Design of Mechatronic Systems
Professor Prasanna S. Gandhi
Department of Mechanical Engineering
Indian Institute of Technology, Bombay
Lecture 12
Compliant Mechanisms

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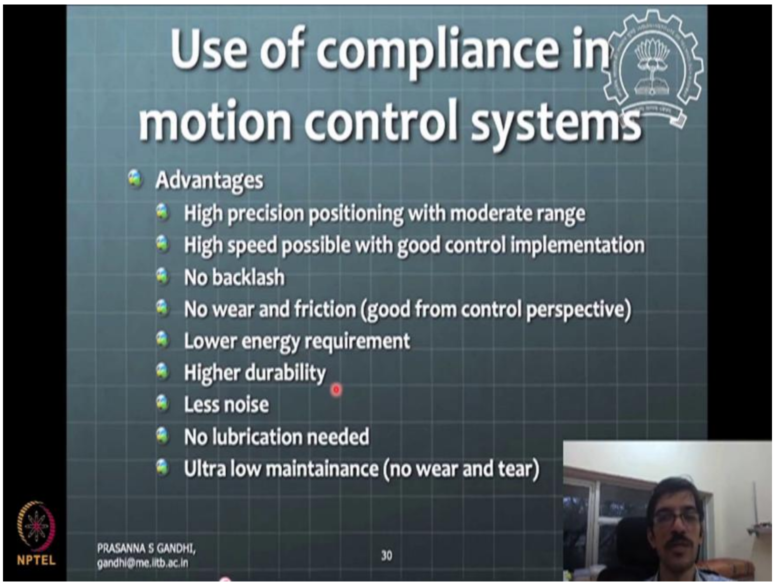

We are going to go a little bit more in details about this compliance. We have already seen its utility in the CD-ROM drive case you remember that we had had this block diagram of the block which is supported by these wires and that was hanging in the magnetic field and it has some coils when the coil the current passes then that block moves and it controls the lens of the CD-ROM drive.

That system may have already seen and that system is used in CD ROM drive for the final positioning as you remember, fine positioning, or fine tracking and then fine focus control. So, now, let us see formally a little bit more formal why compliance people want to use in the systems as you can guess, high precision positioning with a moderate range. So, not very large range that can be possible.

Then it can have high speed possibility because when you use compliant elements typically the weight will go down. So, when the weight goes down you can have higher speeds possible. But there is a flip side to it that because of the compliance you will introduce some vibrations in the system and has to do a control, good control strategy to kill those vibrations off, there is no backlash, no wear and friction in the system.

So, this no wear in the system is because there is no two elements rubbing against each other. So, you do not need any lubrication maintenance nothing that will be gone. Then there is a very low energy requirement because the mass is less, then you will have higher durability because there is no friction there is no rubbing of the elements and see this rubbing of the elements over the long duration of operations would really cause the wear and tear of the system and that is where one needs maintenance and then the durability goes down and things like that.

They are absolutely noise free again because there is no rubbing of things against each other. See, you might have heard some motors when they move, they make some kind of a noise, many coming because of the bearings, bearing and imbalance in the system which will create some kind of a noise. So, since there is no friction here again no noise no lubrication.

So, these are a lot of these different, different interesting advantages and that can help really in very high precision positioning, which is required for this era, I mean when we are talking about a nanotechnology, micro technology already coming up in the market in big way in many, many different devices. Obviously high positioning, high precision positioning systems would have better prospects to go. And compliant, like compliant mechanisms is one of the promising candidates towards that and people have started using compliant mechanisms-based positioning systems, nano positioning systems.

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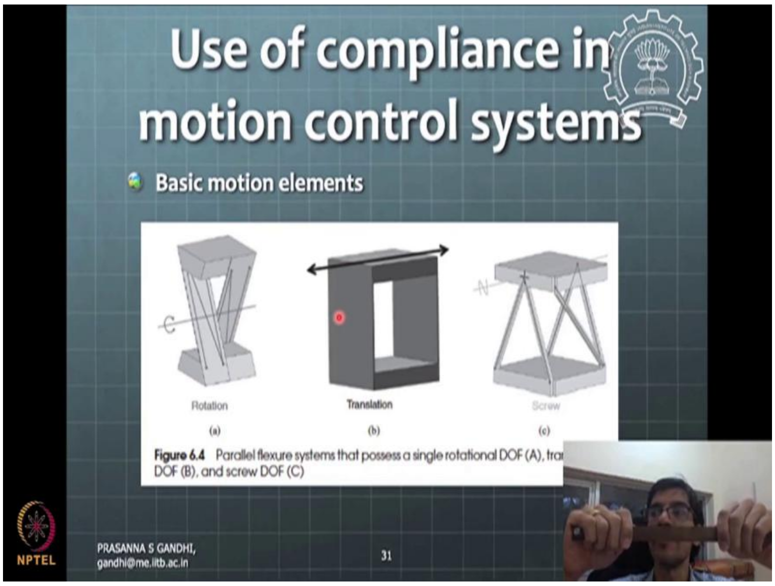

So, there are some a basic motion element that could be identified here, where you can have a rotation possibility. So, you move these some kind of a construction which will make the stage rotate without really having a rotary and a hinge joint in the system or you can have a translation possibility or you can have a screw possibility. So, these are some basic motion elements, what we have seen in CD-ROM drive is this translation element which was used.

So, you instead of this place you can think there are these 3 wires here, 1, 2, and 3 here and 3 wires on the other side, that is that will give you the same a motion in their direction that is shown here. In addition, because of this, because these are wires, see for example, this stage does not have a motion possibility in the perpendicular direction here as shown by the laser arrow.

But because the stiffness of these plates in this direction, bending is way too high. So, they can it is a scale which you can flexible link. I can show you here. The link which you can bend very easily, but you cannot, if you want to bend in this plane, it is not possible to bend it, it is very difficult to bend in this plane. So, this is basic elements of motion for compliant mechanisms.

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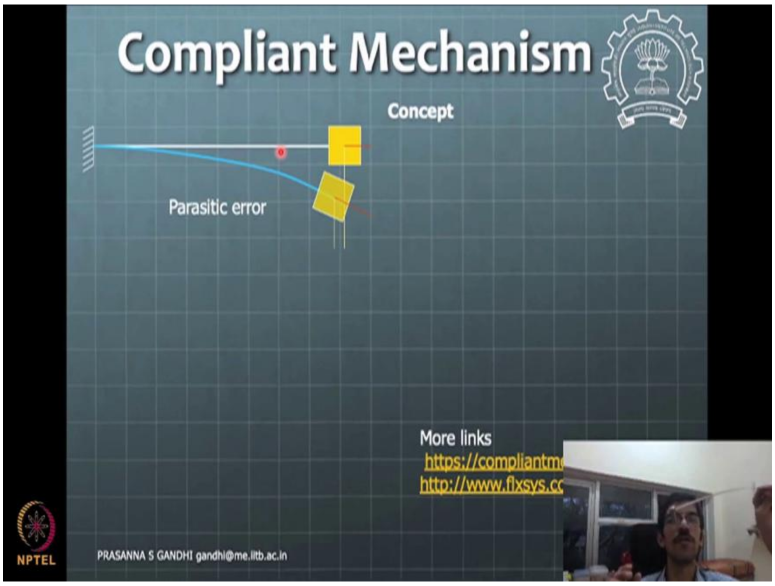

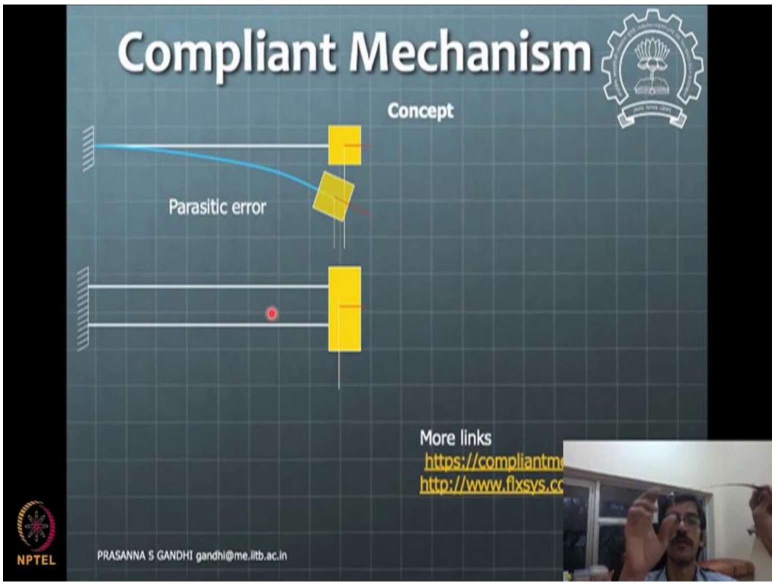

Now, I will just give you this linear motion stages in compliant mechanisms. So, this concept here is very simple if you say I want this block to move in the linear fashion and it should be guided only by the compliant mechanism. So, if I attach one cantilever beam here then the motion of this block as you see here, for this cantilever system is deforming like this. So, it has some deformation.

So, this block is, this block that is not really moving in a straight-line fashion here, it moving in some so to say like a circular arc fashion. So, this block also is going, undergoing some kind of, if you see this bigger size here. Yeah, this block also is undergoing some kind of a rotation. So, it was like this here and then it is tilted. So, this rotation is something which is not desired. We you want this block to move exactly like a straight line down below. So, for these now, we introduced some two elements of the same kind, you just do not have one single beam, but you have two elements, I will show you in the block there.

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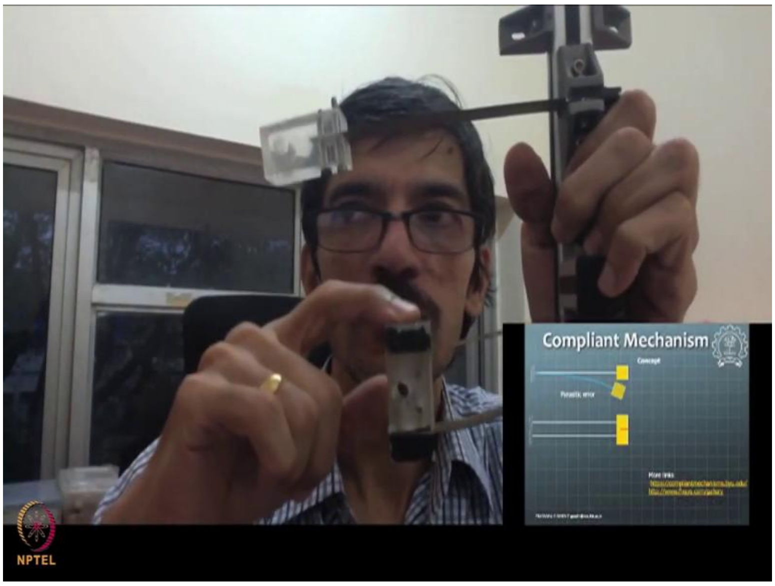

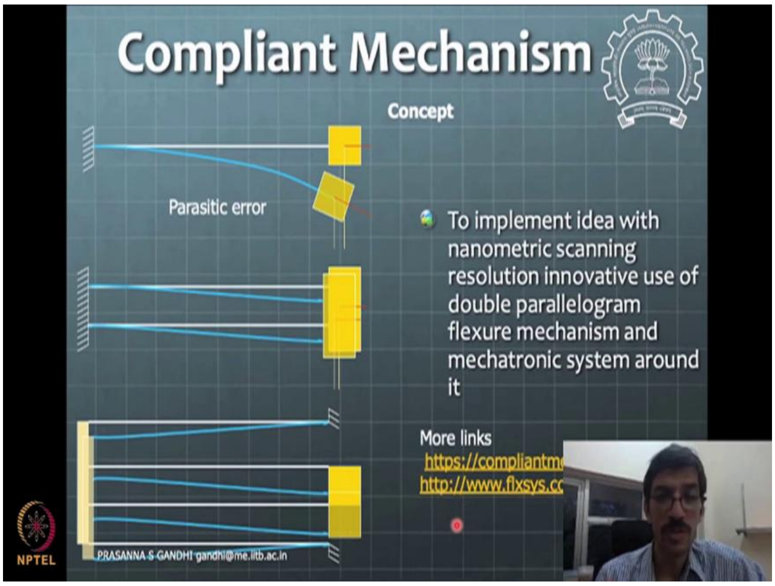

So, you have this. So, you have these two elements here. So, this is one of the single element bending and now you have these two elements, we can see that where this bend it is moving to itself maybe I can change the, we can see that this moves in a way that the block is moving parallel to itself. But if you see on the, carefully here on the slides here you see that there is a parasitic deformation in the other direction. So, there is some axial motion that is happening here this unwanted deformations are called parasitic errors here.

So, to prevent that, you introduce one more such a system, like this. So, you have introduced now two additional beams here and this stage is additional stage here, this is a moving platform. Remember here it was a fixed wall, but now this is a moving platform here and the fixed ends are up here. These are the ends which are fixed to the wall somewhere here.

Now, if you imagine if this would have been fixed exactly the motion that you have seen earlier these that motion happens would have happened. So, and then now, if you just imagine that this block is not there only this block is there then if I give a force which is same force that was there here, then I will get deformation in the same way as was happening for this block, but in the opposite direction.

The parasitic error that is produced will be in opposite direction, the deformation is in the same direction, in the same downward direction, but the parasitic error that will be produced, the parasitic error in this case is going to be in this direction, but when you move this block down only without having this block, then the parasitic reproduce will be in opposite direction.

Now, when I see this in combination that this block is applied a force the reaction force is transmitted here which will deform these two outer beams. So, that give this deformation in such a way that this block is now having some parasitic error motion, which is compensating the parasitic error of this block. And that is why this block will move completely in the straight line that you can see up here.

So, this is a mechanism where you can see that, let me get it here clearly. So, see this, you can see there is 4 beams here 1, 2, 3 and 4, and then, you see this block is moving in exactly straight line. You can put a pen here and see draw it on a paper, and you will see that this motion is did this in a straight-line fashion because this block is absorbing that parasitic error.

So, like that you can have a compliant mechanism design and as you can see that actually this keeps on vibrating, keeps on vibrating a lot. If I give it permission it keeps on vibrating and for long duration and this block is made up of material called beryllium copper, which is having a high fatigue strength material.

So, this is how one can get perfect straight-line motion here and this can be utilized in our lot of mechatronic systems for a straight-line motion which is nanometric accuracy and now a little bit bigger scale than our CD-ROM drives.

So, CD-ROM drive has this principle only up to up to this point. So, CD-ROM drive did not have this parasitic error compensation. So, there will be parasitic error in the CD-ROM drive case a little bit, but it is okay that it will not bother if you see carefully this kind of error will not bother any functioning of the CD-ROM drive application.

So, this is the main concept for having a linear motion with compliant mechanism and there can be a lot of these possibilities many, many different compliant mechanism possibility could be there.

And nowadays, because we can 3D print devices, we can print these mechanisms very easily in polymer material for example. Metal is still difficult, but now with EDM and other processes, you can cut them in the metal, but with the 3D printing very interesting mechanisms can be readily printed in plastic material if that is okay for whatever application you are trying to drive.

So, you can see some more links of compliant mechanisms here and get yourself a little bit more familiar with them, so that you can think whether you want to use them later in your project or in any other application in the future you might be considering.

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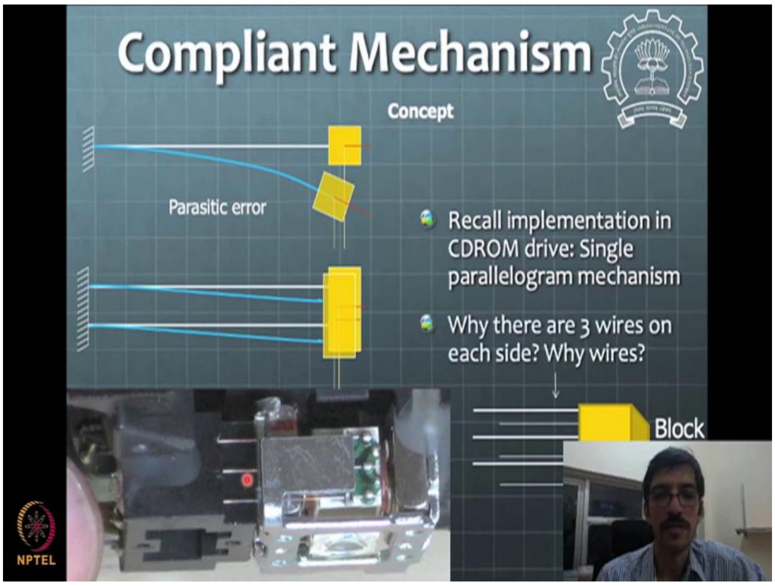

So, we have this concept seen for CD-ROM drive that is again I maybe showing the picture here. So, this same concept as we had for this block up to this point, that is acting here, when this force is given, you had seen when we deform this, these beams undergo some kind of a deformation. So, just to recall you the same case is there in the CD-ROM drive.

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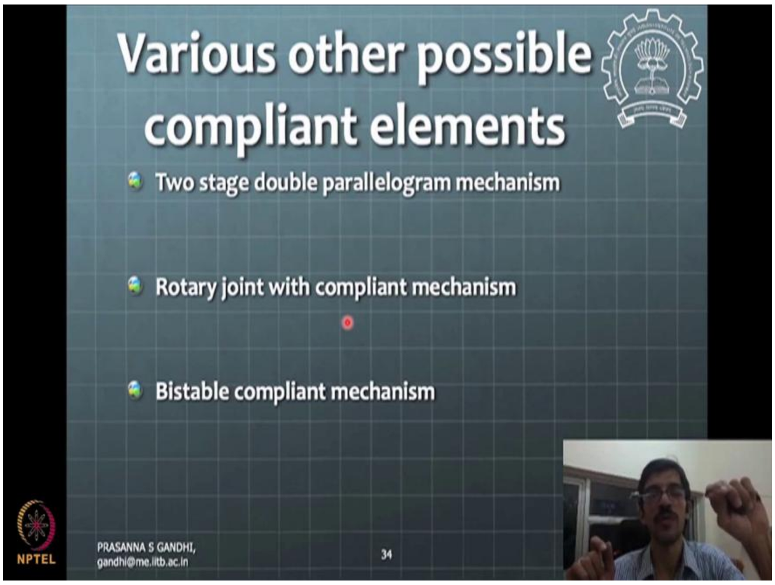

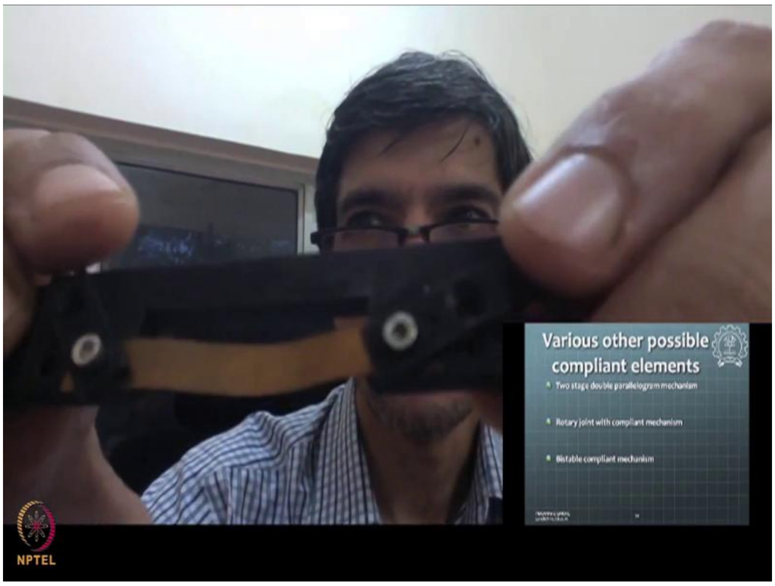

Now, there are many different kinds of other possibilities. So, you can have a two-stage compliant mechanism. So, this two-stage double parallelogram mechanism or you can have rotary joint with compliant mechanics. So, two stage means you have x stage motion possible and you have y stage in the same way.

You think about how this can be possible for having x stage motion and y stage motion in a similar the complainant elements are put in such a way that you have x stage motion also possible, for the same stage the y motion also is possible. See, one of the very easy ways is to say that okay my x stage is carrying my y stage and they are in the series.

And they are, whatever motion that happens for the x stage, the y stage motion would be, y mechanism is put in such a way that the motion produced by that y will be perpendicular to what the motion is produced by the x and the y stage is actually hosting or carrying the x mechanism, that is very easy to see. But if you want to have the same stage, but it is have a x and y motions possible in the same way as what we have for the single stage then it is a interesting case to think about. So, think about that and right now we will see if at all we have time we can discuss this little more.

Then you can have rotary joint with compliant mechanisms. This is little, I have shown you one a case, there are many different other cases for that can be possible one simple case is your cantilever. So, if you see this cantilever, this motion that is happening one can get a fit circle to this motion and say that center of that circle will be my virtual hinge point and that appears to be that.

So, it moves in a fashion that okay almost traces some small little circle here. Then you can have this bistable mechanic. This is very interesting case. You might have seen this mechanism. So, they are having 2 stable states. So let me again show this here. So can you all see these maybe I need to move. So, you can see that there is a beam which is here if I push it, it goes and make this click sound and goes down maybe I can bring it more closer here.

So, I can show you this beam, you can see this beam. So, if I push it, it is now bend like that I push it from this side it goes on the other side and make this click. So, it is moving these 2 stable positions. So, maybe I even show you in this angle. So, you push it, it goes that, push it that it goes down. And these are one position is circled down and one position is circled up like that.

So, these are the positions in which it will go. Yeah, you can see that these are the bistable mechanism system they are stable in 2 positions, but middle position is not stable. And they are very good for switches. So, switching application you can, actually some of our home switches does have these, but they do not have the beams there but they are spring based compliant mechanical systems are there they are springs based but not really this beam based. So the spring gets 2 position so that is why your switch at home that has these two toggle positions, you switch off toggle sits in that position. And, you switch on and it toggles and switch into. That is again, that is a bistable compliant mechanic. So, they find a lot of usages in our day-to-day system as well.

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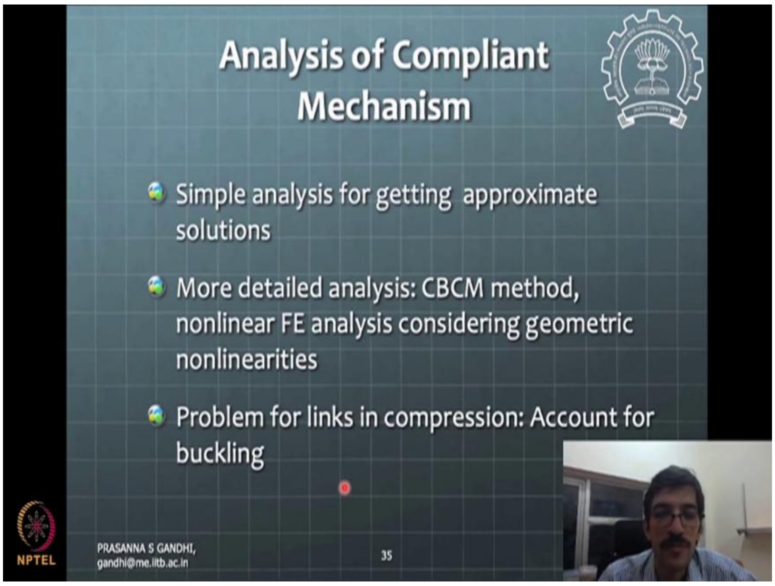

So, we will see a little bit on the analysis of a simple analysis for getting these approximate solutions for these compliant mechanisms for the small deformation, why approximate solution because they are on the small deformation cases. So, I will tell about, little bit broader scope of this analysis and study and then, we can focus on just getting simple solution, by using whatever theory we know a little bit about Euler–Bernoulli beam theory we may apply it and see some simple cases.

And for more detailed analysis, you have this CBCM, constraint beam, this beam constraint model method or chain beam constraint model. So, this is very recent development in the literature, which we may not get into the details, but you need to say that okay there are a FE analysis techniques and there are some other simpler, this is computational little more efficient than FE analysis that is why this is good method in the literature very recently proposed.

Just to sensitize you that, there are a lot of these different analysis tools that are available out there one can use it if you want to do the analysis more. The simple analysis to get and then we can have a more detailed analysis. Then there is buckling is still an issue, there is not a lot of literature of buckled up beams and post buckled beam analysis and things like that. We will, so accounting for buckling is a tricky issue in this and there is some literature and there is some more literature that is to be explored, I mean it is coming some papers are coming in the area, post buckle beam vibrations and things like that.

Especially large deformation, large deformation, these problems are not yet solved. So, this analysis has a lot of rich shear possibility of different problems to be looked at and solved.

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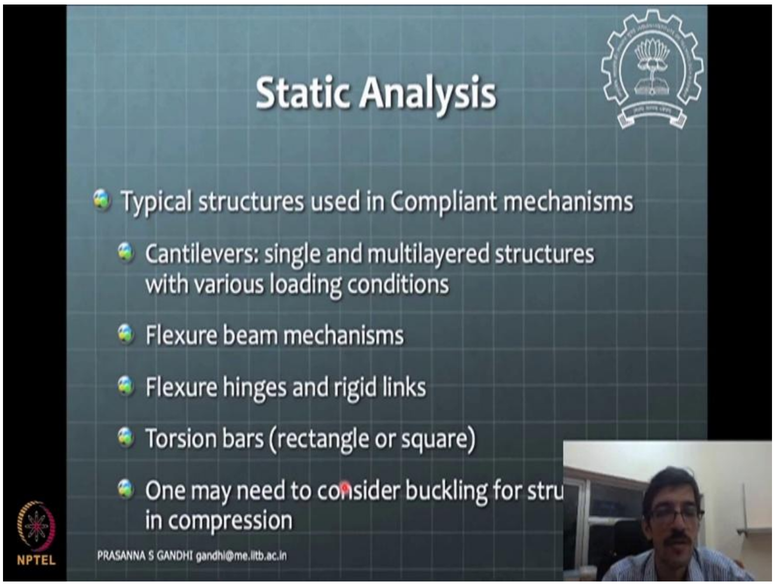

And analysis typically will be, structure that will be used in this analysis will be cantilever structures or with different boundary conditions, you can have multi layered structures and things like that, you can have flexure hinges which are rotary flexure joint. So, one can have some approximation done in modeling saying that, okay instead of cantilever I will model this as a, some torsion spring there, which is having center, some known center and then get up go ahead with the modeling and things like that.

So, there are a lot of these models people have proposed in literature and they are available.

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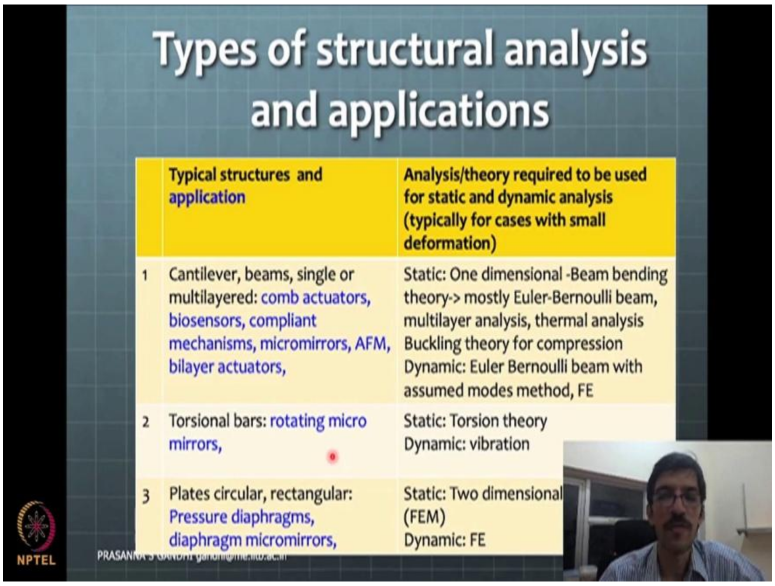

So, this is a table which captures some more what analysis and theory that is required to be used for static and dynamic analysis for different kind of cases that you have. So, for example, cantilever beams single or multi layered, those simple structures, you will do static analysis some beam bending theory, mostly Euler-Bernoulli beam bending theory with small deformation analysis.

Then you may have thermal analysis also possibility for the cases where you have expansion in a structure to be considered in addition. So, the thermo mechanical analysis one can do. Buckling theory, we can use for compression analysis and for dynamics again you can use Euler-Bernoulli beam with a simple something called assumed modes method. So, we may not be having time to go through this technique, but this technique is good for many control applications.

Of course, you can do FE analysis for dynamic analysis study, but FE modeling is not amenable many times for a good controllers to be developed based on the FE analysis alone, because that model becomes really, really many degrees of freedom model where assume modes method can be having only two or three degrees of freedom model can be produced with the assumed modes method, which will suffice for a lot of small deformation analysis of beams.

Then in the torsion you can have torsion theory static rotation of micro mirrors. So, these are some of the applications given here, comb actuators or biosensors, all these compliant mechanisms we talked about till the time we have small deformation analysis in micro mirrors with this attachment. So, AFM cantilever is there in AFM mechanism.

So, those things can be analyzed nicely with using simple Euler-Bernoulli beam theory. And then you can have a plates or rectangular or two dimensional compliant elements and you can have different ways of FE, typically FE way will be there for finite element method will be used for static analysis here. So, this is a way typically the structures will be analyzed.

We will not get into all these details, if you are interested in some more components of this, we can go through, but we will, some small analysis will focus on Euler-Bernoulli beam analysis to get some kind of a flavour of some of the complaint mechanisms how one can apply such whatever the things that you have done in Euler-Bernoulli beam theory.

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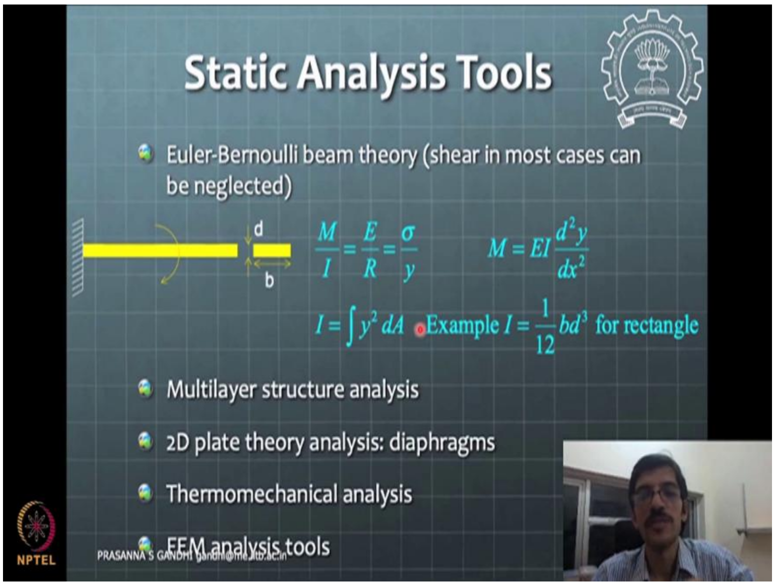

So, this is what we will do analysis by using Euler-Bernoulli beam. So, know all this formula, I am presuming that that this comes from Euler-Bernoulli analysis of, there are section remain plain, small deformations are the deformations are relatively small as compared to the length of the beam. There are no shear effects in the lengthwise direction of course, there is a shear in a cross section, shear forces there, but in the lengthwise direction there are no shear effects.

So, these are very what you say a lot of assumptions which are maybe working for small deformations only they are not really large deformations these kind of assumptions will not work. But people that do that to get some theoretical base to analyze at least small deformation cases very well and for large deformations one can build on this theory further to incorporate large deformation analysis.

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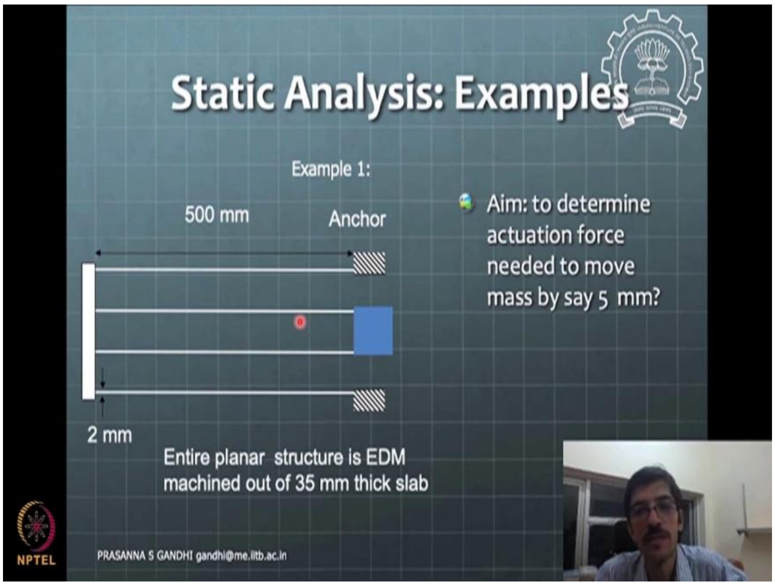

So, let us apply some of these Euler-Bernoulli beam techniques here. So, you are given this length to be say 500 mm and in thickness to be 2 mm and this is a machine out of 35 mm thick slab by using EDM process is what is given. That means, this you start off with the 35 mm thick block and you start cutting these blocks allowing these lines to get this material from here removed, so that you get finally this mechanism.

So, this material from here, here, and here is removed in some way and you get finally this mechanism to be in place. And so, the width of this beams here is going to be 35 mm. And your aim is to determine say some actuation force needed to move this mass by 5 mm and things like that. So, you can think about here pause here and think about, how will you apply that Euler-Bernoulli formula here to see how do you get this deformation.

So, one can think of, what are the boundary conditions for the formula to apply and what is the moment that will be coming on the system. Either you can work with a moment or you can work with a shear force, either way is going to be giving you the same thing. Only thing in you need to make sure that you consider the boundary conditions really, really well. So, I would say you can think about this analysis and do some stuff, I mean, I think these are good, it will be good if this is done and then we discuss it more than right now whatever doubts you have can be clarified much better.

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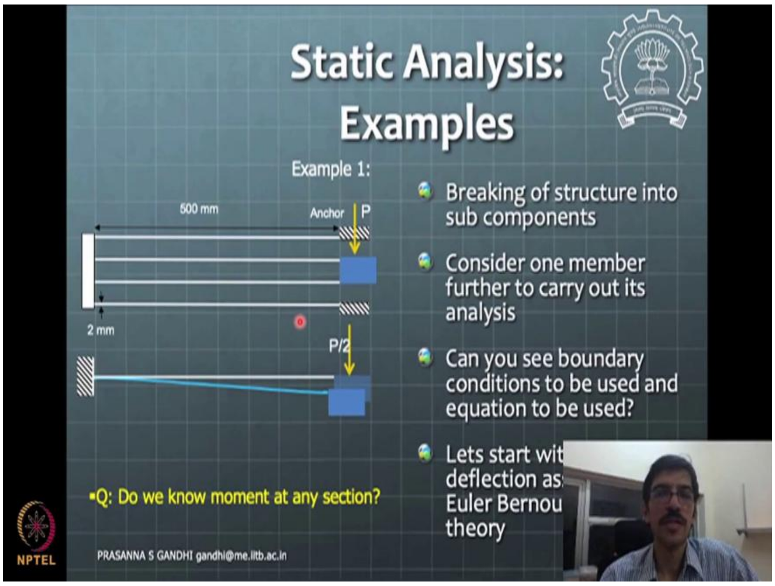

So, I have given some guideline here to see and you do not look at these slides, unless you have done something on your own and got stuck somewhere or you have got solution also then no problem, then you can have a look at and check whether your solution in these matches or what you have missed. So, this is what is the exercise that you would do.