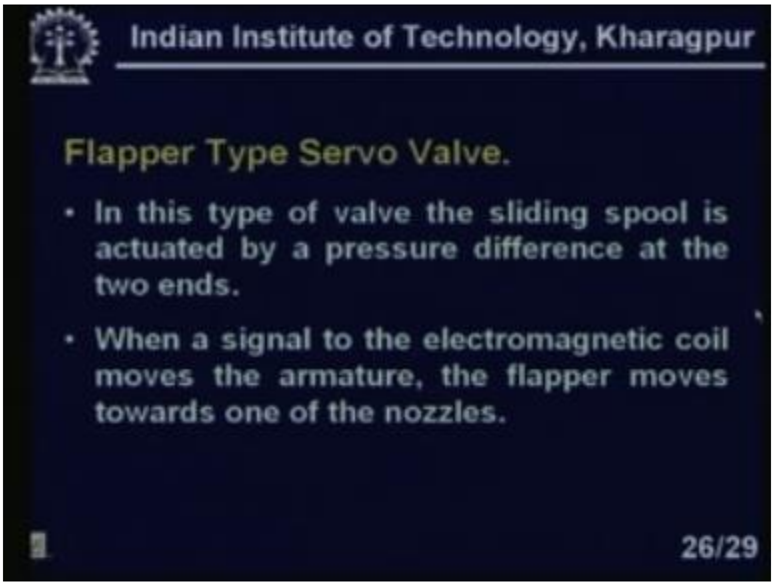

Flapper type servo valve - you see, in this type of valve the sliding spool is actuated by a pressure difference at the two ends. When a signal to the electromagnetic coil moves the armature, the flapper moves towards one of the nozzle.

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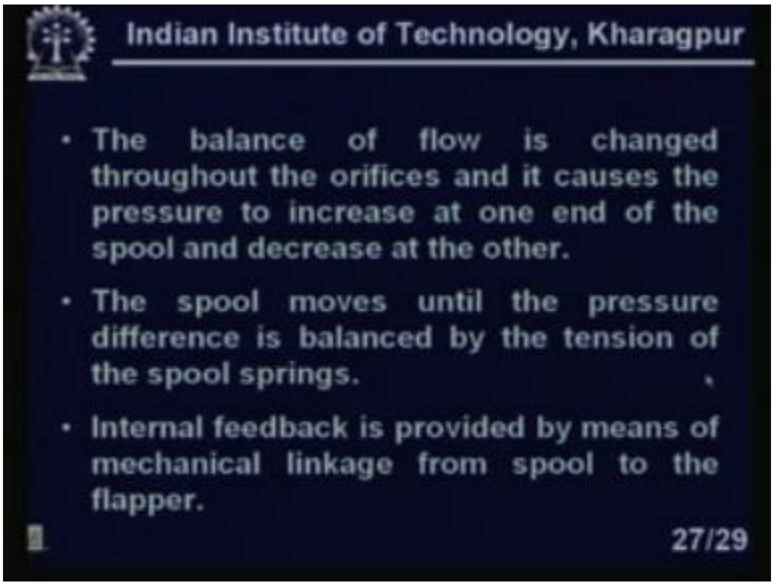

The balance of the flow is changed throughout the orifice and it causes the pressure to increase at one end of the spool and decrease at the other. The spool moves until the pressure difference is balanced by the tension of the spool, spool, spool springs and internal feedback is provided by means of the mechanical linkage from the spool to the flapper.

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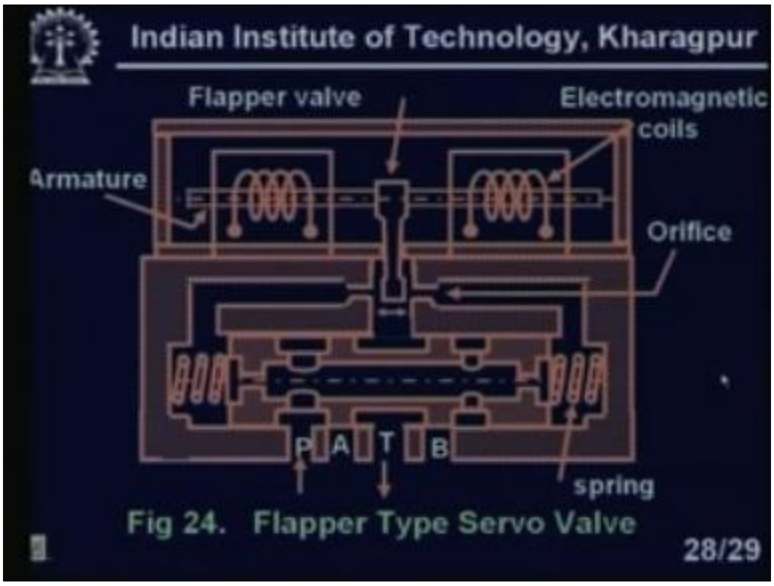

You see, this is our entire flapper nozzle systems, right? This is the flapper type servo valve you see here. This is our orifice, right? This is our flapper valve. So, this is electromagnetic pulse, this is armature, right? So, this is our springs on the both sides. You can see here the springs are on the both side. This side, this side we have also springs and this is our flapper valve, right?

So, in this lesson we will see that at the first part of the lesson we have discussed the, basically the piezoelectric sensors which is used for the measurements of the displacements, accelerations, ultrasonic and which can be used as the ultrasonic generations of the frequencies or ultrasonic waves and also it can be used in the crystal oscillator and the second parts we have discussed a very important, a pneumatic system which is called the flapper nozzle systems with feedback systems, right and it is very fail safe devices as you can, if you compare with electrical devices it never fails actually, this, except the routine maintenance of the orifice, because entire operation depends on the orifice width also. So, diameter of the orifice also is very important.

Over the long use it should not, it should not widen, so that you have to change, you have to make the change in entire calibration, otherwise it is a just fail set device. It never, it never happens that it is not working or it fails. So, that is the great advantage of this type of pneumatic system. For this reason it is used over the years in the industry and still it is used in some of the industries like hydrocarbon industry, where high voltage is restricted. That means I cannot use a voltage or any devices which has a voltage more than 40 volt, because you know there is a, there is a large, you should have a large actuator or large valve control bulb.

I need a voltage of at least of 220 volt to create a large torque. That is not possible because that voltage is not allowed in the hydrocarbon industry. Though the transmitter side of the electrical that is fine, but the basic actuator, basic sensor there are the basic pneumatic, because it is totally hazardous free, right? Because so many supply we have instead of electrical supply, so we have a pneumatic supply there, right? So, with this I come to the end of the lesson 24.

Preview of next lecture:

Welcome to the lesson 25 of Industrial Instrumentation. In this lesson we will consider ultrasonic sensor, right? Ultrasonic sensors, ultrasonic measurements of flow velocity or ultrasonic based flow velocity, we have discussed sometime back. But in this particular lesson, we will basically use the, we will discuss the basic principle of the sensors and how the transmitters, what is the principle of transmitters, its equivalent circuit, how the receiver works and the various applications of the ultrasonic sensors like level measurements, crack detection, as well as the biomedical applications, where the ultrasonic sensors plays a great role, so that part we will discuss in this particular lesson.

Let us look at the contents of this lesson.

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Contents looks like, ultrasonic principle, how the, what is the principle, how it works that is actually we will discuss here. Then transmitter receiver we will discuss in details, then equivalent circuit of the ultrasonic sensors we will discuss. Then its applications, both the level measurements, crack detection as well as biomedical applications we will all discuss in this particular lesson.