Principles of Mechanical Measurement

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Module – 07
Force & Torque Measurement
Lecture - 20
Various load cells & dynamometers

Hello friends, welcome back to the 2nd lecture of our week number 7. Here, we are talking about the measurement of force and torque. Now in the previous lecture, you are introduced to the concept of the unit of mass. Actually all of you know from very childhood days that the s i unit of mass is kg, but we spend a major time discussing in the previous lecture about the new way of defining the magnitude of 1 kg or the value of 1 kg.

Because in earlier days, even when you recorded the very first lecture of this particular course, the measurement standard used to be i p k, but very very recently just about 2-3 months back, there is a change in the way we define the value of kg. And now, it is not based upon the mass of any particular physical unit or physical quantity rather, it is it has now been related to an universal constant which is a Planck's constant. And accordingly, we are we have to modify all relevant definitions where we need to make use of the value of kg to define any of the derived parameters.

Now, after the definition we discussed about a few common ways of measuring force. Generally force measurement is always related to the measurement of mass or I should say the measurement of weight because weight itself is a kind of force and most of the force measuring device actually can also be viewed a way of measuring weight of some physical quantity. So, we have discussed about the mechanical weighing systems, elastic load cells and a few other ways of measuring force as well.

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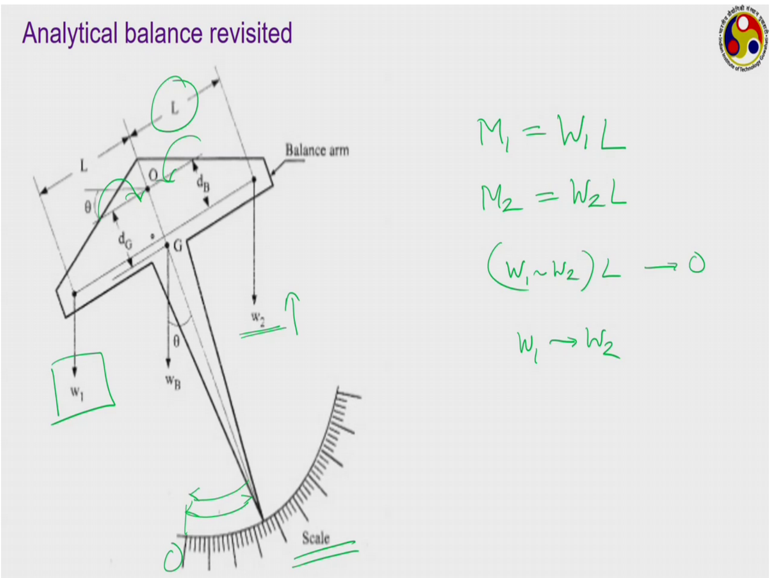

Today, to start with, we shall be going back to the analytical balance; once more because in the previous lecture we introduced you to the concept of this analytical balance or similar kind of other mechanical weighing systems and we discussed about different issues that the operating need to be careful about. Like the effect of possible effect of buoyancy etcetera.

However, we have not done too much of mathematics or we have not focused too much on deriving corresponding relations. Though most of them are quite obvious, but still. Today, let us spend a bit of time in those relations to start with. So, the first in line is the analytical balance and which is also quite often called the equal on analytical balance because this is the one where we commonly have a one fulcrum or pivot located exactly at the center and on equal distance of that fulcrum we have 2 arms or 2 plates on either sides or you can say 2 trays. One of the tray, you have generally houses the mass for which we want to measure the value or the quantity where you for which we want to measure the force.

And the other one, where we put some kind of known or standard masses and by once we achieve the balance at the fulcrum we considered we can easily equate both of them like shown here. Here, this O refers to the position of the fulcrum that we are talking about and here, we have a W 1 force acting on one side and W 2 acting on the other side of the balance arm. Here, the point of application of both these forces are at equal distance from that point O which is this L.

So, then corresponding to this W 1, how much is the moment that is acting at point O? So, that moment corresponding to W 1 if we call that M 1 that should be equal to W 1 into L and what should be the direction of this look at this force a W 1 and also look at the position O. We can clearly see that the force will be acting in this particular direction that is a clockwise force.

Similarly, if we calculate the moment corresponding the force W 2, then M 2 will be equal to W 2 into L and this force will be a counterclockwise or it will produce a counterclockwise moment. When the as L is equal or the distance of point of application of both the force are equal from this point O, so the values of W 1 and W 2 will decide the net moment or net torque that is acting on point O. And in this case that is equal to W 1 minus W 2 into L or, I should, I have mentioned as W 1 refers W 2 or we are talking about basically the difference between W 1 and W 2 depending on which one is larger. We shall be having net moment acting at O.

And then let us say W 1 is the one for which you want to measure the value of the force. So, this is the one that is our measure end and here, we keep on adding more and more standard mass if W 1 is larger than W 2 and we keep on increasing the value of this W 2 till this quantity approaches 0. That is, I should say W 1 approaches W 2. And then we can directly equate the value of W 2 W 1. And other way like shown in this particular diagram instead of trying to equate them we can also get it from a scale like this, means, generally we analytical balance operate based on the null principle.

That is, if this particular when there is an initial deflection, that is W 2 is equal to 0 and we have only put the W 1 into this. Say this refers to this null position on the 0 position on the scale, then we can see there is a big deflection. This much of deflection that has taken place. And now, our objective is to increase the value of W 2 and then get this thing back to its initial null position.

Yes, actually the way I have shown it should be opposite. Means, let us say this is equal to 0 and then initial deflection then talking about this particular one and by keeping on increasing the value of W 2, that is, (Refer Time: 06:26) 0 level we keep on adding more and more standard masses to W 2. So that, this pointer can come back to this initial null position and thereby issuing the balance and providing a way of measuring W 1.

This is something that all of you know this. Let us now try to extend this principle to the balances where, the arm lengths are actually not equal because there are several situations where we may have to deal with balances with non-equal or unequal arms. Just like the one shown here.

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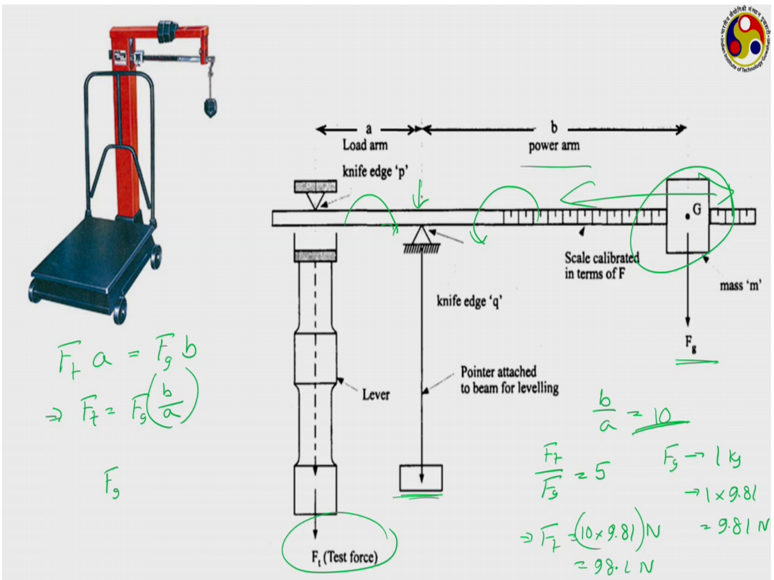

Here, this is generally used when you are looking for very large mass measurement. So here, the mass will be put in somewhere here and you will be equating this by adding some mass on this particular scale somewhere here. And here, the length of both the arms are not at all equal to each other. Generally, we can represent them with a schematic representation like this. So here, this is your fulcrum which houses the pointer which is connected to some kind of scale. The scale only mounted somewhere here. Now, the test mass or the mass for which you want to measure the force is connected to this particular point. That is, it is acting at a distance e from this particular knife edge or fulcrum.

This particular arm, corresponding arm length is generally called the load arm or as on the other side, we have the power arm and at the end of this power arm we are putting this known force generally by adding standard masses and the length of this power arm in this particular case is b.

Then, how can we write a balance equation so that we can get a relation between this F t and F g? Remember F g is a known mass F t is the one which we are trying to calculate or the value of F t, the force it is one that we are trying to calculate. So, how much is the force or moment? Rather, this F t is producing F t is imposing at this particular point. That is, very easily you can calculate that to be F t into a and the direction of this one will be this clockwise. Correspondingly, a counter clockwise moment will be created by F g and when they achieve the null position, then this two should be equal to each other.

So, from there we can write F t is equal to F g into b upon a; that means, this particular ratio b upon a is very important about the range of value of this F t that we can measure with this. For example, suppose if your b by a is equal to 5. Then what we have? We have F t upon F g is equal to 5. That is, if F g corresponds to a mass of 1 kg which actually will lead to a how much force 1 kg of mass will lead to? This is of course, equal to m into g, that is 1 into 9.81 that is, 9.81 Newton.

So, just by adding a mass of 1 kg which will lead to a 9.81 Newton of force then, we can get a measurement of F t equal to 5 into 9.81. Correspondingly, whatever value you will be getting, this much of force can be measured and this way if we keep on increasing the value of this b by a or keep on increasing the ratio b by a, let us see if we make it 10. Then easily we can measure 10 times larger force that is, 98.1 Newton force can be measured or in a way if we instead of writing in terms of Newton, if we write in terms of mass, whatever F g amount of force, that we can measure using F t, we can measure this times this many times larger mass using this.

So, when you are looking for a very large quantity of force measurement that is, we are dealing with a very large value of this F t. We can, actually this particular point is flexible. We can move this particular point along this particular scale in either left or right direction. Thereby, changing this ratio b by a; as per our requirement and we can get quite large range of F t to deal with.

Commonly, b by a is greater than 1. Significantly greater than 1, but if situation requires sometimes we can also make it less than 1 thereby, allowing some standard masses to measure much lower value of force. So this way, non-equal sorry, the balances with non-equal arm lengths can provide us measurement over quite wide range of forces.

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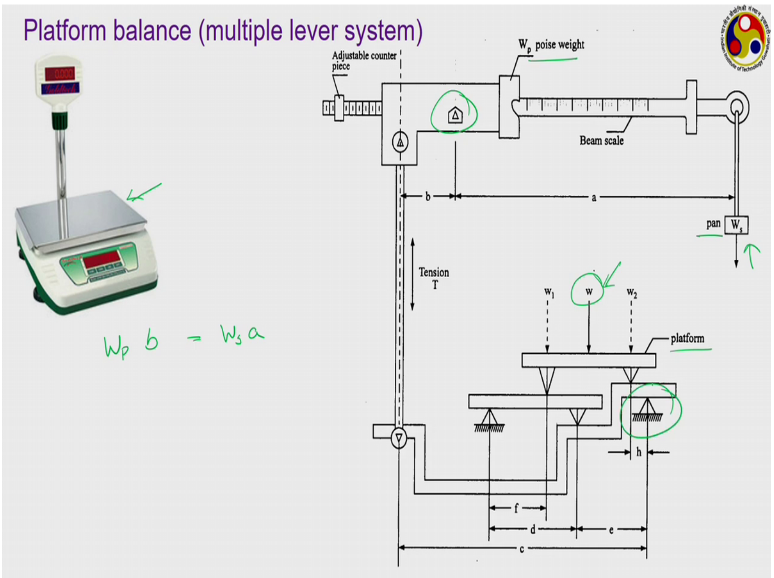

And then another very common type of mechanical loading system there is a platform balance. Something I mentioned in the previous lecture also, something you can very commonly find in the shops or markets, where actually, none of the arms are visible. Here, we just have a platform on which we put the quantity which you want to measure somewhere here and generally in digital mode we get the output from here.

Now, then how this one operates? It is not an equal arm system, not an non-equal arm system, [FL] it is not analytical balance at all. It actually operates on a principle of multiple levers. So, if we get a schematic representation of this, generally we will get a situation like this where, this is the one that you have kept on the platform. This is the platform, this platform basically refers to this one and here, you have kept this force W. W refers to the mass or the force corresponding to the mass of the weight corresponding the mass which you have kept on top of the platform.

Here, on the instrument side, we generally use two different weights; one is this poise weight and other is the pan weight. Poise weight W p and pan weight W s. We generally keep on adjusting both of them and accordingly we get a balance. Generally, W p during a particular measurement W p is kept constant and W s is kept on varying. When we this is not at all subjected to any kind of force, W s is 0 and the situation need to be or rather the device needs to be kept in balance by using a counter poise. That is something equal to the value of W p.

But as soon as we have put this W on the platform, then we have to keep on adding something to this W s to restore the balance. Now, for the situation shown here, if we first take a balance with respect to this particular thing then, what we are getting? We are getting W p into b is equal to W s into a by looking at this and similarly, if we take another balance corresponding to this particular one, actually I have written it wrongly; now it can be.

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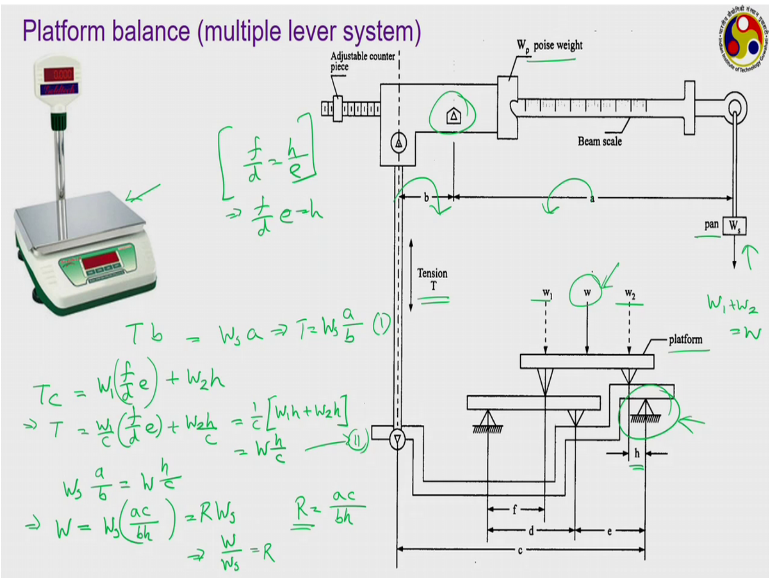

So, in W p does not come into the picture. Rather, if we take a balance corresponding to this we have W s into a which is imposing a torque in this particular direction and the tension which is acting here on this is imposing a torque in this direction. So, this should be T in to b thereby giving, T is equal to W s into a upon b.

Now, focus on the platform and let us take a moment corresponding to this one. This weight W can be considered to comprise of 2 parts; one is W 1 other is W 2. W 1 plus W 2 gives equal to W and their value can be anything or the way we divide this W into two parts can be our choice. So now, if we take a another moment balance corresponding to this, then we have T into c on one side. This should be equal to W 1 into f upon d into e. Looking at this picture and conclusion coming from W 2 is just W 2 into h; h is this particular distance. So, or T is equal to W 1 upon c into f by d into e plus W 2 into h.

Now, the values of all this lengths, that is, f d e c etcetera these are our choices. So commonly, we design this lever based systems or multiple lever system such that we have f by d is equal to h by e or f by d into e is equal to h. So, if we put it back here, actually I have missed an h here, so we have 1 by c into W 1 into h plus W 2 into h. That is, W into h upon c. Just look at here the final relation what we are getting.

If we can ensure this particular condition then, the division of W 1 and W 2 does not matter. Ultimately, what we are getting back is the original value of W itself and now, we equate these two equation. So, let us say this is equation number 1 and this is our equation number 2. So, if we equate the value of this tension T between these two equations, then we have W s into a upon b is equal to W into h upon c or W equal to W s into a c upon b h or commonly written as R into W s.

Where, this R is nothing but what we originally had in a bracket a c upon b h that is a term comprising of all these four lengths a b c and h. This is sometimes called the scale multiplication factor or scale multiplication ratio. So, again by adjusting the values of all this a b c and h, we can keep on varying this value of R. And once for a given system we know the value of R. Then, we can easily adjust the value of W s to get the system back into balance and then get the corresponding value of W. Finally, look at here. Again in this case also, W upon W s is equal to R.

So if we have, if we make R a large value, like say if we have R equal to 10 then this W can be 10 times larger than W s. Similarly, we can also go from a smaller measurement as well using this. So, this is a platform lever system or I should say a multiple lever system in the form of a platform balance. Similarly, we can also have a few other kinds of multiple lever systems as well used for common mass measurements.

So, these are the common types of mechanical weighing systems which we mentioned in a previous lecture and little bit more information about them in today’s lecture. With this, let us move to a few other kinds of force measuring system.

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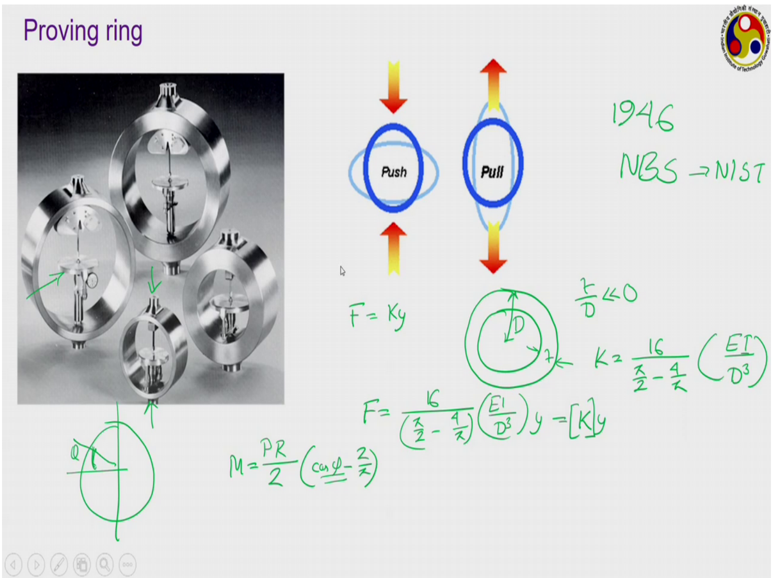

This is another one. A very important one actually which is called the proving ring. Proving ring truly speaking is a kind of elastic transducer or elastic load cell. Something again which you have discussed in last class, but this is a very common device a very popular one and a very important was one as well. Here, as you can see its nothing, but a ring, but with something in between. Look at any one of them you can, say if we take the smallest one.

So here you have this ring, but inside the ring you have something there. The idea of this one is that the ring of some known dimensions will be subjected to some kind of force at these two ends. The way I have shown this is actually compressing force or compressive force, but proving rings can be used for both tensile and compressive stress measurement or force measurement.

As we are putting some kind of force tensile or compressive whatever it may be that will cause some kind of deformation or deflection in the diameter of this ring. Our objective is to measure that change in diameter of the ring and whatever machinery or instrument that you can see inside, the purpose there is solely to measure the change in this particular diameter.

So, we can have both kind of situation when it is subjected to some kind of compressive load there will be a reduction in the length or diameter. Similarly, when it is being subjected to some kind of tensile load there will be an increase in the diameter and now we can have some kind of instrument here which will measure this change in length. We can have any kind of length measuring instruments like to expect the kind of instruments that you have learned for measurement of displacement or deflection.

Anything can be used here, commonly we can have a micrometer. Basically, a microscope based instrument or we can also have LVDT which can give us information about very very small deflection. LVDT being a quite common choice if you are looking for quite accurate proving ring, and something of high accuracy.

Proving rings are available at wide range of sizes like the picture I have shown here. There you can see there are 4 proving rings and each of them are having different diameters. Similarly, we can design them with any possible dimensions, each of them have their own ranges of forces and accordingly we can get a quite wide range of force measurement.

Through the design of proving ring generally is governed by the guidelines set by the National Bureau of Standards in 1946, National Bureau of Standards in US that sets that standard. Actually, you will not find this name now. It is presently called the NIST National Institute of Science and Technology.

Which is one of the leading global body is to set up the standards, primary standards. So, based upon the guidelines they set up in 1946 proving rings are still designed. Here, idea is very similar to any kind of elastic transducers. There we have seen that for any elastic transducers we generally get a relation of F equal to K y where, K is the corresponding deflection constant for the transducer, F is the force which you are trying to measure and y is the deflection.

Now, in the last class we have discussed about a few possible kinds of design of elastic transducers and corresponding expressions for K. Something I intentionally left own there that was, a ring. When we are dealing with a ring of a shape like this, a ring having a diameter of D.

Let us say, the thickness of the ring is t. If this thickness is extremely small compared to the value of D then, the expression for K is something called the thin ring approximation; is a very standard one. 16 upon pi by 2 minus 4 minus pi into EI by D cube, where E is the Young's modulus, I is the moment of inertia for the ring and D is this outer diameter.

Of course, the thickness, I repeat, has to be extremely small. Now it has been proved by Timoshenko and a few others that even if the thickness is, if it is significant still we can keep on using this thin ring approximate relation even for thicker rings as well without introducing too much error. Even for a quite significant thickness or rings with quite significant thickness generally the thin ring approximation is found to provide less than 2 percent error and that is why we are going to continue this relation.

So, if you continue with this, then, the expression for your force is going to be 16 upon pi by 2 minus 4 upon pi into EI by D cube into y. So, the or task reduces to the measurement of the value of this y which is a deflection because everything else are constant. E depends upon the value of the, E depends upon the material that you are using D and I both depends on the design and generally provided by the manufacturer itself or in a way, this entire thing comes as a constant or I should not say R because I already using key K.

So, this K generally already comes from the manufacturer just by measurement of y we can get the value of this corresponding force or F. And if we are looking for an LVDT kind of measurement then, this allowance sufficient sometimes instead of measuring this way we go for the measurement of the angle of deflection. That is if this is the original shape, I am trying to draw a circle actually, but it is ending up with something quite odd shape. Let us assume this is the initial shape.

So, these are the primary dimensions. Now, if there is a deflection of this one and the deflection is measured in terms of an angle phi. Then, the corresponding bending moment can be related as is equal to P R by 2 into cos phi minus 2 upon pi. Where R is the radius of this particular circle, initial radius, P is sorry I have written both to be R. It should be P; P is the pressure that is acting on this and m is the corresponding bending moment. From there also we can easily calculate the deflection just by measurement of the value of this phi. So, proving ring is another quite common type of elastic transducers used for measurement of large forces.

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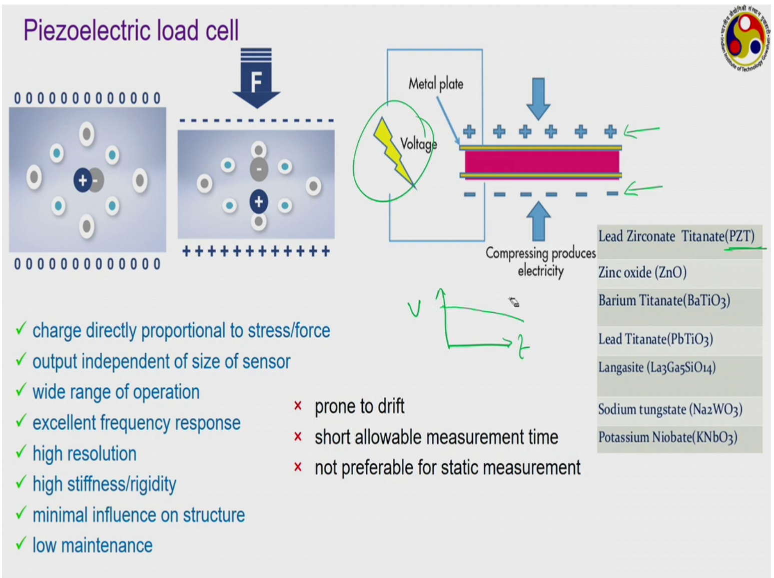

Let us move to the next one, piezoelectric load cell. Well, the mechanical weighing systems proving rings etcetera are classical devices edge hold devices this is something much more modern. The principle of piezoelectricity we have briefly touched upon while we talked about the displacement measurement; the same principle coming back here. There are certain natural crystals and certain artificial materials which when subjected to some kind of force leads produces certain charge. Actually without going into too much detail what happens that, initially the positive and negative ions are uniformly distributed over the entire crystal body.

But when they are subjected to a certain kind of stress, compressive or tensile, certain kind of force or pressure then they distribute themselves such that one side show develops net negative potential other side develops a net positive potential. And thereby, it is possible to get some kind of flow of charge; if we connect them by an external circuit like this.

That is one side of the plate becomes positive other side of the plate has become negative and now we are collecting them by an external circuit and that gives us some kind of voltage output some potential difference. And this potential difference, if we measure properly can be found to be related to this force or directly related to this force.

So, I have mentioned there, I can clearly remember that piezoelectricity is a very very modern and important branch of measurement and lots of research are going on in this particular line and commercial devices are also available; simply because this is extremely advantageous from several contexts.

Of course, there are certain natural material like DNA can be a very important example and several crystals also which produces or shows piezoelectricity, but generally, we keep on using synthetic materials and these are certain common synthetic materials. Again, this table I have already shown there. I have just taken the synthetic part of that table. PZT that is Lead Zirconate Titanate is probably the most common material, but barium or lead titanates are also used in piezoelectric devices.

Now, the biggest advantage that we get with piezoelectric load cells is charge being directly proportional to the force. So we of course, we need some kind of mathematical relation for this, but generally that is provided by the manufacturer and therefore, once we measure this charge in by the means of the external circuitry we can directly get the value of the force. And other big advantage is piezoelectric load cells are the output independent of the size of the sensor. That is, the size of the crystal does not limit the amount of force that can be measured with this. Even with a very small size crystals we can get the measurement of very large forces.

And therefore, we can comfortably attach the load cells to any kind of specimen depending on whatever kind of contour that we have on the surface that we are dealing with, we can get the measurement. Then, wide range of operation as just I just mentioned. This, it is generally showing excellent kind of frequency response for any kind of transient input therefore, we can easily use this piezoelectric load cells particularly for dynamic measurement or I should say, they are very suitable for dynamic measurement or dynamic force measurement mainly because of this excellent frequency response.

Because the response strains have a quite small and they hardly have any kind of amplitude distortion or phase distortion. High resolution is again a very desirable characteristics, high stiffness or rigidity. Once the force is removed, the cells are generally able to recover back their original shape thereby, allowing or being ready for another measurement.

And again another quality very much desirable for dynamic measurement because as the force keeps on changing with time the cell is able to adjust immediately and provide the corresponding output. And minimal influence of the structure because of their small size and high stiffness they hardly affect the surface on which we are putting them. Their maintenance costs are quite low.

So, all these are very much advantageous features, but there are a few other issues also that we have to consider. One big issue is piezoelectric load cell is they are prone to drift. That is if we subject such kind of load cells to some kind of constant force then if we say, plot the time on one side and the output, on the other side in the form of voltage or charge, whatever, they generally they are not able to maintain a constant level of output or desirable situation is something like this. That is, a constant voltage with time.

But, they generally show some kind of drift that is output keeps on changing with time. That is because nature does not tolerate any kind of imbalance or rather nature always tries to get back to the situation of balance. So, that no unbalanced potential are left. Accordingly, the charges always finds some way of readjusting themselves so that they can go back to the situation of balance or system of balance inside the crystal body itself and that provides this drift or leads to this drift. That is why we generally have quite short time to take the measurement and also they are not at all preferable for static measurement again precisely for this particular phenomenon.

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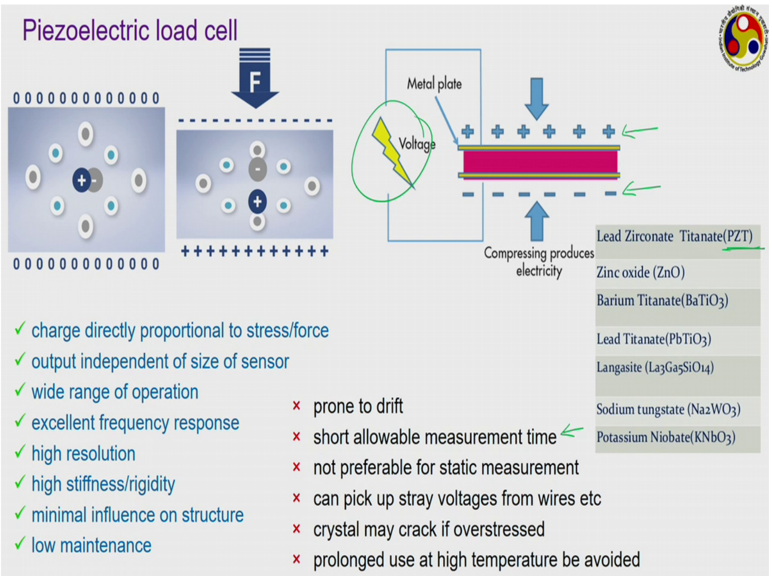

However, if we can somehow provide some kind of output measuring device which has a very good response time, that is in a very short interval we can get the reading then we can get some idea about the static measurement, but if we are looking to looking for some kind of application where our objective is to ensure that the force value remains constant over long period of time, then this is not the device to use. We have to find some other device. This is particularly suitable for dynamic load measurement. Another issues can be if it can pick up stray voltages from the wires and it will be very difficult to separate that out from the final output.

Because, in the output level there is no difference between that and if the crystal they may be quite delicate. So, you get subjected to overpressure they may crack or deform and prolonged use at high temperature must be avoided; because they may show some kind of mechanical deformation when they are subjected to high temperatures for long duration time. Despite this problems piezoelectric load cells are here to stay and they are probably the most suitable device among all the ones that we have discussed so far for a dynamic force measurement.

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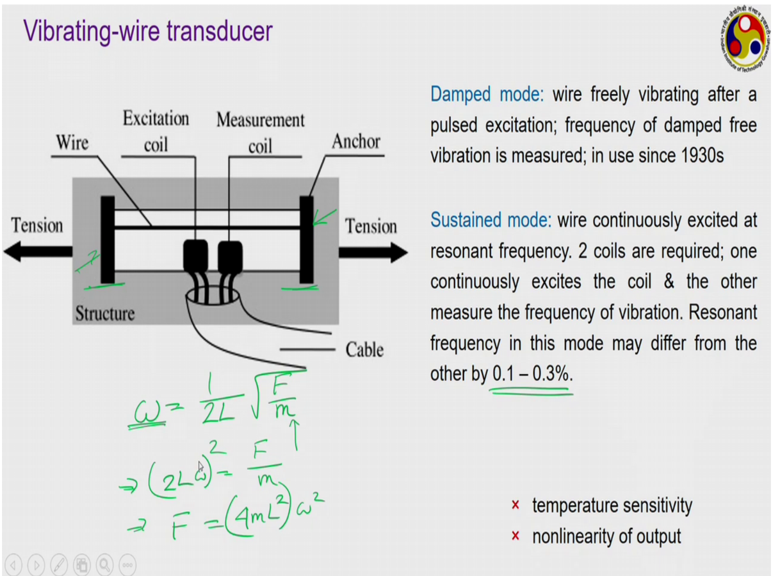

Next one, another very important device, vibrating wire transducers. It is just wire, we have an wire which is connected to or which is being torque at two different ends. This is one end, this another end and the force has been connected to this two these two ends and they are fixed. Now, among these two anchors, generally one of them is fixed you may think about say this is the fixed one and the other one, the other anchor that is this one this is able to move as this one is so when the second anchor is subjected some kind of force, there will be a change in the length of this.

Or whenever this is being subjected to some kind of tension if both the anchors are fixed then there will be a change in the by natural frequency of this particular wire or we can visualize the other way also. Like suppose, if this anchors is being subjected to a force then the wire will start to oscillate or fluctuate with it's own natural frequency; which we can represent as omega is equal to 1 by 2 L root over F by m. Here, m refers to the mass of where per unit length of this. That is this m is having an unit of kg per meter, F is the force which you are trying to measure.

So if we know the value of this omega, then easily we can calculate the value of this force and to know this natural frequency; we generally have some kind of excitation coil some magnetic field which tries to pick up this oscillation and provides a way of measuring the value of this omega. This vibrating wire transducers can operate in 2 modes; one is a damped mode where the wire is allowed to freely vibrate when that is being subject to a past excitation. That is, there is a force application for a small instant of instance of time and then the there is no force, but the wire keeps on vibrating freely with its own natural frequency. The frequency of the damped free vibration is measured.

It is the older or of the modes and in use since 1930's. The second one came around 1960's which is called a sustained mode; the wire continuously excited at resonant frequency and now we need 2 coils. One coil continuously excites the wire and the other one measures the frequency of vibration.

The resonant frequency among these two modes actually has found to be a bit different; particularly the resonant frequency the sustain mode generally it is called that the resonant frequencies depending on the length and material and diameter etcetera of the wire, but that has not been found to be true always. Because the resonant frequency among these two modes the damped mode and the sustain mode has been found to be little bit different. There is our 0.1 to 0.3 percent difference.

So, if you are looking for very high accuracy, generally this is the level of accuracy that we also expect from our device. So, it has to be we have must be very very careful in which mode we are working with and should use the corresponding value of resonant frequency to avoid any kind of error.

There again quite accurate device, if we can prove; if we can prove measure them properly or measure the frequency properly, there are certain issues like, they are generally temperature sensitive the where itself being conductive in nature can sub there can be very sensitive temperature and the non-linearity of the output is another concern. The here, omega and F does not have a linear relationship or rather, if we express this one in terms of the force, what we are getting? We are having 2L omega whole square is equal to F upon m. That is, F is equal to 4 mL square omega square.

So, F and omega are actually having a quadratic relationship and not a linear one. So, this non-linearity of the output also needs to be very we have to be very careful about while taking the output measurement. But this vibrating wire transducers are particularly suitable in permanent structures like for measurement of deformation or crack generation in structures like just shown here.

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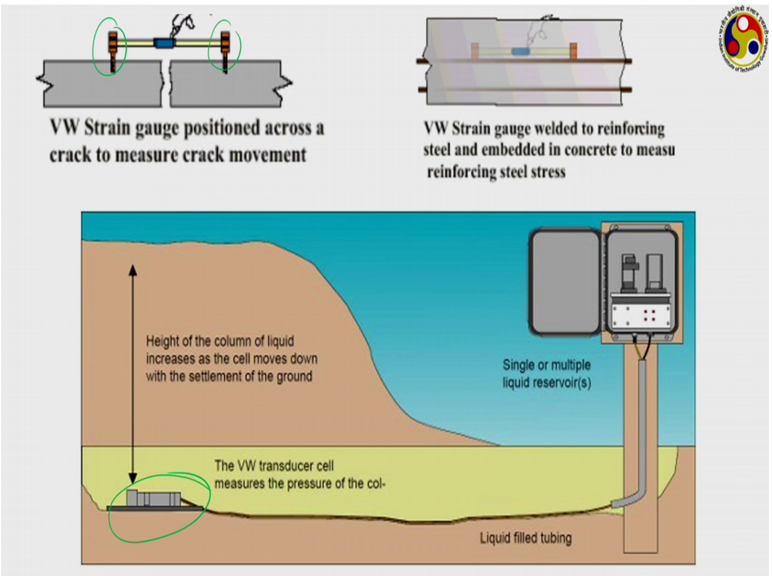

Say we already have a crack. We know there is a crack somewhere in the structure and we want to see whether the crack is keeping on developing or just remains the same. Then, we can produce you can attach a vibrating wire transducers like this where two anchors are fixed to two different sides of the crack and now, if there is a change means if the crack widens then there will be change in the distance or changing change distance between these two anchors.

Thereby, changing the tension on this particular crack or sorry this particular wire accordingly there will be a change in its natural frequency and if we can measure that then we can get an idea about this change in the length of the crack. This kind of things are quite often welded inside the reinforced concretes or steels to measure their corresponding stresses.

Another quite new application that I have seen where here, the vibrating wire transducer has been mounted or housed at the base of a river and there are single or multiple liquid reservoirs on top of this and here objective is to measure the height of the column of liquid on top of this. Now if there is a change in the height of this liquid sorry, if there is a change in height of this liquid column; corresponding force acting on the transducer will also change. And from this corresponding response we can get both the ideas whether firstly, whether there is any change in the water level or if the water level is same, then whether there is a change in the position of this earth crossed. That also we can measure from this. So, these are certain quite interesting examples of the application of vibrating wire transducers.

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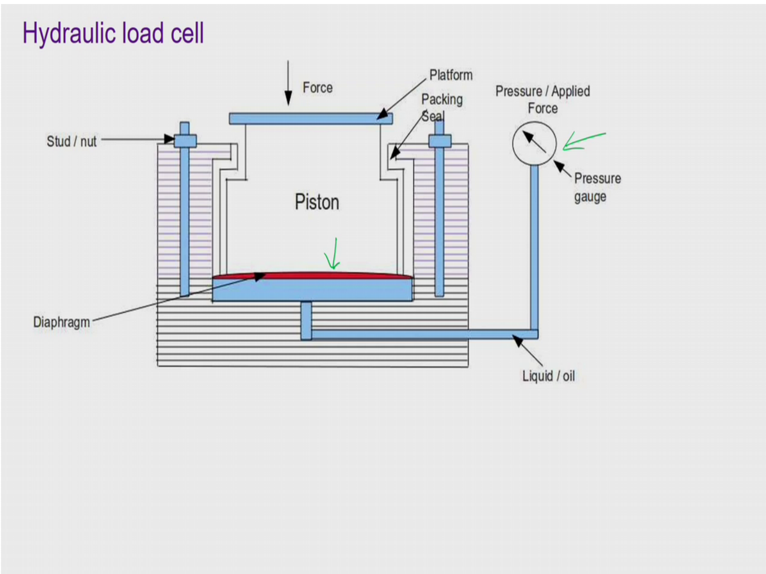

Next, something most common mentioned in the previous lecture also hydraulic load cells; very simple operation. We are applying a force on some platform, on the other server platform we have a liquid filled cavity so the force is being transferred to this diaphragm and thereby causing an increase in the pressure on the diaphragm and this increasing pressure is sensed by a pressure measuring device a bourdon gauge or any kind of common pressure measuring tool, pressure gauges.

We shall be learning just in the next week only, but the application is very very simple because whatever force the upper plate is being subjected to that will easily transmitted to this lower diaphragm and they are directly proportional to each other. So, we can get a direct measurement of the force that is acting on the diaphragm. Hydraulic load cells are very very common in industrial applications when also in several common force measurement applications.

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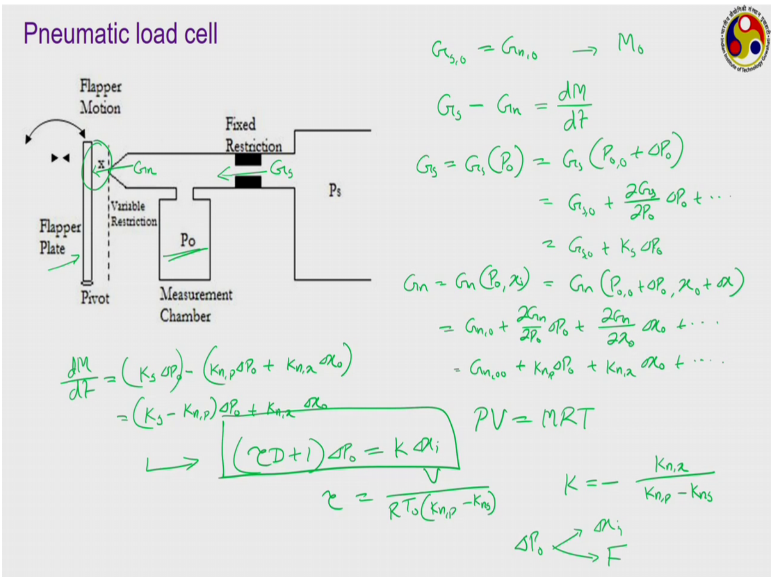

And next is pneumatic load cell, operating principle is quite similar, but instead of liquid we are using a gas. Now have you seen this particular picture earlier? I have intentionally put the same picture here. This is the nozzle flapper transducer which we are introduced to the during the displacement measurement and the operating principle is very same here. Here, one just for repetition. Here we have a big tank which is maintained at a constant pressure of P s and the gas is there. Now the gas is allowed to pass through a fixed restriction here.

So, we have this nozzle on one side we are having a gas coming through from a tank maintained at a pressure P s and fixed restriction and the other end of the nozzle we have this flapper. This flapper is being subjected to or it is connected to the location where you want to measure the force. So, whenever there is some force applied on a flapper plate, the flapper moves, there by changing this opening. This x refers to the distance of the flapper, this x refers to the distance of the flapper to this nozzle opening and so on application of the force the value of x changes thereby, modifying the delivery pressure

And accordingly, the mass of gas stored in this measurement chamber that keeps on changing. Thereby, changing the pressure in this measurement chamber itself and by measuring the pressure in this measurement chamber we can easily measure the or easily get an idea about the force that is acting on the flapper plate or the displacement; whichever we would like to measure.

Do you remember the operating principle? Let me very briefly repeat this one. Let us say G s is the let me remove all this marking first. Let us say G s is the mass that is coming from the tank and G n is the mass that is going out to the nozzle. So, under steady state operation G s 0 will be equal to G n 0 is refers to steady state and so, total mass in the measurement chamber that remains constant.

Let us say corresponding mass in the measurement symbol is M 0. Now if there is a change in the position of the flapper plate because of some, some force application on this. Then, let us say G s is the mass flow rate that is coming through the restriction and G n is the one that is going to the nozzle outlet if they are not equal then there will be some mass accumulation.

So, the rate of change of mass stored in this measurement chamber can be given by this. This G s is generally a function of this tank pressure P naught. It say only and now P naught can be written as P 0 0 which is the initial steady state value plus delta P naught which is a change in this pressure of this and so, we can write this as G s naught plus plus the higher order terms that is, case into delta P 0. Similarly, the G n depends upon both. This P naught and x on both or let us say x i.

So, G n can be expanded like this. Let us say x 0 is the initial position. So correspondingly, we are going to get G n 0 plus this exercise we have done earlier. I am just doing it very quickly for a recap. This can be written as K n plus K n x delta X naught. Actually forward and exactly what notations we have used, but these are the common notations.

So, if we come back to the original equation your D m d t can be now written as K is delta P 0 which is coming from the first equation. Delta P 0 plus K n, x delta x 0 we are neglecting. Of course, all the terms from second order onwards, that is, sorry this symbol should be negative. So, K s minus K n p into delta P 0. Commonly we use the ideal gas approximation for this and if we use the ideal gas approximation and use the relation that is P V equal to M R T on this gas stored in the chamber then, it can be shown that this relation finally reduces to something like this where a very much first order relation.

Where the time constant tau comes out to be volume the of the tank divided by this R T 0 into K n p minus K n s and K comes out to be minus of again x by K n p minus K n s. This derivation we have done in the that week itself this repeat of that, but still for the sake of continuity I have done the entire derivation once more. So, this relation actually provides us a way of measuring the value of this delta x or for a given delta x we can get a measurement of this delta P.

So, if we measure the delta P we can correspondingly measure the delta x itself. But the same way we can also modify this delta x, in terms of force and we can get a measurement of the force. So, the delta P that is a change in the pressure, in this measurement chamber. This one can be calibrated either in terms of the delta x that n that is in terms of the change in position of this flapper plate or in terms of F which is a force.

That is, this flapper plate being subjected to we can calibrate this one in terms of either of them depending upon what is our objective and accordingly, we can use the same device either as a displacement measurement one or a force measurement one operating principle remaining the same. So, any pneumatic load cell operates very much the same way.

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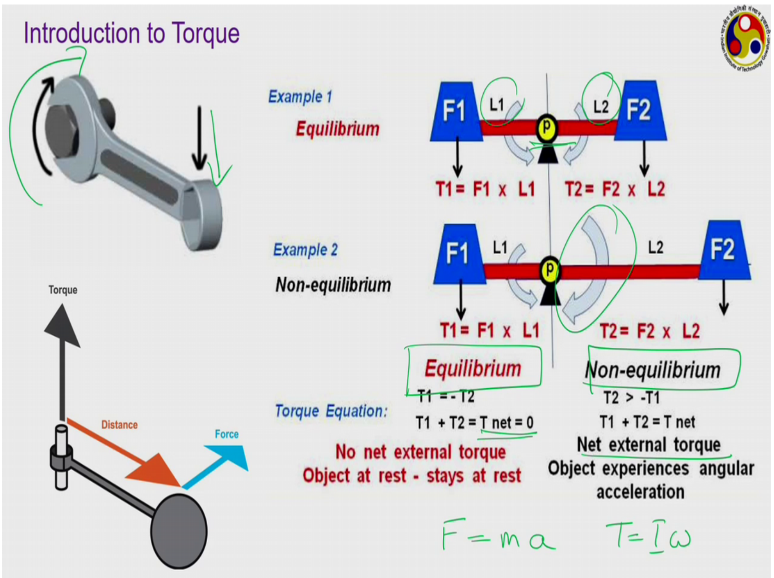

So, this takes us towards the end of our discussion on force measurement. We shall very quickly be discussing a bit about the measurement of torque. I am to finish up on this particular chapter. Now what is a torque? I am sure all of you know even from your high school level physics that torque refers to a force which leads to rotational motion. Just like that shown here that is on the application of the force at this particular position instead of a linear motion we can get an angular rotation.

So, this is the way we can calculate the direction of torque. I am quite often we can relate this one to a elect and thumb rule kind of situation or whatever. Like if we place quite similar to what we do in electricals. If we place the these three fingers of your left thumb perpendicular to each other then, if the index gives you the direction of the force and the middle finger gives you the direction of the distance then thumb is going to give you the direction of the torque or sometimes, we can also relate them by something like this.

If your force is acting in this direction and then that depending on whatever way you are looking at the force or if you are standing at the point with respect which you want to measure the torque then, whether you are looking in clockwise direction or anti clockwise direction to find the force, accordingly also we can decide the direction of the torque.

Now, from your vector algebra, you have learnt quite a bit about torque measurements or I should not measurement, I should the properties of the torque. Again, a very quick recap, just what we have discussed a while back about the analytical balance. Say when your the fulcrum is being subjected to L 1 and L 2 the two equal torques then both of them and both of them are equal. Then, the it will remain in a place of balance and you shall be having an equilibrium. So, that you have t not to be equal to 0. So rest thereby, the null position is restored; however, if one of them is larger like in this case T 2 is larger than T 1. So, there is a net external torque and you are into a non equilibrium location.

So, then an object the object will experience an angular acceleration like we have started this particular chapter by referring to Newton's second law of motion where we have force is equal to mass into acceleration. We can easily convert this one to corresponding torque equation that is, t is equal to I omega where I is the moment of inertia, omega is the angular deflection and t refers to the torque for this.

Now, for the measurement of torque; actually a torque measurement is quite commonly related to the measurement of power because, whenever you are talking about something, a shaft may be rotating with a speed then with a particular r p m then and a torque is applied on this. We can easily relate the torque and its angular velocity with the power with which we can get from this shaft. If you are talking about the power producing device or how much power the shaft is absorbing, if you are talking about a power absorbing device. So, whatever you are going to talk about regarding a measurement of torque they are all applicable to the measurement of shaft power.

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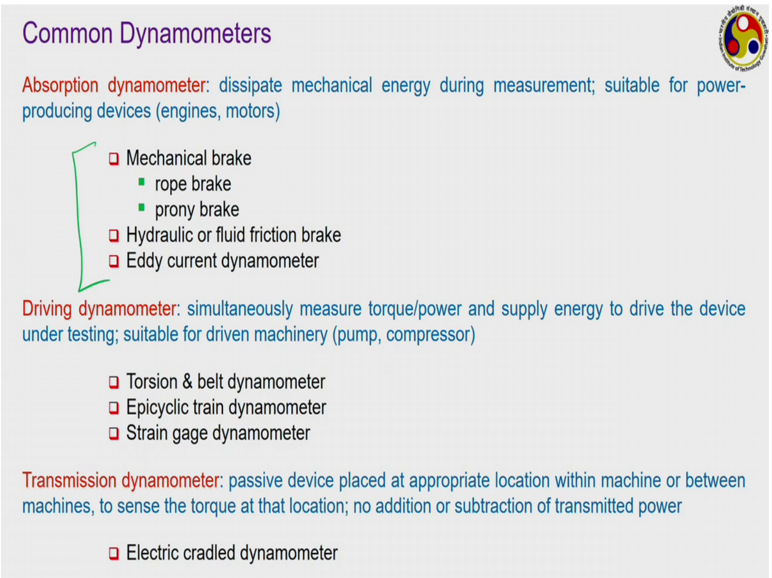

So, dynamometer is the term that is used for any device that is commonly used for the measurement of torque. Now dynamometers can be commonly of 3 types. One is the absorption dynamometer, the more most common type where the entire power that the dynamometer receives. They dissipated to the surrounding or to some other device or I should not say to the other device where the entire power is being dissipated that is, the mechanical energy but that dynamometer is receiving from the source. It does not supply to some downstream device, everything is dissipated.

And so, therefore, these absorption type dynamometers are commonly connected to power producing devices like engines or motors. Examples can be mechanical brake systems, hydraulic or fluid friction brakes. Eddy current dynamometer, mechanical brake. The oldest examples can be the rope brake or prony brake system. You can relate this one. Just the term brake is there.

You can relate this one to any brake of your vehicle. What we do during the braking is just the way and absorption type dynamometer works. Means, the entire power the engine is producing on applying the brake, we are dissipating the entire power in the form of friction. Thereby, reducing the velocity of the vehicle to 0 during the braking operation, the second kind of dynamometer is the driving dynamometer. Here, it measures power and or torque and also supplies energy to drive some kind of downstream device.

So, they are suitable for driven machinery like the palms or compressors. Common examples can be torsion and belt type dynamometer, epicyclic train, dynamometer or strain gauge dynamometer, there is a third kind also called the transition transmission dynamometer. They are more like passive devices. They are placed at appropriate location within a machine or between two neighboring machines to sense the torque precisely at that particular location. The it does not dissipate the power thereby, causing no subtraction in the value of the power, but they also not add anything.

So, the magnitude of the power therefore, generally does not change too much. Common example can be electric cradled dynamometer. We shall quickly be discussing only about a few types of absorption dynamometers here just to give you some idea about how they work.

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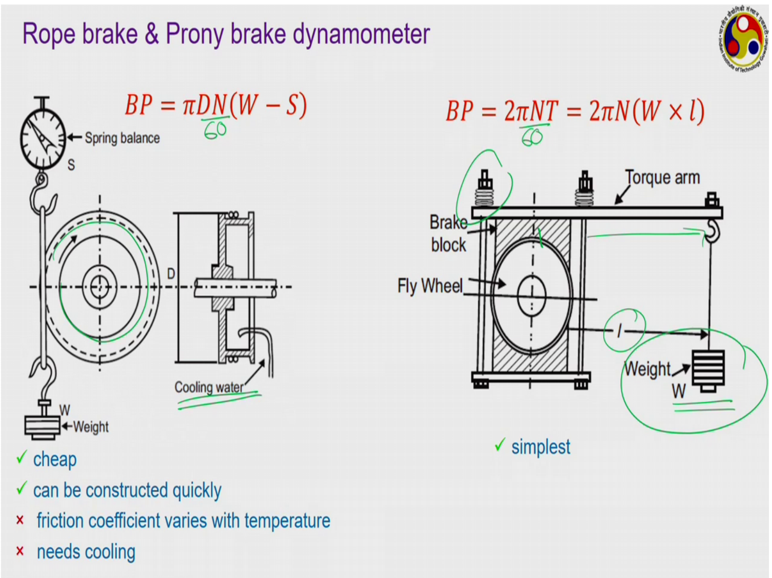

So, we have the rope and prony brake dynamometers. First, the one shown here is a schematic of a rope break dynamometer. Here, a rope is wrapped around this particular (Refer Time: 52:27) or maybe a shaft. On one side you have a spring balance on the other side you have this weight. And whatever force or power this rope is receiving because it is a or rather whenever the rope is being wrapped down on the shaft it absorbs entire power in the form of friction and the corresponding brake power can be added to this particular from pi D N to W by 60 or I should say it should be N by 60 because capital N generally refers to r p m.

So, N by 60 refers to r p s revolutions per unit second. So, pi D N gives you the distance, angular distance traveled and W is the corresponding counterweight. S is the value on the spring balance and their difference multiplied by pi D N by 60 gives the brake power. This is a very very simple way of torque measurement. It is their cheap very old way of torque measurement and therefore, very simple; can be constructed very quickly because you hardly need any device for this. Just to a suitable rope on spring balance and some counterweight and with a view with suitable connection between them and you are done with. But the problem is the friction coefficient as the rope is absorbing particularly when the capital N is large.

That is the r p m is quite large. Then a large amount of power needs to be dissipated in the form of friction. So, it can increase the temperature of the rope quite significantly and therefore, we need to provide some kind of cooling option is the cooling channel which must act to keep the rope temperature within certain range. Because one problem is, the rope may suffer some kind of damage because of the elevated temperature levels. Second issue is that the friction coefficient keeps on varying with temperature.

So, it becomes difficult to get a measure about the torque value or the brake power value if the temperature obvious quite a bit the other variation of this one is a prony brake. In case of prony break, we have to break blocks, generally wooden blocks, one here another one there; by suitable application of these nuts and bolts. We can apply them on top of this flywheel or shaft and generally we have been helical springs located somewhere here, between the upper block and the flywheel.

So, to control the speed at which the brake is being applied on this and then we have the torque on the sliver based systems on which you are putting this weight. So, using the value of this W, we can get a measurement about the total force or rather total power that is getting dissipated and also corresponding value of torque. This is the way we generally measure this one. The brake power will be 2 pi N T again, it should be N by 60.

So, t is a torque and torque is nothing, but this W into L; L being the length of this torque arm. This is L again, this is the simplest possible design quite similar to the rope brake. Prony brake probably goes back even more in terms of time, but very large heat dissipation or heat generation that we have to be dealing with.

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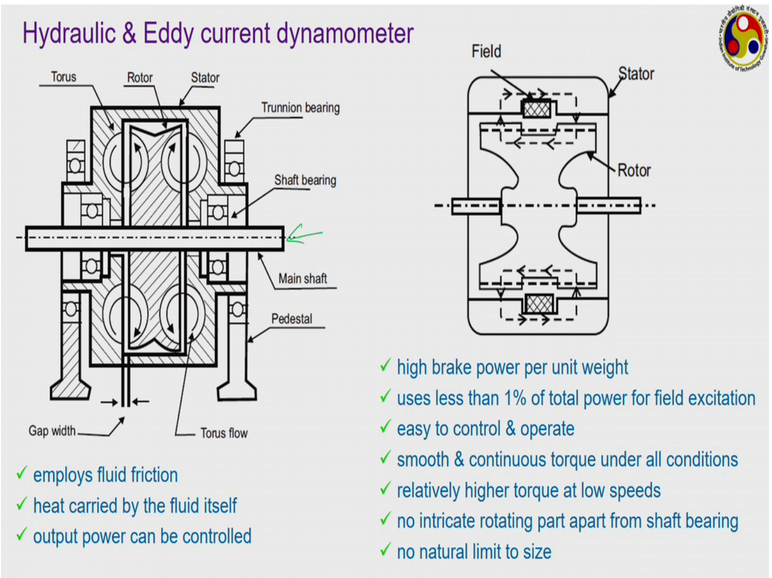

Next of the hydraulic dynamometer a very common device. Here we have fluids which are being circulated over the main shaft, around the main shaft and the power being dissipated is transmitted into the water or the corresponding temperature. Therefore, we can keep into limit that is, the working medium which is fluid and general not why should not say its water it can be some kind of oils also that also act as the cooling medium.

That is, it is also double purpose both of the working media and also as the cooling medium. So, it implies fluid friction which is always better to work with compared to solid friction. Like in case of rope or prony brakes we have the heat carried by the misguide by the fluid itself. So, no separate cooling has been required and the output power can easily be controlled by mounting.

If you squeeze gets thereby, controlling the flow of the fluid around the shaft. And the final device to talk about is the Eddy current dynamometer where you have a stator part. You have a rotor part and just the way any common generator works, Eddy current dynamometer works the same way. As the magnetic field is there, as a power is applied it produces a voltage output and that from that voltage output we can get a measurement of this corresponding torque.

Eddy current dynamometer probably is or it definitely is the most popular one among all the absorption type of dynamometers and a very common instrument for torque measurement, because it offers huge set of advantages like high brake power per unit weight. It uses less than 1 percent of total power for producing that field excitation.

So, there is hardly any loss in the value of power very easily to control and operate just by controlling the field excitation. We can always control the operation of this dynamometer. They are smooth and can produce continuous torque over all conditions or over the entire range of operating conditions at very low speed. Also, they can produce relatively higher torque. No intricate rotating parts apart from the share bearing itself and also no natural limit to size that is another big advantage that you can have Eddy current dynamometers starting from very small to very large scales as well.

So, these are some common devices for torque measurements. We are not going to lend in this, this discussion any further because then it will be difficult to limit this one to the scope of a class. If anyone is interested, you can search a bit more, maybe refer to some textbooks, may go to internet to find about the other kinds of dynamometer and also other types of force measuring devices.

Like there can be a few other types of force measuring devices as well. There can be optical modes, there is gyroscope brakes, load measurement which are more like research topics and if anyone is interested can go for it. But I am trying to limit myself more to those which are easy to understand and also have very much practical relevance. So, that takes us to the end of this chapter.

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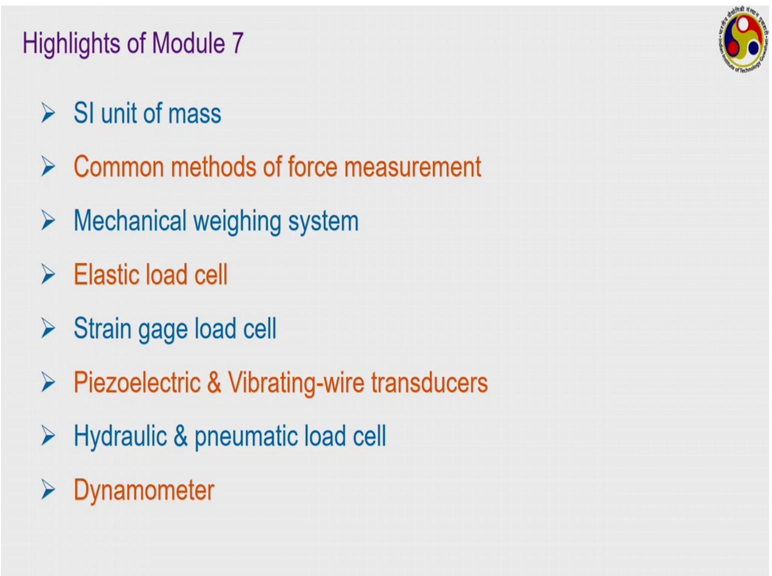

So, we have here talked about the S I unit of mass the new S I unit of mass. The common or I should not say new S I unit I should say the new definition of the S I unit of mass. Then we have discussed about the common methods of force measurement talking about the mechanical weighing system analytical lever with both equal and non equal arms and also the platform balance system which uses multiple levers.

Then we have talked about the elastic load cell proving ring in particular. Then the strain gauge load cell we have talked about in the previous lecture. Today we talked about the piezoelectric once the vibrating wire transducers pneumatic and hydraulic load cells and the finally, we briefly talked about the dynamometer four different kinds of dynamometer. We have talked about or I should say we have talked about mostly the absorption type diameters like the probe rope and prony brake dynamometers, Eddy current dynamometers and the hydraulic dynamometers which you have talked about.

So, that is it for our module number 7. Please try to solve the assignments which will be which are already available with you and next week we shall be discussing about the pressure measurement.

So thank you very much.