Mechanics of Machining
Prof. Uday S. Dixit
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Lecture - 11
Measurement of cutting forces

Welcome to the 11th lecture of Mechanics of Machining. Till now we have discussed that how we can estimate the cutting forces. We discussed some mathematical models, now we are going to discuss how we can measure the cutting forces because you have to verify most of the analytical models may not you very accurate results. Therefore, measurement is must. So, in this lecture we are going to discuss about measurement of the cutting forces.

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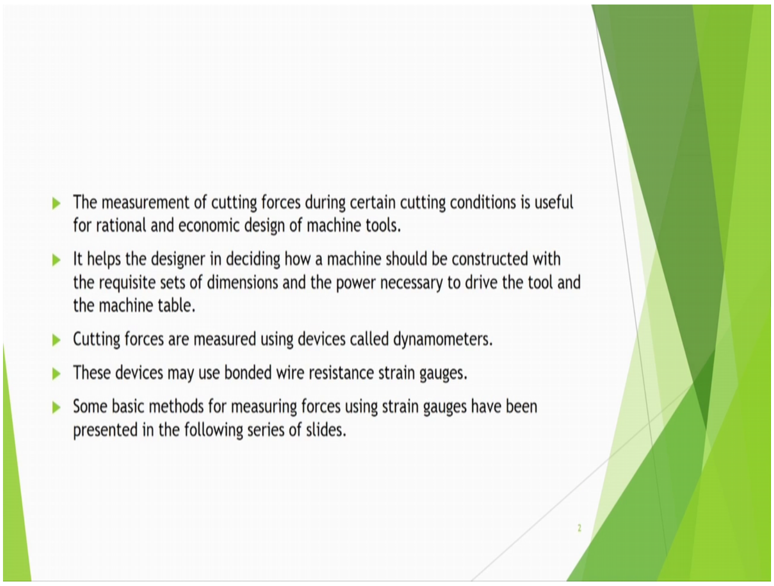

Measurement of cutting forces during certain cutting conditions is useful for rational and economic design of machine tool. If you want to design machine tool you must know how much forces are coming. So, that is why we must find out some estimate of the forces. Usually the theoretical models may not be accurate. That is why sometimes the measurement may be necessary. It also helps the designer in deciding how a machine should be constructed with the requisite shapes of dimensions and the power necessary to drive the tool and the machine tool.

So, designer can design he will know that constraints and he can even develop some control system also. So, cutting forces are usually measured using devices called dynamometers. We have cutting force measuring dynamometers. These devices may use some bonded wire resistance strain gauges. In strain gauges, we have got some strain which are gauges which are some wires. And their resistance changes by changing the length. So, you can get estimate of this one because force will produce some strain. That strain can be measured as change in the resistance of the wire.

Some basic method for measuring the forces using strain gauges are presented in the following series of slides, but actually there are many other methods also.

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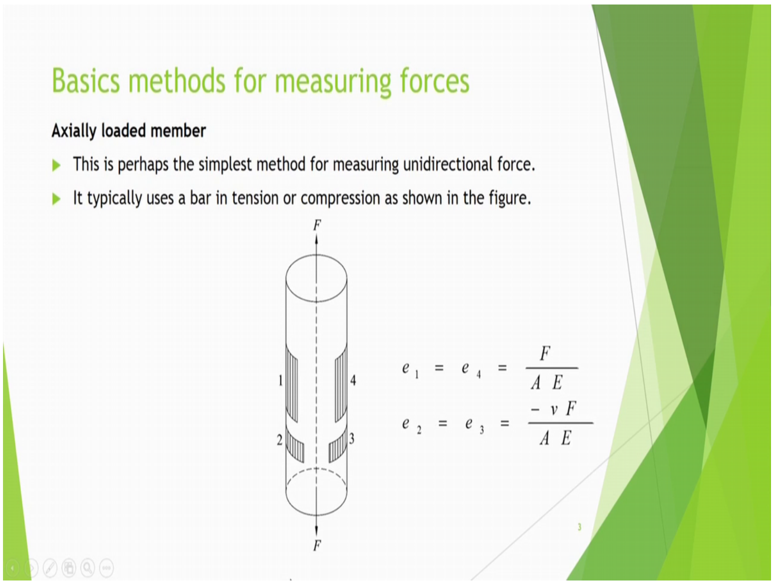

So, let us discuss first the measurement of the forces by means of the a strain gauges. Consider that there is axially loaded member, this is some member and in which some force as being applied on both sides. Now you want to measure this force. So, it is very simple method. In this is a bar, it will be it can be put in tension or compression.

So, suppose we are putting the forces like that then in the strain gauges 1 and 4 which are lined in this direction, strains will be e 1 is equal to e 4 will be equal to F divided by A multiplied by E. F is the force supplied, A is the cross sectional area and E is the Young's modulus of elasticity. Because F by A is stress uni-axially stress and if you divide it by E, you get strain.

So, we got this 2 type of strains here, but as we know that if we have got longitudinal strain, then because of the Poisson's effect there will be transverse strain also. So, that is why this transverse strain is given like this, e 2 is equal to e 3 that will be minus nu, nu is the Poisson's ratio. This is the F by A E, nu value of the Poisson's ratio is limited between actually theoretically between minus 1 and 0.5, but practically it is generally between 0 to 0.5; that means, you cannot have a Poisson's ratio more than 0.5 and for most of the metals this value is actually positive ok, although theoretically it can be negative also and some people have constructed such type of materials.

So, here that transverse strain along this direction e 2 and e 3 will be actually minus nu F divided by AE; these strains will be there.

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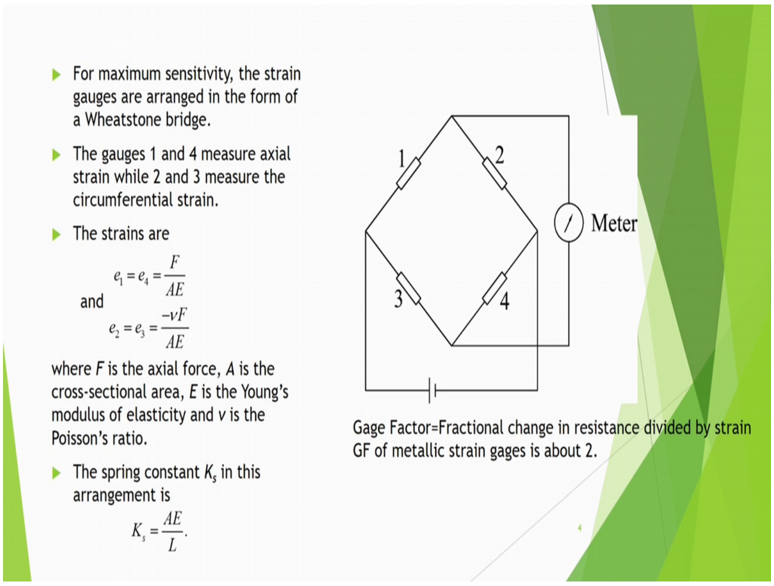

Now, let us go to if we want to measure this forces. So, we can use one Wheatstone bridge type of circuit. So, for maximum sensitivity, the strain gauges are arranged in the form of a Wheatstone bridge. This is a Wheatstone bridge and here we are having this is 1 2 3 4. So, in this way here we can measure the voltage across these 2 points and then there is a this is meter. So, gauge 1 and 4 they measure axial strain. So, we have arranged here and here diagonally and 2 and 3 measure the circumferential strain we have arranged it here and here.

Then the strains are e 1 equal to e 4 is equal to F by AE and e 2 is equal to e 3 is equal to minus nu F by A E. So, this then what happens that this effect will become additive, if we have arranged like this then this effect will become additive. Suppose you instead of putting that this gauge 4, here if you put the gauge here, then in that case you will not be able to measure that so, the same voltage here across this. So, difference will be 0. So, you have to arrange it properly and a spring constant K s in this arrangement is given by K s is equal to AE by L. Now, we define one term called gauge factor. Gauge factor is equal to fractional change in resistance divided by strain. So, that means, suppose I change a strain by 1 unit, how much change is in the resistance?

So, fractional change in resistance is basically change in the resistance; that means, fractional change means percentage; that means, delta R divided by R that is the fractional change and you divide it by a strain. So, this value should be actually somewhat high. Because then only it will be sensitive. Suppose the force is changing too much force has become double, but here there is only one percent change in the resistance, then you will have difficulty in the measurement. So, sensitivity should be high. Gauge factor for metallic strain gauges is about 2 ok. So, that way it is like that; that means, if there is a unit change in strain then it is fractional change will be 2 times of that.

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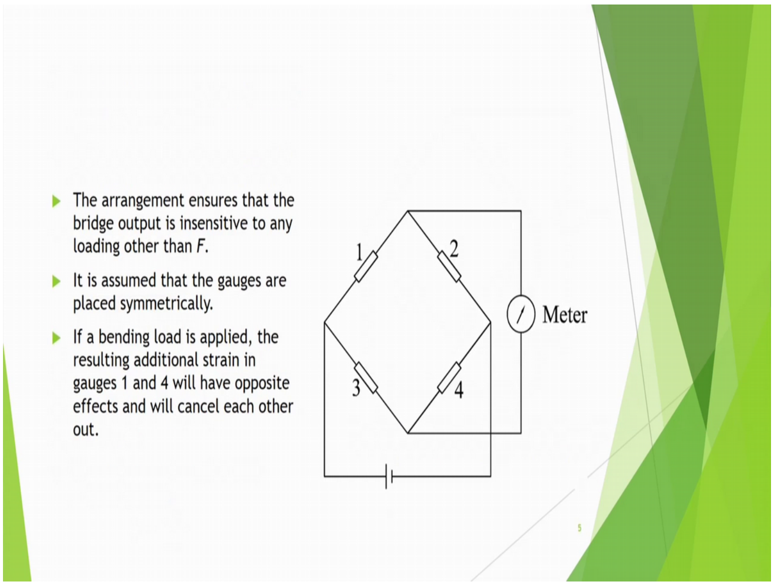

Now, here this arrangement this type of arrangement ensures that the bridge output is insensitive to any loading other than F. Suppose, there is a cross loading etcetera then that effect will be minimized. It is assumed that the gauges are placed symmetrically. If a bending load is applied the resulting additional strain in gauge 1 and 4 will have opposite effects and we can see each other. This can get some bending load also, but because it is on one side of the axis and gauge 4 is on the other side of the axis. So, that is why that these effects will nullify each other; that means one portion; let us say 1 will be in tension and 4 will be in compression. So, there will be opposite effect. So, this will be nullifying each other.

So, that is the also one point, because other loads it should not be sensed to other type of loads.

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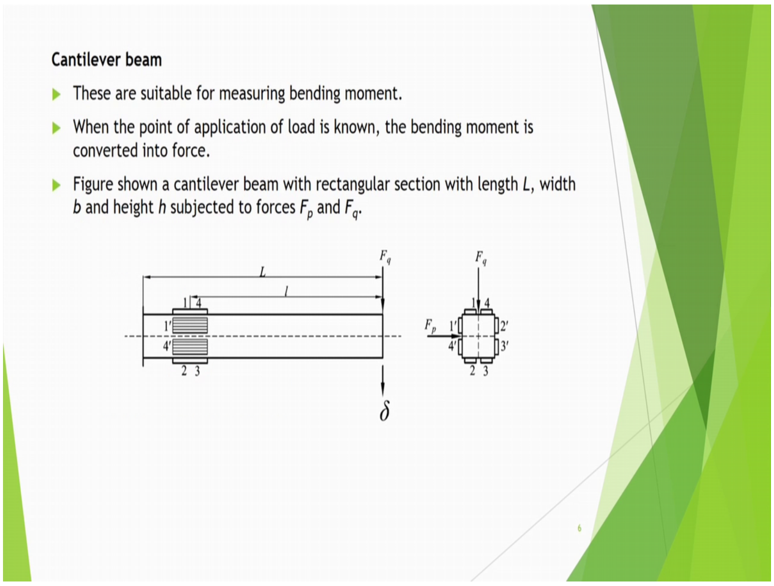

So, now suppose we take a cantilever beam type of a structure. So, we can then measure the bending moment also. So, when the point of application of load is known the bending moment is converted into force. So, we can know the force also like that. So, we can measure the bending moment. You know that if I fix a cantilever beam here on the left hand side and apply the load on this my right hand side then in that case this there will be some deflection, but here at this point there is no strain because there is no stress maximum strain is actually very near to the fix support. And that will be proportional to distance L and also it will be proportional to F q.

So, if we know that this distance is small l then we can find out the force also. So, when the point of application of load is known the bending moment is converted into force. Now this figure shows a cantilever beam with rectangular section. It is a total length is L width b and height h is subjected to suppose force F q. And there is another force also which is perpendicular to your screen. This is showed in the side view. There is a force F p also. So, at one time we want to measure 2 type of forces; F q and F p say cutting force and may be thrust force also.

So, then we have arranged the gauges like this. The when we apply F q these 2, 1 and 4 will be subjected to tension and then the gauges 2 and 3 will be subjected to compression. So, we have to arrange them properly.

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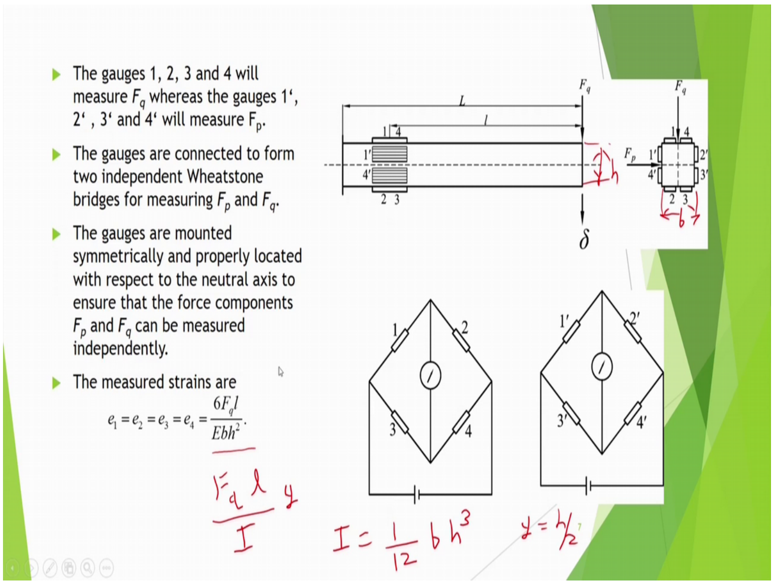

So, gauges 1, 2, 3 and 4 will measure F q, whereas, the gauges 1 prime, 2 prime, 3 prime and 4 prime will measure F p. So, here we have got total 8 gauges. Now, we put lie this; the gauges are connected to form 2 independent Wheatstone gauges for measuring F p and F q. So, we have arranged like this. This is one and 4 because they are having same type of strain. So, we have put on the opposite side. So, that effect gets amplified and this is 2 and 3 and in between I am measuring the voltage.

Similarly, this is another Wheatstone bridge in which we have put the gauges 1 dash, 2 dash, 3 dash and 4 dash like this. Gauges are mounted symmetrically and properly located with respect to neutral axis to ensure that the force components F p and F q can be measured independently. So, we may locate them like this. If you know if we put the only suppose F q, then naturally it will produce the stresses in this one top and this side here also they may say some stresses may be produced, but here that effect will be nullify. So, that is why this stone Wheatstone bridge will measure only F q other will measure only F p.

So, measured strains are given like this. A strain will be e 1 e 2 is equal to e 3 equal to e 4 and that will be 6 F q L divided by E b h cube that way the strain will be coming here. So, this is the formula because you have got the moment at this point is actually F q into l. So, we have got suppose moment is F q into L that is the moment and then m divided by I into y that will give maximum strain on the surface. Now, what is I? I is the second moment of area that is 1 by 12 b h cube where h is the depth of this one this is h this is h and then b is the width in this direction, it will be busy width. So, this is the rectangular cross section.

So, I is equal to 1 by 12 b h cube and y is equal to h by 2. You substitute these values here you will get this expression that is 6 F q L E b h square ok. So, we it means a that if the thickness is small, if this thickness is small then you will have more strain if the length is more. Then also you will have more strain and it also depends on E and b in this manner ok. So, next.

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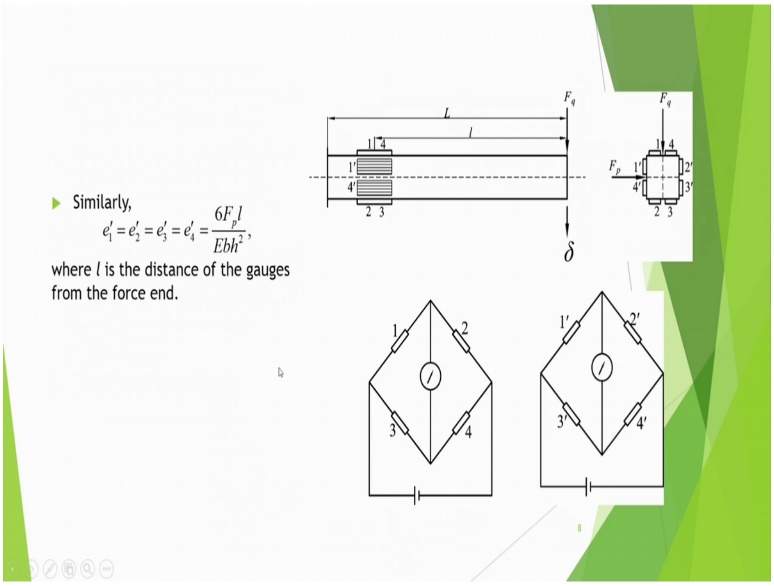

Similarly, e 1 prime e 2 prime e 3 prime e 4 prime is equal to 6 F p L divided by E b h square where L is the distance of the gauges from the forced end. So, that is what this has been done and these things have been arranged like this.

So, then you can measure because of these strain, there will be change in the resistance. As you know that for meters suppose the length increases, then it is resistance increases and if length is a decreasing then it is a resistance decreases. So, that way we can do and we can measure.

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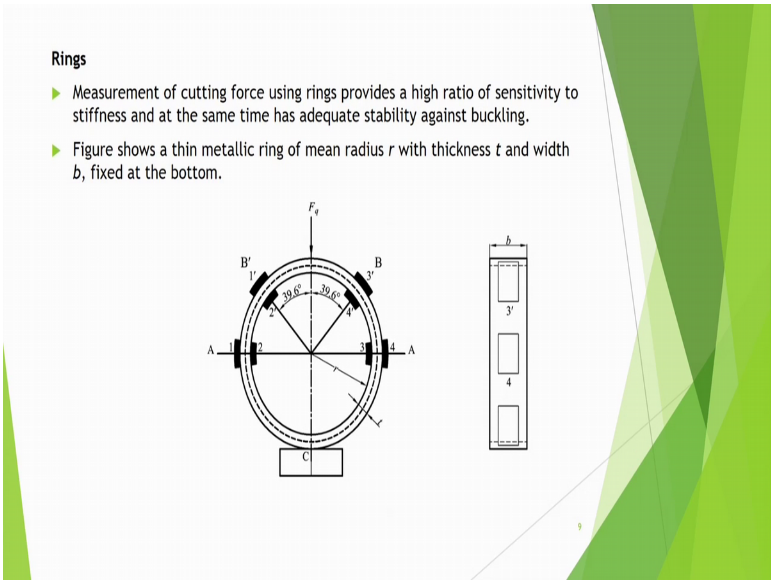

So, then there can be other type of things also. Suppose we have rings actually. So, we can measure the cutting force using rings actually. Because in this case you will be getting high ratio of sensitivity to stiffness; that means, actually they are very stiff also, but at the same time they give high sensitivity and they have adequate stability against buckling. Although they are very thin, but they will not easily buckle. So, this figure shows a thin metallic ring of mean radius R with thickness t and width b fixed at the bottom.

So, this is thickness of the ring is t and this width is b and we have put the strain gauges at these positions. You if you want to find out the complete analysis of that that how much will be deformation, what will be the stresses you have to do analysis using may be techniques of the strength of materials, but here we are not going in that detail. We are indicating that we have put the gauges like this. One gauge is this side other gauge is here 1, 2, 3, 4 and then 1 prime, 2 prime, 3 prime 4 prime these are at 39.6 degree from the vertical this angle is shown here ok.

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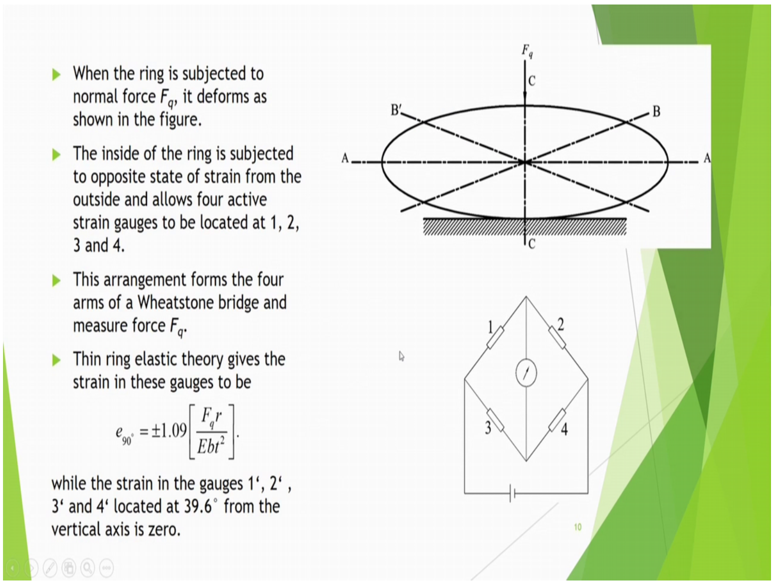

Now, when the ring is subjected to normal force F q; that means, vertical force F q it deforms like this as shown in this figure. It deforms circular ring will become elliptical and it will become like this. So, inside of the ring is subjected to opposite state of strain from the outside ok. So, outside there is a different strain and inside it is opposite. And in this case there are 4 active strain gauges they are located at 1, 2, 3 and 4 ok. So, this is like this. This arrangement forms the 4 arms of Wheatstone bridge and we can measure the force F q. So, what happens that if you see this one, I will put one here and then I have put 4 there. Opposite side this is outer side this is outer side one. And 4 will experience the same type of strain. So, I have put here in the diagonal way. And 2 and 3 will experience another type of strain. So, I have put it here and this one.

So, this arrangement will help in the measurement of force F q, and by thin ring elastic theory it gives the strain in these gauges which I am indicating by e 90 because at 90 degree from the vertical line this comes out to be plus minus 1.09 F q into R E b t square. This thing actually has come from the elastic theory. In those books you will get this type of expression. Here we are not going to derive completely in detail, but here it shows that strain is proportional to F q. And strain is also proportional to radius; that means, if you increase the radius then the strain will increase and it is inversely proportional to thickness t; that means, thinner the ring more strain will be there it is inversely proportional to e also; that means, if the we have got softer material, naturally strain will be more and it is proportional to b also.

So, strains in the gauges 1 prime 2 prime 3 prime and 4 prime these are located at 39.6 degree from the vertical axis. At this time the strains in these gauges will be nearly 0. That is why we have arranged it in this fashion. This has come by analysis that this has to be about 39.6 degree, then you will getting strain in this because at this time we do not want any strain in these gauges because these gauges have been arranged to find out another type of force that is F p.

And there should not be cross sensitivity; that means, I am measuring that F p actual prime load is F p, but you are getting F q. Are you apply F q and you are getting F p these type of things should not be there that is called cross sensitivity; that means, I am going to measure the vertical force, but even in the instrument which is measuring horizontal force there also there is some deflection that type of things should be minimized.

So, we have decided that is why we decided precisely that this should be put at 39.6 degree. So, that strain will be 0 there.

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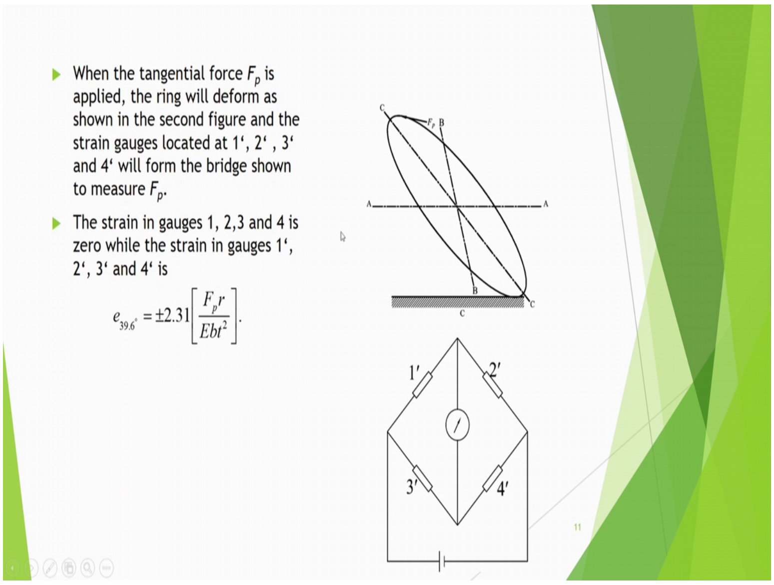

Now, when the tangential force F p is applied; suppose, you apply the tangential force F p then the ring will deform as shown in this second figure. And the strain gauges are located at 1 prime 2 prime 3 prime and 4 prime; that means, at these locations you will have you will make the bridge. So, these gauges will be there. Here 1 prime then 4 prime

2 prime 3 prime you have to arrange in this fashion if you arrange in the different way suppose you take 1 prime here 4 prime here then there will not be proper result.

So, strain in the gauges 1, 2, 3 and 4 is 0 at this time here it is 0. So, in this and while the strain in gauges 1 prime 2 prime and 3 prime and 4 prime is actually this e at 39.6 degree is given by plus minus 2.31 is equal to F p R E b t square almost the same type of expression, but in the previous case this was 1.09 and here you are getting 2.31. So, in a way it is slightly more sensitive in. In fact, more than double strain gets almost 2.3 times more ok.

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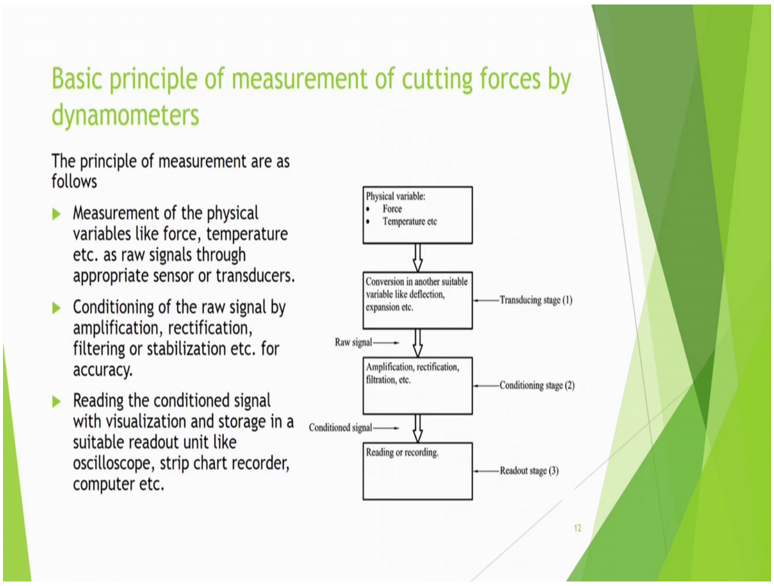

So, this way we can measure. So, we can put 2 Wheatstone bridges. One can measure F p, one can measure F q and we have arranged these bridges in such a fashion. So, that there should not be pricing; that means, there should not be cross sensitivity; that means, force in one direction should not show any reading in the other Wheatstone bridge. So, this was a strain gauge type of method which is used, but nowadays instead of wire type of strain gauges, people use piezoelectric type of crystals and other things you can use of course, many other devices also we will discuss them one by one

But first let us now come to the basic principles of measurement of cutting forces by dynamometers. You got these strain on the strain gauges and then because of the strain their resistance changed, but this is not enough resistance, got changed 5 and then after that you can measure the change in the voltage. Thanks to Wheatstone bridge because of

Wheatstone bridge you are able to measure the change in the voltage. That voltage can be calculated means we can say 1 volt is equal to this much force, if there is a change of 1 volt then it will be considered this much force and if it is 2 volt then it will be considered that it is double the force like that we can make the arrangement. So, there are means lot of means steps lot of modules.

So, this is explained in terms of this type of block diagram; that means, I this is general principle not only for the measurement of force, but even for measurement of temperature etcetera; that means, we have a physical variable, like force and temperature then what you need to do that, you want to converge in another suitable variable like deflection extension etcetera. Force how you will measure force you can only measure the effect of the force.

So, one effect of the force is what? That you can measure that what is the change in the length. If I am outing the force in particular direction so; that means, that you will see force is doing deformation, I can measure that deformation because it is easy to measure the deformation right. You have to see the effect. In fact, force is there then you apply a moving body then it reproduces acceleration F is equal to m a. If you can measure acceleration you can know that what is the force because already you know the mass of that object.

So, here in this case it is static situation. So, we are measuring only the deformation. And then we are doing convergent in another suitable variable like deflection. And suppose I want to measure temperature then I may measure that how much is the extension of any rod. And if by that I can find out that how much was the temperature. Because more will be the temperature more will be the expansion of the rod. So, this is called transducing stage; that means, this job that converting force to some variable like deflection that is called transduction. And the thing which does that type of job is called transducer.

So, you know that terminology transducer ok. So, measurement of the physical variable like force temperature etcetera as raw signal through appropriate sensor or transducer is done that is the first task. So, we say transducer and are sometimes we could say sensor, there is a very certain difference about sensor and transducer. Many times in many books actually they will use sensor and transducer interchangeably, but where there is a some difference means sensor you can say is like a sense organ, it is a complete thing it may include that complete even the computer processing and all those type of things connected with that complete gadget. We can called sensor whereas, transducer we can say that part only which does this specific task.

That means converts force to deformation. So, we can say it is a transducer. We correct many other things it becomes the sensor, maybe we put some display and we can see those readings on the screen if we put that complete thing then it becomes sensor. Next step is what you got this raw signal that we are calling raw signal; that means, it converted force got converted into deflection, but then this has to be amplified rectified and it has to be filtered etcetera.

Force got converted to deflection and may be deflection in turned got converted to voltage like the strain gauge that deflection was there it produces strain. And therefore, it produced strain then it produced basically change in the resistance. So, we got some voltage that voltage may be very, very small we can say that that voltage which we got.

So, transducer is what transducer ultimately did the transduction of transduction of force to voltage. We got some voltage right, but that voltage will be very small. There was change of the force of let us say 1 kilo Newton means 1 thousand Newton, but this got changed only by say let us say 0.01 millivolt. It will be difficult to measure such a small voltage. So, we have to amplify that we have to do amplification; that means, somehow that one millivolt is amplified by 100 times.

So, suppose there is one millivolt, it becomes 100 millivolt. Then it may be have you may have to do rectification it may be a c also, but you want I want only the d c component you can put rectifier. And then you can you may have to do filtration; that means, there may be some noise components some spikes etcetera you want to remove that. You want that only some low frequency components should go such type of task you do then you put some filter there are some electronic filters etcetera.

So, this type of job; that means, lot of electronics is there in this portion that voltage is there and then you have to do amplify, you have to put filter. This is called conditioning stage. So, conditioning stage is also very important part conditioning of the raw signal by amplification rectification filtering or stabilization etcetera for getting more accuracy. Then what you have to do condition signal has come, but you have to measure it you have to read it. So, you have to read it or you have to record it in your computer. Or you can put some data acquisition cable and it can put that complete system. So, it can acquire the data. So, it can go in the computer, it can directly go in a excel file such type of job you have to do that is called read out stage.

So, in this stage reading the conditioned signal with visualization and storage in a suitable read out you only we can see in the oscilloscope. We can see in a PCR also nowadays. We have that is computer and we can have other type of recorders. So, this one is this stage.

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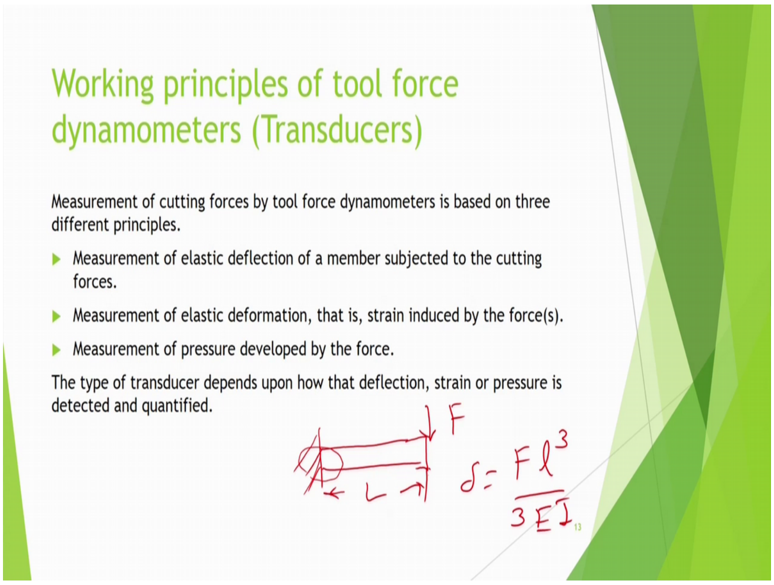

Now let us say working principle of tool force dynamometers; that means, concentrate on the transducers side. So, measurement of cutting forces by tool force dynamometer is based on 3 different principles; that means measurement of elastic deflection of member subject to the cutting forces. I can put a continuous beam type of structure, see that how much it is deforming and I can know that elastic deflection that also can be done and this is one job that is we can have this one we can have something like that.

Suppose there is a continual beam, these continual beam is subjected to forced F. Then there will be deflection at the free end and if this length is L then that deflection delta is equal to F L cube by 3 E I. So, very correctly you can measure the deflection also. Then also you can get one force in that that is also one method there are some dynamometers which will not measure these strain rather they will measure some deflection. That is also can be one method another thing is that we can measure the elastic deformation by measuring the strain.

So, we can find out the strain. If you want to find out strain, then we have to focus in this area in the beginning that area. And then we can also measure in certain situation measurement of pressure developed by the force. We can put the some load and we can make some what is the pressure that also can be measured. Maybe we can put even pressure gauge also to measure; that means, we can put a hydraulic system type of thing put a force and then that produces force divided by area will be pressure and this can be done.

Type of transducer depends upon how that deflection strain and pressure is detected and quantified, which is more convenient for you this you have to consider.

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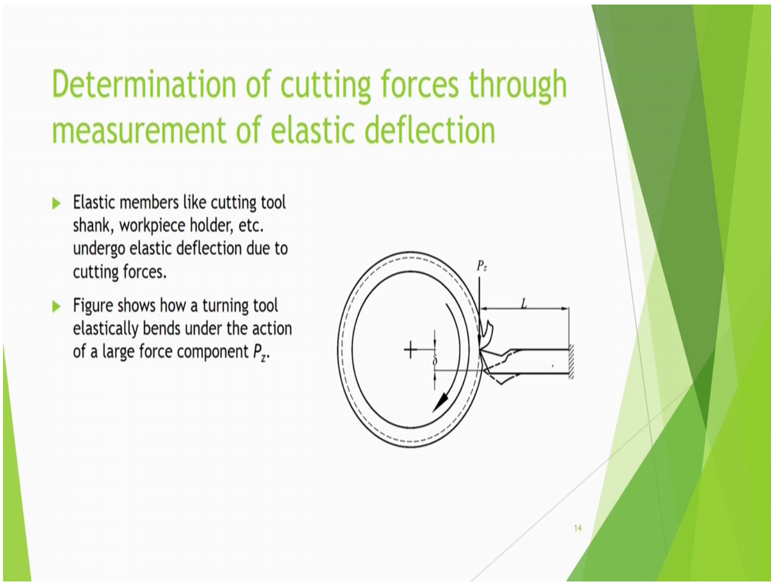

So, determination of cutting force through measurement of elastic deflection, that was also attempted there are dial gauge type of dynamometers still in the market which measure. They may not be very accurate, but they measure the forces. So, here we have put a continual beam it is length is L. And automatically when I am doing cutting then a cutting force is coming that force is downward that force is downward that is Pz, we are indicating by Pz. Because of that the tool has deflected because it is a continual type of structure. So, it has deflected.

Now, in this case, elastic members like cutting tool shank this is a cutting tool this portion is cutting tool then there is a shank here you can say shank portion. And then work piece holder this is a holder they all undergo elastic deflection. So, you have to consider the stiffness of all of them. May be tool holder is very rigid, it may have very small effect, but one has to see that whether it is having small effect or it is not having a small effect. So, this figure is showing how a turning tool elastically bends under the action of a large force components Pz.

Now, if you put large amount of force only then you can see the deflection and you can maybe measure by putting simpler scale, but when the deflection is small then you may have to do some amplification then only you can measure.

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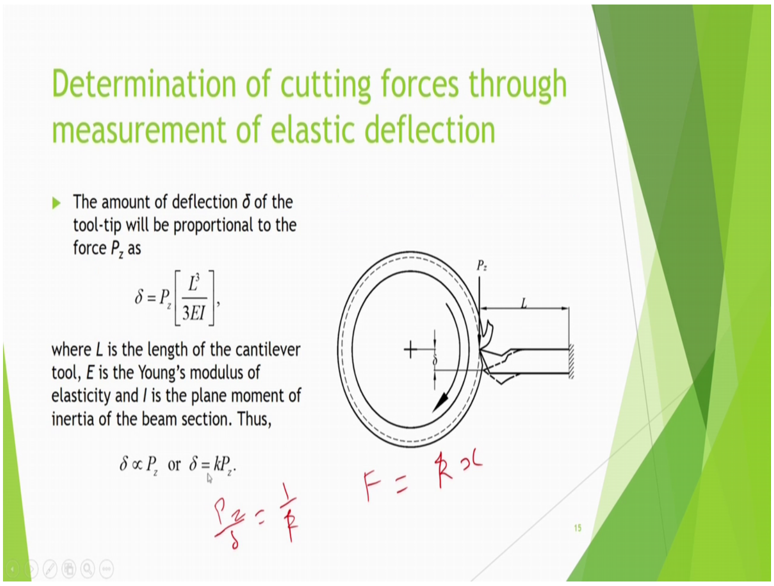

So, this is one way. Now in this case so, we have seen that we have put like this. And then amount of deflection delta of the tool tip will be proportional to the force Pz. There is no doubt about that delta is Pz L cube by 3 E I ok. So, we have got this factor this is a type of indication about sensitivity L cube by 3 E I. If I want; that means, for small force, I must get large amount of deflection I must concentrate on this parameter L cube by 3 E I. If you increase the length it increases drastically.

Suppose I double the length my sensitivity may increase by a times L cube 2 to the power 3 and E and I. E is the young's modulus of elasticity and I is the plane movement of a inertia; that means, planar moment of inertia; that means, second moment of inertia of the beam section. So, basically what we are getting that delta is proportional to Pz. So, we can write delta is equal to k Pz. It is a spring type of equation and we can see it is something like a spring constant. You know that this equation very well we used to write F is equal to k x x was the displacement and k is this one. So, in this case that it is in this case k is equal to, but in this case this k is written in reverse way it is Pz by delta is the stiffness that is 1 by k ok.

So, be careful about this unit I have written delta is equal to k Pz. So, k is basically that factor which is multiplied by with Pz. It is not usually the stiffness it is opposite of the stiffness. Now here; so, constant of proportionality.

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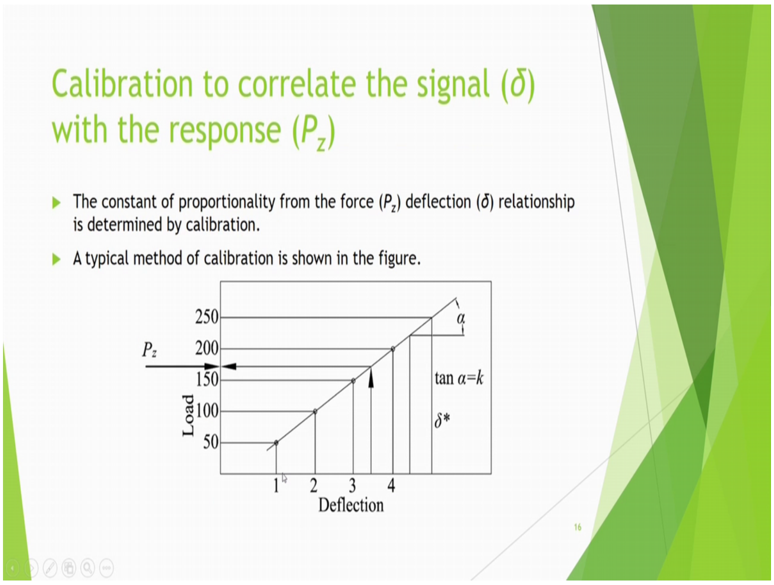

So, we see that delta and Pz both are proportional to each other and we can plot if we graphically, if we do calibration means first you have to calibrate we have to see that with known load we measure the deflection. We understand the instrument what is the relation between the force and deflection. So, that process is called calibration. After that you can use. So, we have to do calibration to correlate the signal delta with the response Pz.

So, I have got this type of things, I took the measurement. If I put the load of 50, I got this deflection of 1 unit. Then I put 100; I got 2, then I put 150 here, then I put 200 unit force I got this 4 then I put like this. So, I have got suppose 150 you got like this then you can see that more or less it is straight line. In fact, in this case it is a perfect straight line in actual case it will not be perfect strain line. So, you will generally you try to fit proper curve line. So, in this case suppose we have got this type of may be by least square fitting I got this type of line straight line and then I can find out it is a slope.

It is a slope is tan alpha which is k this angle is alpha. So now, if I know some deflection delta star, I can find out that what is the corresponding force here that I have got suppose this one, but usually when you have calibrated some graph like this, it is not a good idea to do extrapolation; that means, do not if you have done during calibration stage you have fitted a straight line. And that time you have gone from deflection of 1 mm let us say to 4 mm then you should not subject it during your experimental condition that deflection becomes 5 mm and you will extrapolate.

Instead, try that your deflection should be limited between 1 and 4. Otherwise already in calibration stage you take care. If you know that actual if I know that my actual deflection is going to be 4, I would try to have calibration from 1 to 5, so that I can get fair idea. So, this is variation shear and this linearity is a good option because you will have same level of accuracy and other ease of measurement. That is why we prefer like this.

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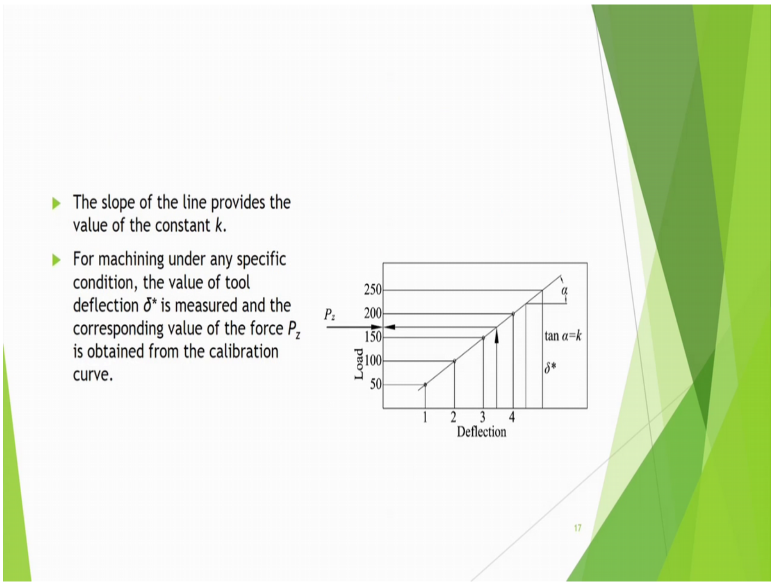

Now let us go to this one slope of the line provides the value of constant k for machining under any specific condition, the value of tool deflection delta star is measured. I have measured this delta star and the corresponding value of the force Pz is obtained from the calibration curve. Because already I have made a curve although in this case as I pointed out there is a small flaw that we are actually trying to do extrapolation, but supposing it is behavior remains straight line. So, this point goes here and this goes here and then it becomes lie this delta star. So, this is equal to Pz 250 and this one.

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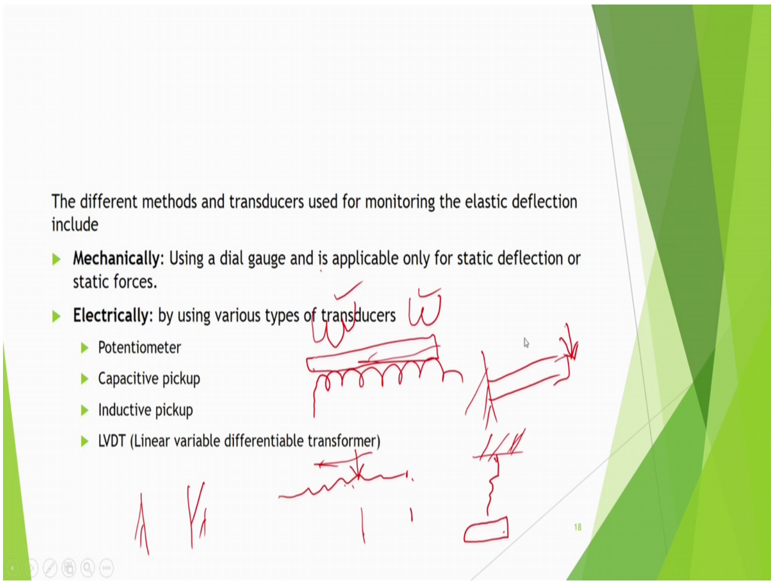

Now, different methods and transducers used for monitoring the elastic deflection include what are the different methods and different type of transducers. Mechanically we can measure the deflection using a dial gauge. So, dial gauge type of dynamometers are still available. And sometimes they are used also they are somewhat cheaper you can get in somewhat less price and it is, but it is generally applicable only for a static deflection or a static force. It will not be very suitable for dynamic deflection because if it is going rapidly suppose you have a dial gauge suppose you have got a beam. And in this beam you apply some force.

So, first you put a force, may be it will go some dynamic deflection type of thing, but you know usually it stop. You know that when you stand in a weighing machine, it says that in the weighing machine you stand and there is a wheel actually in the railway weighing machines and then the wheel stopped rotation, then only you should measure the weight because. So, that everything gets stabilized actually.

Otherwise in the beginning suppose I just put my foot on the platform and I have a stood there and my weight has been applied all of a sudden. So, deflection may be more also.

So, first it will go in the another means with more deflection then deflection will try to reduce, there will be vibrations and ultimately it will stop at that equilibrium position. In even any spring you hang a spring in your home if you want to do this experiment, put a load you see that it will start vibrating and finally, it will stop and this will thing. So, we want to do when it has this one. So, this type of mechanical measurement using deflection is very suitable for a static deflection, because the forces are not rapidly changing with time and you can measure.

But suppose the forces are changing with time, you applied some force here and then all of a sudden these and then you change direction of this one. So, actually it we will not get the correct measurement. In fact, if I have a continual beam and I apply some load and keep changing it is direction at a very high speed, then because of inertia it may not move at all and it will show you that 0 type of reading. So, it will not be suitable because it is changing by the time it wants to go in that side suddenly the force has gone in a opposite side. So, you are not seeing any change.

So, dial gauge type of thing is only suitable for static type of deflection. Not very much suitable for dynamic. Then electrically you can measure various type of transducers we can have we can have this is potentiometer. Then we can have this is the mechanical part mechanically it got converted to displacement, but displacement has to be measured in some way. So, may be displacement is taken another one and second transduction is applied. One transduction was force got changed to deflection.

Another one is that deflection will get changed to voltage. So, deflection is that it is potentiometer. So, the voltage will be changed to potentiometer. Then it will be we can see that by potentiometer; that means, because in the potentiometer usually there will be resistance and with the change in the deflection it resistance we will change. Suppose I put a resistor like this, and if I put a pointer here and I want to measure the voltage between this and this. So, if I deflect this pointer then effective resistance length will change and because of that voltage will change.

So, potentiometer is one way, but I can because of the change in the deflection, even capacitance can get changed. If you have got 2 capacitor rates and if I reduce the distance between those capacitor rates then also I can change the voltage.

So, that is called capacitive pickup; that means, using capacitor or it can be inductive pickup; that means, changing of the inductance or it can be it is called LVDT; that means, linear variable differential transformation. So, LVDT is usually obtained in that there are it is basically a type of transformer I am making a very simplified, is case here suppose I put here some primary winding like this. And I put here secondary winding like this and in between I put core if entire thing is symmetric, then whatever voltage is here same voltage is coming here. So, you are seeing the difference between them is 0.

Now, suppose this core gets displaced, it is comes more on this side then you may get more voltage here because that magnetic coupling is there. There the voltage may reduce because coal portion has reduced. Then you will see the difference between the voltage and then you will get the idea how much coal has moved ok. So, this type of technique is called Linear Variable Differential Transformer, LVDT.

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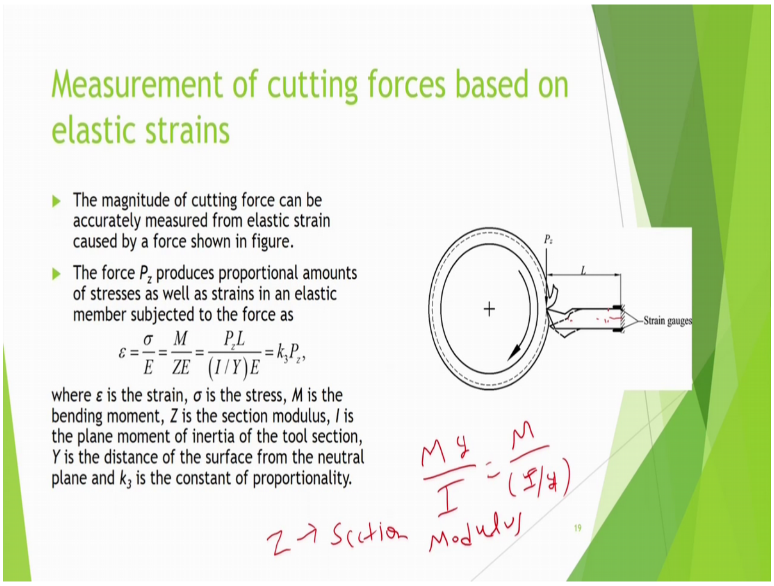

So, it is now the magnitude of magnitude of cutting force can be accurately measured from elastic strain caused by a force shown in figure; that means, I can instead of measuring the deflection now I can measure the strain shear.

So, I can put strain gauges here. The force Pz produces proportional amounts of stresses as well as strains in an elastic member subjected to the force. So, a strain will be a epsilon, this is well known hooks law. Epsilon is equal to sigma by A, stress divided by A because there is only one stress there are no other stress in other direction and this can be written as sigma is basically there is a bending moment known. So, there is a pure bending assume that there is a pure bending. And this becomes My by I where y is the distance of the top fiber from the neutral axis. Neutral axis is midway in the rectangular section. So, My by I, but I will say that this is M divided by I by y. So, I is what? I is the second moment of area; that means, that is for rectangular section it is 1 by 12 b h cube and 1 by is actually h by 2.

So, these are dependent only on the geometry, what type of cross section is there; that means, it is the parameter of geometry. So, I by y is called z, and which is also called section modulus. So, this z is called section modulus section modulus. So, we can have section modulus. So, we have m z by e expression, becomes very simple or we can say Pz L I by y, I by y and z both are same and this becomes k 3 Pz. K 3 is the proportionality constant that constant of proportionality is k 3. So, epsilon is strain sigma is the stress, 10 is the bending moment because of this force Pz, z is the section modulus I is the plane moment of inertia of the tool section y is the distance of surface from the neutral plane.

So, middle is the neutral plane. Here this is the neutral plane top side there will be tension bottom side compression.

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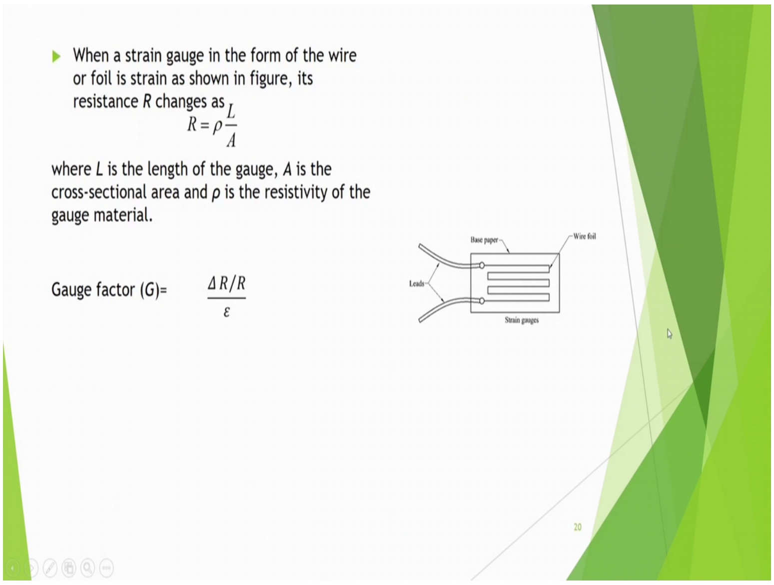

So, y is the distance from neutral plane to the top surface and then you will get this one. So, when a strain gauge in the form of the wire or foil is strain as shown in the figure;

that means, when the strain is there. So, it will be experienced by some wire this strain gauge you have properly bonded. So, it is you are seeing that we have put many bounds here. So, that the effective length of this thing gets changed. So, resistance R changes as, R is equal to rho L by A, where L is the length of the gauge A is the cross sectional area and rho is the resistivity of the gauge material.

So, rho is the resistivity of the gauge material, that this one R is the in ohm. And this is L is in meter A is in meter square. Then you can find out unit of rho. And then gauge factor is defined as delta R by r. Delta R by R is means fractional change in the resistance. Suppose it percentage change is one then fractional change will be 0.01 and this is epsilon is divide by epsilon that is called gauge factor. So, this gauge factor should be very high actually, but it is always not possible to have such a high gauge factor, but generally people take it more than 2 or something or mostly 2.

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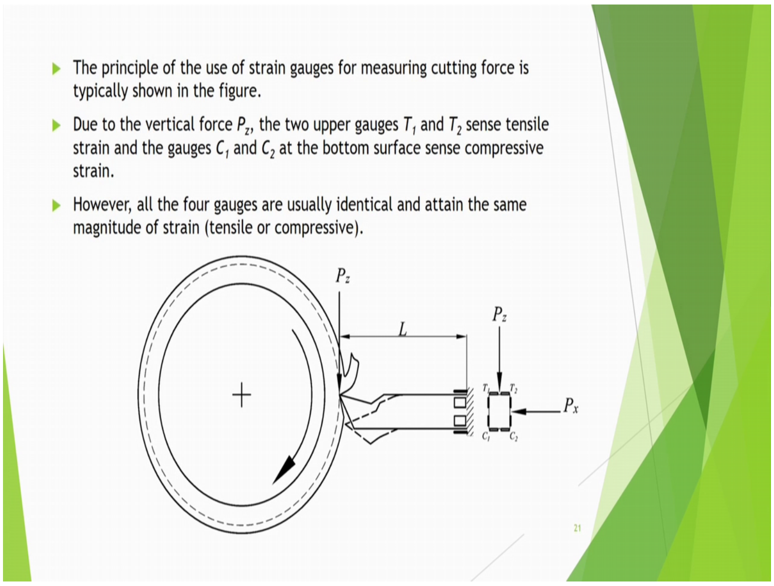

So, principle of the use of a strain gauge for measuring cutting force is shown in this figure. Now due to the vertical force Pz the 2 upper gauges t 1 and t 2 sense tensile and c one and c 2. They sense compressive this time I have written t 1 to t 2 c 1, c 2 just to emphasize that it is tensile and this is compression; however, all the 4 gauges are usually a identical and attain the same magnitude of strain tensor or compression. So, they magnitude wise same, but it is positive here and this is negative strain here.

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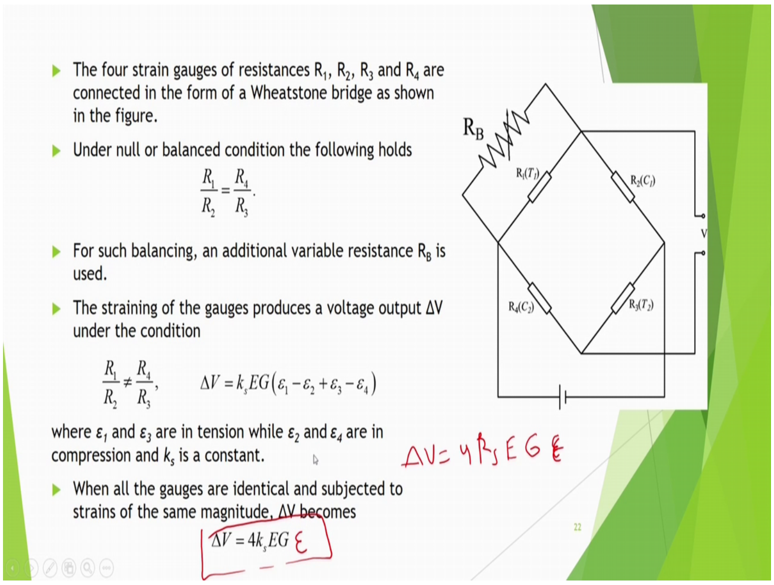

So, then the 4 strain gauges resistance R 1 R 2 R 3 and R 4 are connected to Wheatstone bridge. So, in this case may be if it is tension, then R one may increase R 3 may increase R 4 and R 2 may decrease. Under null or balanced condition the following thing will hold this you can even in your plus 2 level also you have studied, that about Wheatstone bridge that if there is a if it is totally balanced in that case R 1 by R 2 will be equal to R 4 by R 3.

So, it is totally balance in that case. Now, s o, in the beginning it is totally balanced maybe R resistance is R equal. Now once I put the force then these strains will change. So, it will become disbalanced and then we will be able to measure it, but for then or so, one thing is that we can how to measure that small thing. Maybe I can put another resistance variable resistance R B which will balance that I can have. Even in the beginning also suppose they may not be balanced properly. So, you have to do some adjustment. That for that adjustment I can put some RB type of resistor and I can actually change it is this one. So, that it becomes balanced.

So, for balancing we put generally additional variable resistance. The straining of the gauges produces a voltage output delta V, under the condition that R 1 by R 2 will not be equal to R 4 by R 3. And then in that case delta V will be generally proportional to this one. It will be K s times EG epsilon 1 minus epsilon 2 plus epsilon 3 minus epsilon 4.

You can see epsilon 1 and epsilon 2 3 means these 2 diagonal strain gauges they are having additive effect. Whereas, epsilon 2 and epsilon 4 they are having subtractive effect. So, epsilon 1 and epsilon 3 are in tension while epsilon 2 and epsilon 4 are in compression. So, they further right that thing. So, suppose strain and all the gauges is same and it is epsilon, so, whole thing becomes, but this is plus epsilon and epsilon 2 is minus epsilon. So, plus and minus will get added.

So, you will get 4 epsilon. So, it will be when all the gauges are identical and subjected to strains of the same magnitude. Then delta V becomes basically, delta V will become 4 times K s E and then I am putting it like a gauge factor here because this is delta V. In fact, it will become if I have identical this one. So, delta V will become 4 time Ks E G gauge factor I have written and this is epsilon ok.

So, that epsilon is missing here, that epsilon has to be there, otherwise this is the thing; that means, delta V is proportional to 4 Ks EG into epsilon. That has to be there and then it is like this. So, this is one method here we have arranged in this way we have increased it is sensitivity. In fact, 4 times if we just measure that one.

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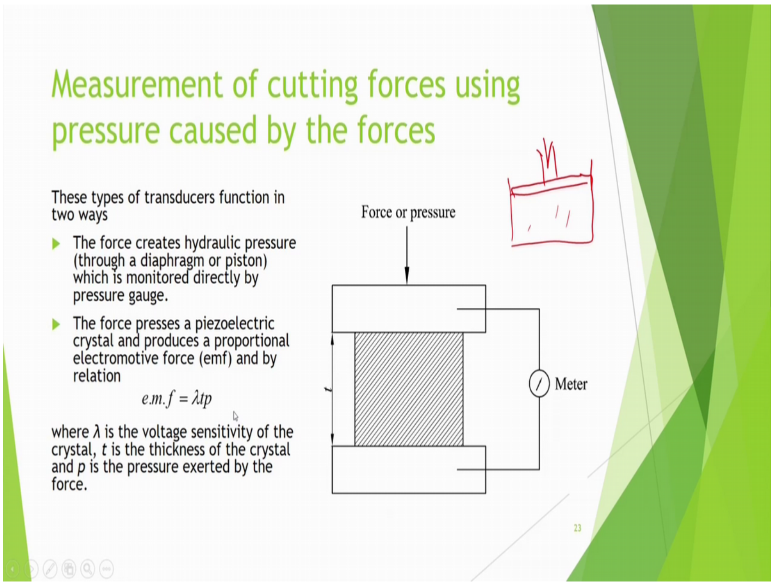

Strain now we can measure cutting forces using pressure caused by the forces also we can measure the pressure. So, these type of transducers function in 2 ways. One is force creates hydraulic pressure, we can put a hydraulic cylinder on top of this there will be piston. And if we put some suppose put a force here naturally this will produce pressure and that pressure will be monitored directly by pressure gauge. That is one method of hydraulic system, but it may become very cumbersome. So, that is one thing.

Another most popular is that force process a piezoelectric crystals. Some there are some crystals which have got that property that they will produce a proportional electromotive force by this relation emf will be lambda times t p. Lambda is the voltage sensitivity of the crystal, t is the thickness of the crystal and p is the pressure exerted by the force. So, it will be lambda is t p. So, this is what voltage sensitivity, t is the thickness and p is the thickness means this is thickness from here to here. So, we can have this type of arrangement. Now it is proportional to thickness and p.

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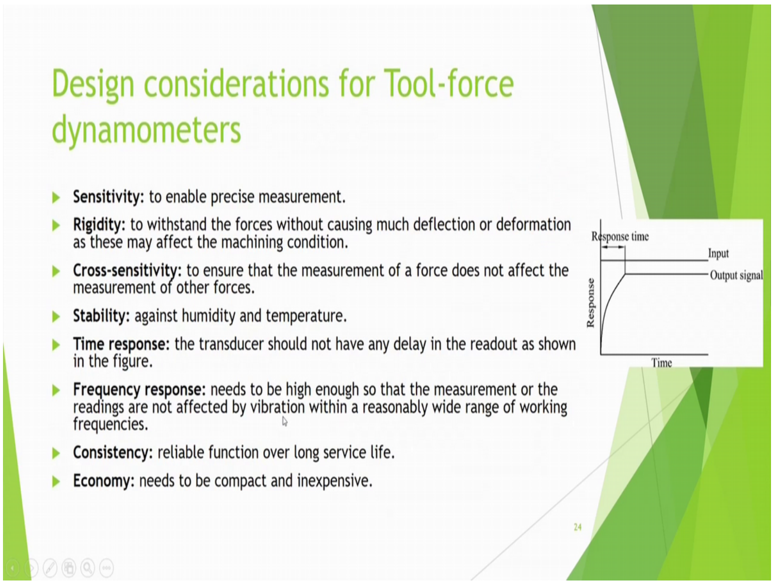

So, this we can measure. So, most of the dynamometers are produced and they are having this type of. Particularly crystal is making this dynamometer other companies also sometimes making this type of dynamometers. They are based on the piezoelectric crystals.

Now, let us consider design consideration for tool force dynamometer. One is we need high sensitivity. So, that we can measure pressurize measurement; that means, it is decided by gauge factor, then rigidity. It should be sufficiently rigid to withstand force without causing much deflection or deformation as these may affect the machining condition. If it is not rigid, so, that is why there is a conflict. You want to have if you want that high sensitivity; that means, you should have more deflection of that particular tool, but if it is a more deflection, then cutting condition will itself will be destroyed. So, that is why you have to make a balance you have to optimize here.

Then rigidity to withstand the force without causing much deflection or deformation as these may affect the machining condition. Then cross sensitivity; that means, it is if when I am measuring the vertical force, it should not affect the reading of the horizontal portion meter. It should not affect that Wheatstone bridge which is for horizontal one. So, cross sensitivity to ensure that the measurement of a force does not affect the measurement of other forces.

Stability, it should be stable against humidity and temperature if temperature changes humidity changes. It should not happen that today the temperature is 30 degree and tomorrow it will be 45 degree then the reading will be different time. Response the transducer should not have any delay in the readout as shown in the figure; that means, there is a response time, quickly I must be able to change. So, this is response here and this is input.

So, it has reached here this much time it took to reach that value. So, this response time should be less. Frequency response it needs to be high enough. So, that the measurement or the readings are not affected by vibration within a reasonably wide range of working frequencies; that means, in these frequencies it can measure.

And consistency reliable function over long service life and economy needs to be compact and inexpensive.

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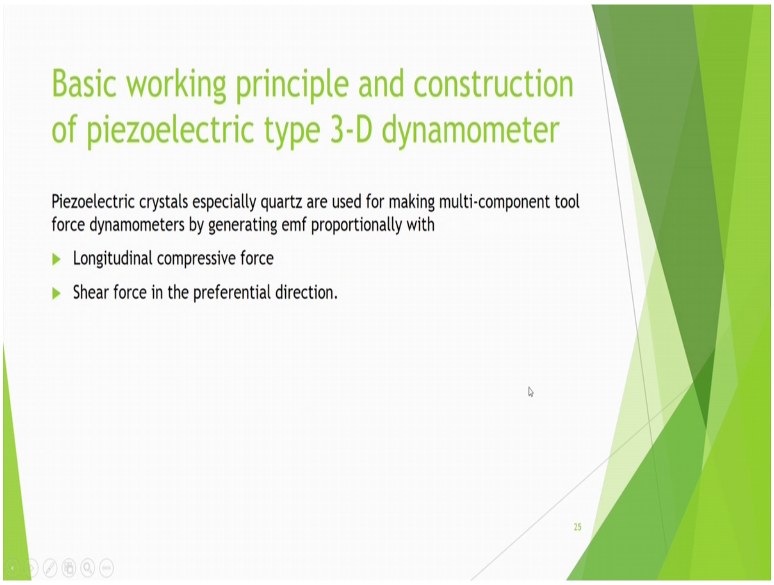

So, basic working principle and construction of piezoelectric type 3-D dynamometer which is like crystal is making in that what is there piezoelectric crystals especially quartz are used for making multi component tool force dynamometers. One piezoelectric crystal is quartz. By they generate EMF proportionality with longitudinal compressive force and a shear force also in some preferential direction; that means, in some particular range if there is a shear then the voltage charge may be generated.

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So, it is a typical that piezoelectric dynamometer is shown here. This I have taken photograph from my workshop. And this is a Walter P Kistler was one Swiss engineer who invented charge amplifier in 1950 by putting piezoelectric crystals. And a along with before that along with Sonderegger he had invented force sensor in 1944.

So, Kistler himself founded that company which makes now Kistler dynamometer.

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Now, this is these are basically called charge amplifier because, of the compression of the piezoelectric crystal charge is generated, but that may be small. So, you have to amplify it and then properly you have to measure also. So, complete amplifying and this one measurement is done by charge meter. So, these are charge amplifier and charge meters combined for Kistler dynamometers this we have taken.

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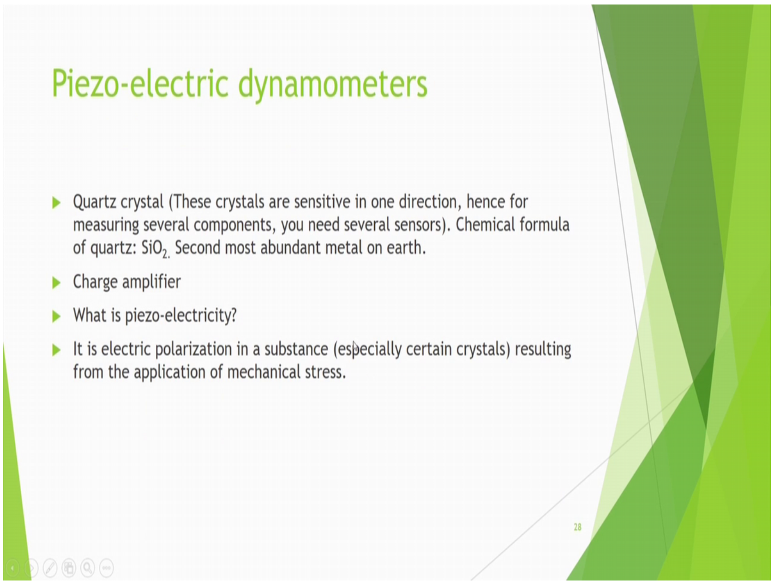

And then at quartz crystal these crystals are sensitive in one directions. Hence for measuring several components you need several sensors. Because it is if you want to measure horizontal force then it should be put in that direction.

So, chemical formula for quartz is SiO2 and it is second most abundant metal on earth. You can say that it is like this. And then charge amplifier, we need to amplify this thing. Now piezoelectricity definition is that it is electrical polarization in a substance especially certain crystals resulting from the application of mechanical stress.

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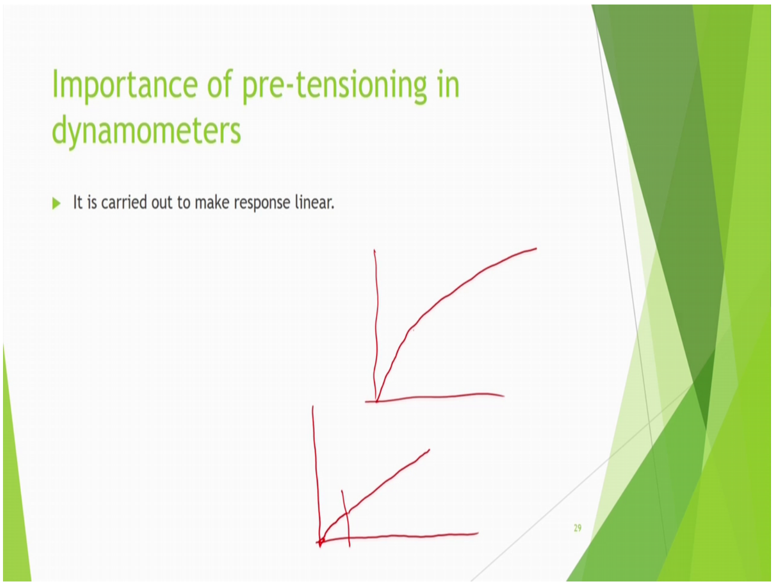

Now we have to we have to put some pre tension in dynamometers it is carried out to make response linear; that means, initially you have to apply some load suppose relation between the force and this one is like this, like this ok.

So that means, let me make in a exaggerative way; that means, it may be like this and then it becomes linear; that means, after sometime force it will become linear. So, it is better that you put that much force. So, that your response does not become non-linear and that is why we already put some load that is called pre tensioning of the dynamometer.

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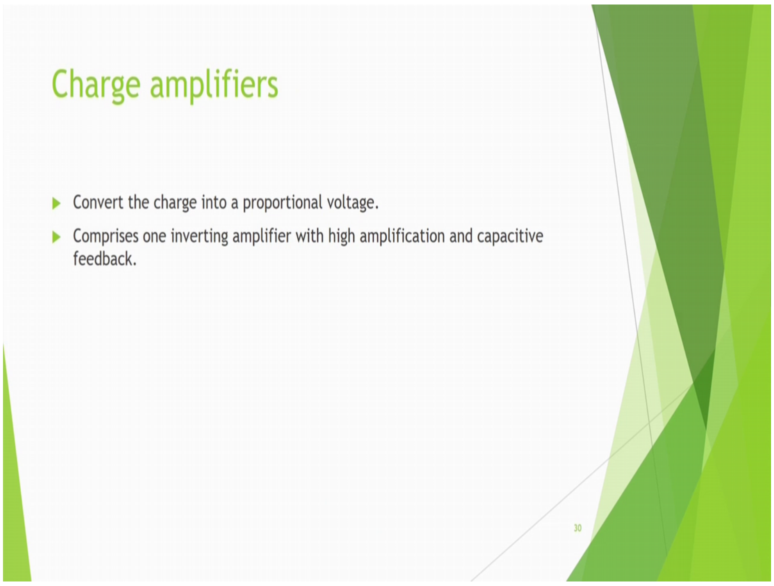

Charge amplifiers they convert the charge into a proportional voltage. And it comprises one inverting amplifier with high amplification and capacitive feedback. So, these type of things are do.

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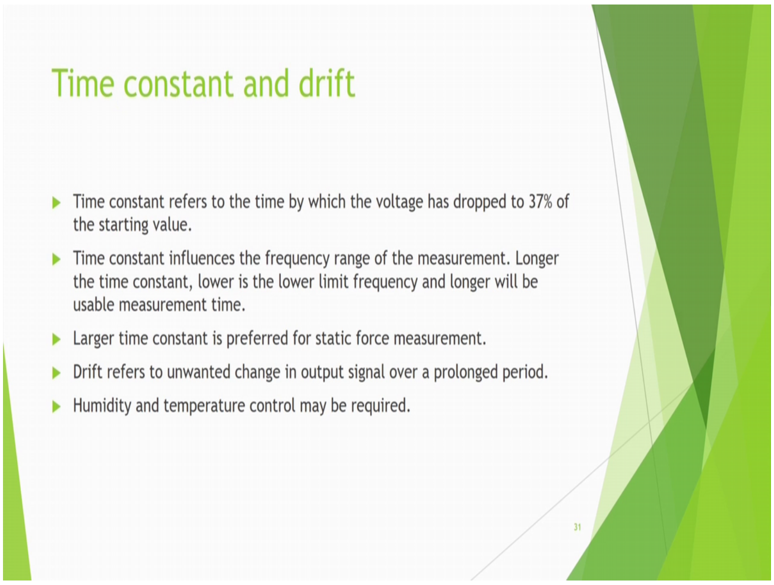

Time constant refers to the time by which the voltage has dropped to 37 percent of the starting value suppose some voltage where there how much time it will take to. Time constant influences the frequency range of the measurement, longer the time constant lower is the lower limit frequency and longer will be usable measurement time. So, time constant has to be selected. Longer time constant is preferred for static force measurement then you need this one. And drift refers to unwanted change in output signal over a prolonged period. If you adjust that after sometime you see automatically leadings have changed that is because of drift.

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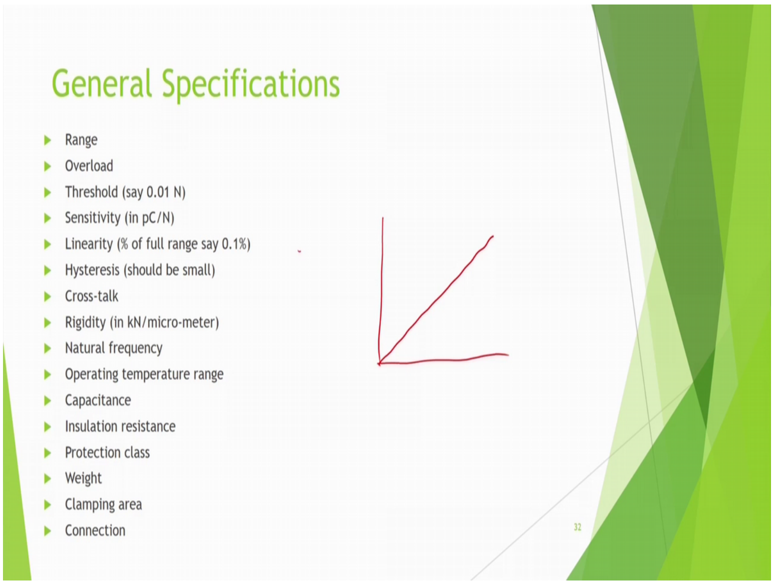

Humidity and temperature control may also be required. In general, the specification of this may be general specifications may be that range means how in which range it can measure. Then it can be overload, then it can be means how much overload actually designed was for suppose 30 Newton, but it is measuring suppose by mistake load has become 32 Newton then also it should take up that much, threshold means minimum quantity which it can measure say 0.01 Newton less than that there will be nothing, you know. After 0.01 only it will know that there is something applied. Sensitivity it can be measured in Pico coulomb per Newton, Pico is 1 into 10 to the power minus 12.

Linearity that means, percentage of full range say 0.1 percent ok. So, this is linearity means how much is the deviation. Suppose you linearity suppose percentage of this one. So, actually had suppose there is no deviation then percentage of full change range is 0, but suppose there is a 0.1 percent deviation from linearity that type of thing, he here it is written hysteresis should be small. Hysteresis means if I apply the force in one way then I apply the force in the other direction. So, then there should not be are loading and unloading then there should not be difference much difference in the readings.

Cross talk means it is same as this cross sensitivity. Rigidity can be a specified in terms of kilo Newton per micrometer. Natural frequencies are also important because it should not be coincide with that. Operating temperature range then capacitance insulation resistance should be high. Protection class what type of protection class is there for your wires etcetera. So, that there is no the accident then weight and then clamping area and what type of connections are there.

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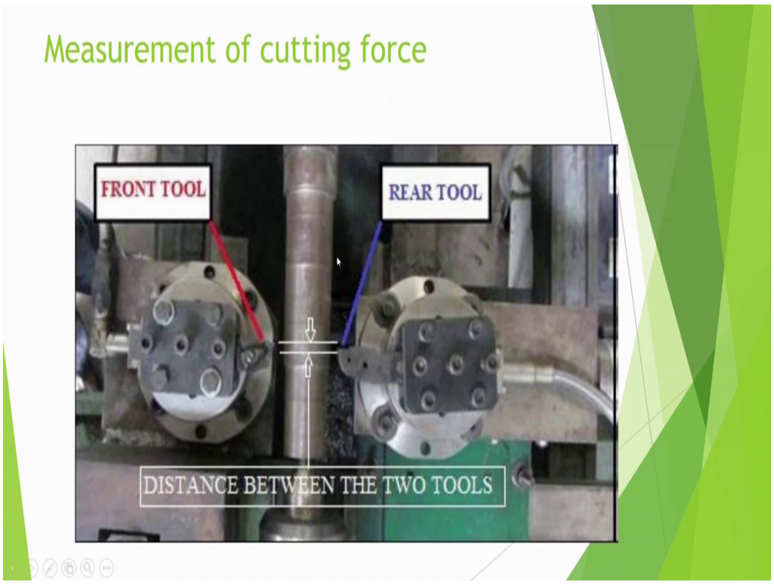

So, it is the we have actually measured in our workshop cutting forces. We have got the we are doing double tool turning one tool is here one tool is here. Now distance between the 2 tools is separated it is shown here. And we are putting this 2 dynamometers and they are connected by cables, that cable is going into charge amplifier and this one. So, this we are doing.

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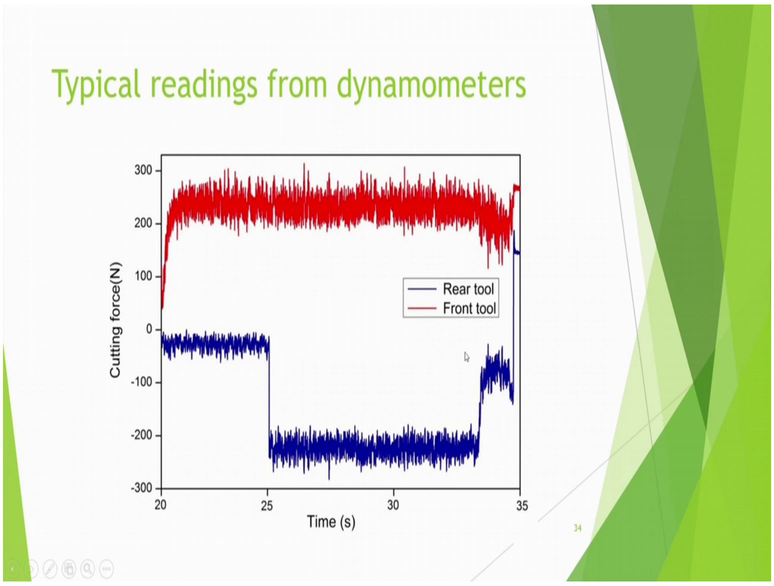

And then typical readings from dynamometers we are getting like this. See cutting force from the front tool it came like this. More than 200 and something just than 300 something 225 or something average, but there is a some fluctuation also. Means forces do fluctuate in a dynamic manner. And maybe I may be interested in having the mean value. Similarly, if you see in another tool the forces are fluctuating like this and mean value is fairly constant more or less fluctuations are less you are doing like this here and then force can also be measured by the measurement of motor currents.

They can be measured I can also measure by measuring the motor current that current that can be one method.

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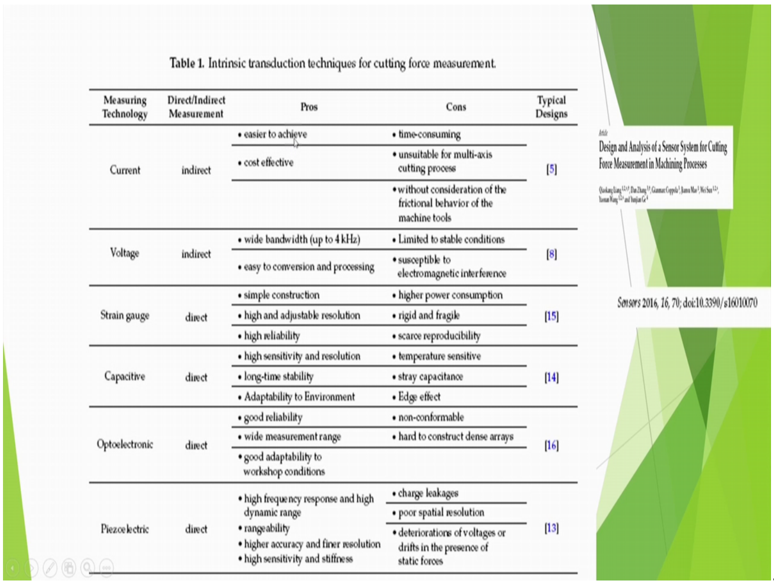

Table 1. Intrinsic transduction techniques for cutting force measurement.

Measuring Technology	Direct/Indirect Measurement	Pros	Cons	Typical Designs
Current	indirect	• easier to achieve • cost effective	• time-consuming • unsuitable for multi-axis cutting process • without consideration of the frictional behavior of the machine tools	[5]
Voltage	indirect	• wide bandwidth (up to 4 kHz) • easy to conversion and processing	• Limited to stable conditions • susceptible to electromagnetic interference	[8]
Strain gauge	direct	• simple construction • high and adjustable resolution • high reliability	• higher power consumption • rigid and fragile • scarce reproducibility	[15]
Capacitive	direct	• high sensitivity and resolution • long-time stability • Adaptability to Environment	• temperature sensitive • stray capacitance • Edge effect	[14]
Optoelectronic	direct	• good reliability • wide measurement range • good adaptability to workshop conditions	• non-conformable • hard to construct dense arrays	[16]
Piezoelectric	direct	• high frequency response and high dynamic range • rangeability • higher accuracy and finer resolution • high sensitivity and stiffness	• charge leakages • poor spatial resolution • deteriorations of voltages or drifts in the presence of static forces	[13]

In fact, there are many other methods for measuring for example, it can be measured by current. It is called indirect method it is easy to achieve and cost effective, but disadvantage is that, time consuming unsuitable for multi axis cutting forces. You will not know that which is this current is changing because of which thing. Then without consideration of the frictional behavior of the machine tools that may also affect. Then voltage is also indirect method and there are some advantage easy to convergent and processing, but limited to stable conditions it is susceptible to electromagnetic interface. A strain gauge I have told this is called direct method, in this simple construction high and adjustable resolution high reliability.

But it is higher power consumption rigid and fragile. And it is and reporting it should be reproducibility is very difficult. So, capacitive and is temperature really good one. Here advantages are there, but disadvantage is there may be stray capacitance, it is sensitive to temperature. Then up 2 electronic may be there, good reliability is there, wide measurement range, good applicability to workshop condition, but it is hard to construct dense up to what electronic sensor system.

Then piezoelectric I have already told the high frequency response and high dynamic range is there, suitable for doing the dynamic measurement, but higher accuracy and final resolution. High sensitivity and stiffness, but there is a charge leakage problem is there. In my workshop many times the dynamometer was not functioning properly, then poor a spatial resolution deterioration of voltage or drifts in the presence of static forces. So, these type of things are there. So, you are quite aware about that dynamometers are very expensive and mostly they are used in lab conditions also.

Sometimes these measures are like current measurement technique can be suitable. If you want to do measurement and simultaneously you want to do control.

So, today I will stop at this stage because I have told you about the cutting force measurement. And we will study another topic in the next class.