Compliant Mechanisms: Principles and Design
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Lecture – 66
Summary of the course

Hello. Bearing case studies, 6 case studies it will discuss in the 12th week of this course we have come to the end of the course. So, after this lecture we will have six more which will be case studies of six different applications or devices that we will discuss in somewhat detail one in each lecture.

So, today let us recall or recapitulate what we have learnt in this course. So, it is like a summary of the course and let see what we learnt about our compliant mechanisms.

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Let us see what we have covered. We covered little bit of history. So starting from the very early on the history it is not like the historic books more like 50s and 60s, 60s is when people started thinking about compliant mechanisms we did that. And then we did mobility analysis, that is what is the degree of freedom the complaint mechanisms has, it is clearly not infinite we emphasized. And we tried to see from structural perceptive as well as rigid body linkage perspective how to marry the two concepts which something I have tried to do throughout the course. Compliant mechanisms sit between the two extremes, we did that mobility analysis. And then we took up the deformation analysis that is, displacement deformation stress strain whichever way we want to call. Basically elastic deformation analysis we discussed that in a few different ways.

And then we discussed a number of design techniques, that is will be specific we covered six different techniques for designing compliant mechanisms. And then we also discussed somewhat can be called principles or finer details pertaining to compliant mechanisms. And we also had covered various applications of compliant mechanisms throughout this course. And then we also are going to consider after this lecture six different case study, so you get an idea of how we can put all these things together to design some real compliant mechanisms for real applications.

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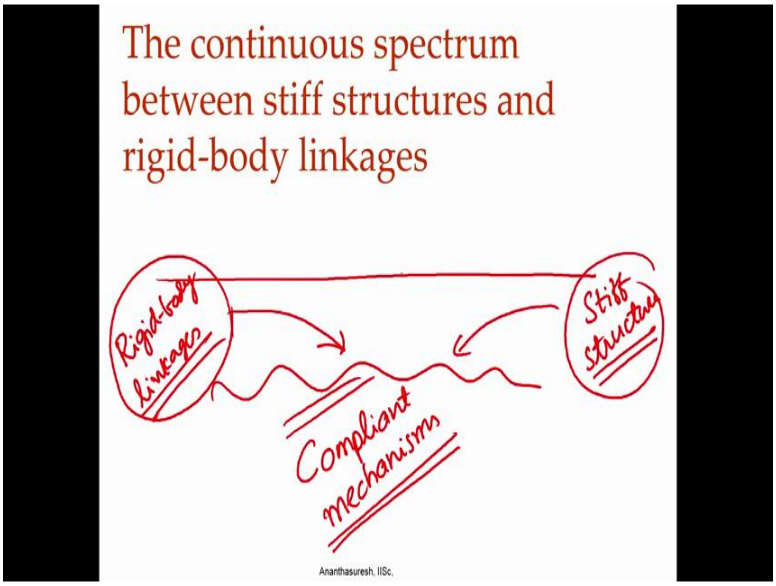

So, the first thing we should note which is the emphasis of this course is that if I say that there is a continuous spectrum one end are occupied by rigid body linkages, and the other end is occupied by stiff structures. So, we have this entire space in between which occupied by compliant mechanisms. And we had said right at the outset that compliant mechanisms are straddled between these two extremes; they bear the loads stiff structures, they support the loads. Rigid body linkages transmit force motion and energy. Compliant mechanisms can do both and you can have flexibility and strength together in them.

So, you have rigid body linkages are very very flexible because they have joints, stiff structures are very stiff, and hence we can call them actually even rigid. But now compliant mechanisms combine both of these. So, we have the advantage of learning from both and apply that to compliant mechanisms and then see how the entire spectrum between these two extremes is covered.

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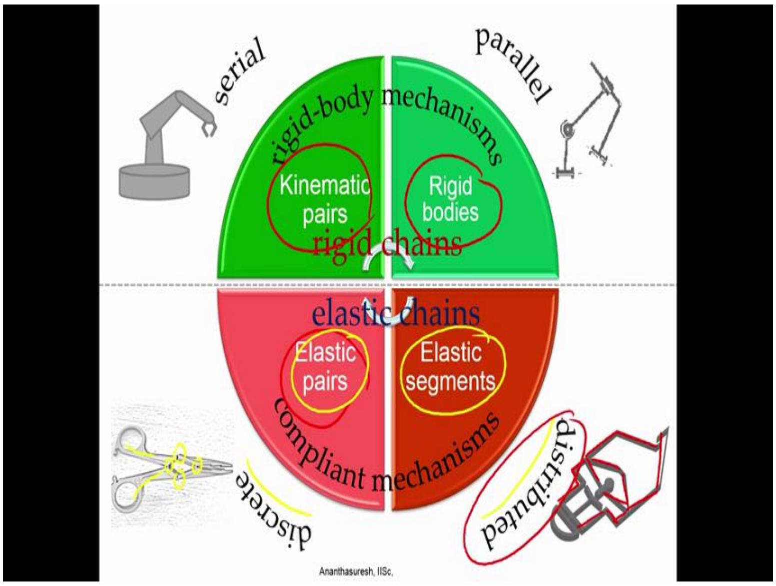

And we also took this view that there are rigid chains, meaning that there are serial robots and parallel robots and close loop mechanisms. They have kinematic pairs connecting the rigid bodies to get rigid body mechanisms.

Whereas, compliant mechanisms have elastic pairs and elastic segments; so we have this elastic pairs and elastic segments to make what we can call elastic chains. There is a four steps here, there is a contact period compliant mechanism which has distributed compliance as opposed to discrete compliance. So, that is how we could do view, otherwise everything is the same. Here also there are relatively rigid portions and then these elastic pairs or joints and here there are flexible beams that endow the motion and force and energy transmission capability here.

So, we can use either one and use rigid bodies segments whenever we need and try to make interesting things. But compliant mechanisms have to have at least one elastic formal element to be called a compliant mechanism, but most often the all the advantage of compliant mechanisms come through when we make a fully compliant and that to a distributed compliant mechanism.

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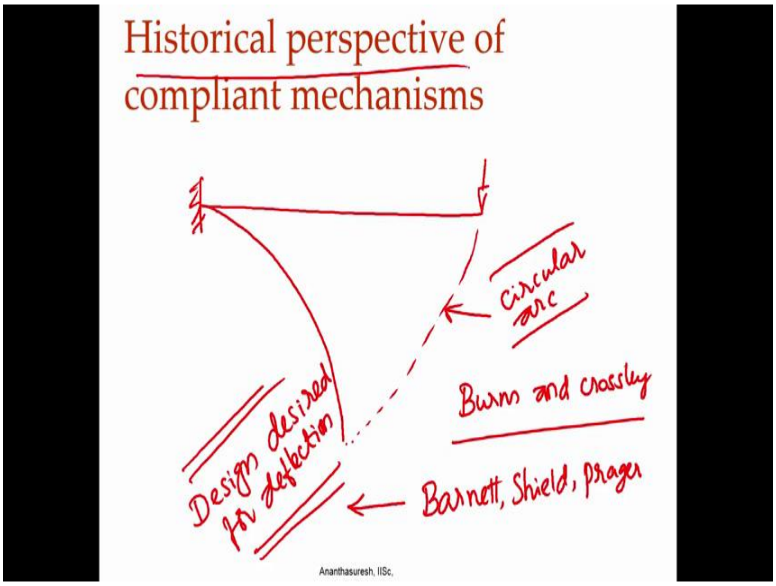

So, what is the historical perspective here? Historic perspective is that in order to design mechanisms instead of relying only on rigid body segments using elastic formation when did the thought process start. People have been using like ancient archers bow and catapult. These are all examples of ancient compliant mechanisms which people have used in various ways. In fact if you look carefully there may be a few examples so that people have used, but modern engineering practice has been emphasizing rigid body mechanisms and not compliant design until recently.

So, if you look back in 50s and 60s people had looked at compliant mechanisms and notably Bishop and Decker had done the analysis of the cantilever beam under very large displacement, Fishwick has an entire book on large deformation analysis. And then we also had Burns and Crossley actually extracting or abstracting the behavior of a cantilever beam and observing that; a cantilever beam when there is a load at the tip when it deforms they observed that the locus of this is close to a circular arc.

And that was a remarkable observation if that they had a overly synthesis method this is Burns and Crossley, and that is kind of the early history. And then we also had looked at Barnett a civil engineer and Shield and Prager and Chan and others. So, where they had looked at design for deflection, so basically to see that who wanted to make structures deform intentionally. So, that is the design for deflection. In the past who wanted to make things intentionally flexible. So, Burns and Crossley did that and then Barnettt

Shield and Prager had even developed design methods for designing things to be flexible so that there is a prescribed deflection, designed for desired or prescribed deflection.

So, that is the historical perspective we need to before that there is not much evidence, there was instances but there were no systematic treatment to design compliant mechanisms that have a flexibility requirement, a deflection requirement that is what we did.

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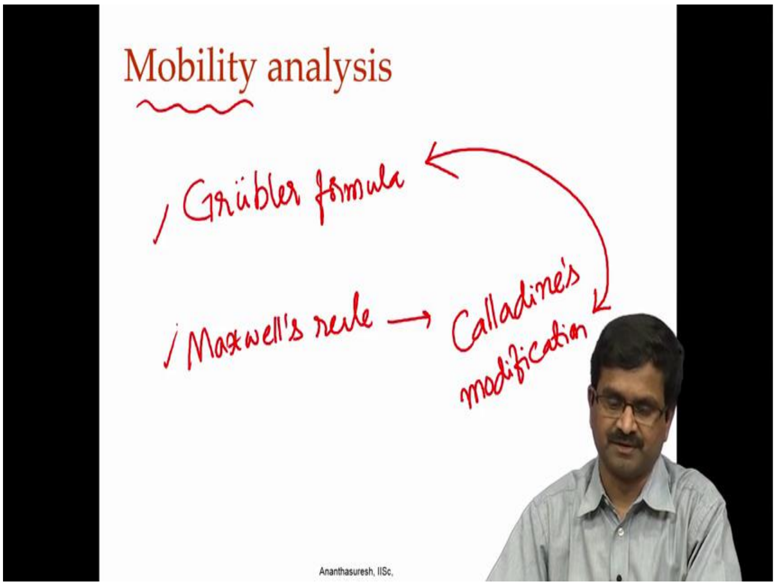

And then we took up this mobility analysis, just to clarify that compliant mechanisms are in this intermediate space between rigid body linkages and structures. So, both structures and rigid body mechanism people worry about mobility. Rigid body mechanisms people worry about mobility because, the number of degrees of freedom is equal to the number of actual it has required. Structures people worry about it because they want to basically have something that rigid that is there is 0 mobility. But then they worry about what are called states of self stress; that is when they assemble a structure if there is stress sometimes it is beneficial most of the times it is not beneficial, so you have to worry about the constraints.

So there was Maxwell's rule, there was Grubler's formula we put them together it will be considered compliant mechanism mobility analysis. We have Grubler's formula that we discuss in kinematics, and then there is this Maxwell's rule that he used to analyze structures. And there is a modification of this by Calladine which we considered in the context of states of self stress; Calladine's modification, he is Civil Engineer Professor at University of Cambridge and we connected these two. To say that: the states of self stress and degrees of freedom are both given by in a way either Maxwell's rule or Grubler's formula.

So, we also discussed how do we do this when there is a case where Grubler's formula Maxwell's rule fail when there are special geometric conditions or special symmetries in the mechanisms. We discussed a numerical way of doing that as well. So, mobility analysis is where we combine the structural approach in rigid body linkages to have a uniform thing for compliant mechanisms. Compliant mechanisms can be generalized to rigid body linkages or two stiff structures both are possible over here.

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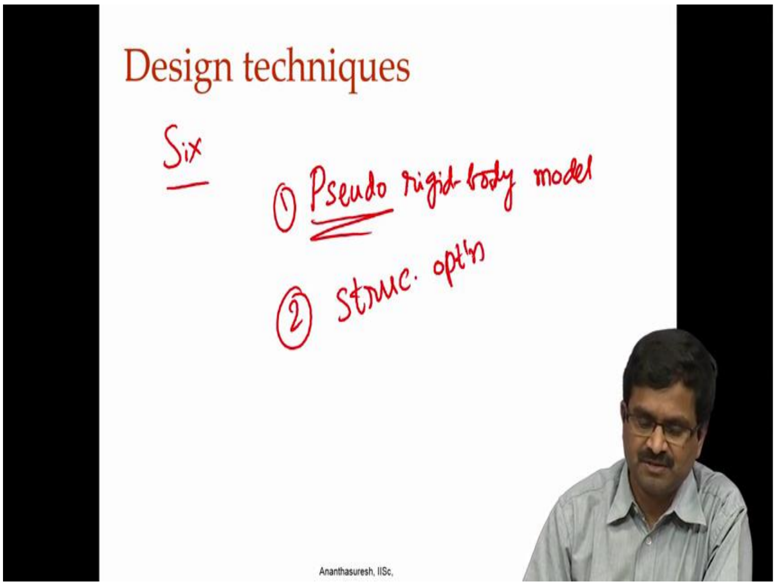

And then we consider deformation analysis also. So, deformation analysis well there is finite element analysis and there is large displacement beam analysis (Refer Time: 10:57) elliptical integrals for a elastic similarity and a few other techniques that we discussed here. And the number of design techniques we discussed; six different techniques. Starting from the linkage synthesis based where we had what is called pseudo rigid body model for compliant mechanisms. Where we model a compliant mechanism whether it is partially compliant or fully compliant to make the rigid body linkage and add springs to it that is where the word pseudo it is not rigid really it is a pseudo rigid we put springs and try to do that; that was one technique.

And then we used structural optimization technique to design compliant mechanisms, and then four other techniques that we discussed.

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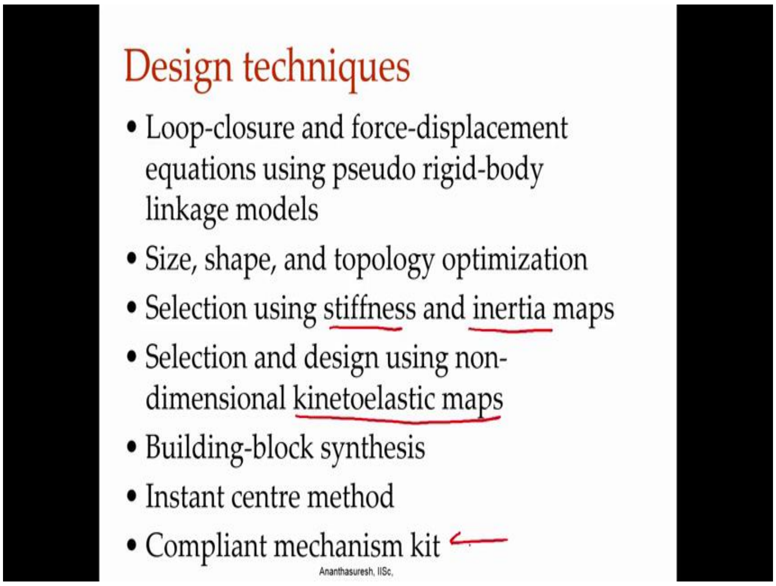

So, all the things are here. So, in the case of pseudo rigid body model we have loop-closure equations, kinematic equations and then force-displacement equations put together for the pseudo rigid body model uses enough equations to solve for the unknowns. So, that is one technique. And then we discussed the size, shape, and topology optimization. And we also discussed the selection using stiffness and inertia maps. Stiffness maps for statics and both stiffness and inertia maps for dynamic applications where you have a database of compliant mechanisms the database we shared in one of the lectures with you in this course.

We also have the selection and design using non-dimensional another set of maps called kinetoelastic maps. That is another design technique we discussed. And then we had this building block synthesis where you can take different building blocks and make up compliant mechanism, we also had the instant centre and we also had a compliant mechanism kit like a (Refer Time: 13:08) you can do this. We discussed even if we discount this as a design technique, we have six different techniques that we discussed.

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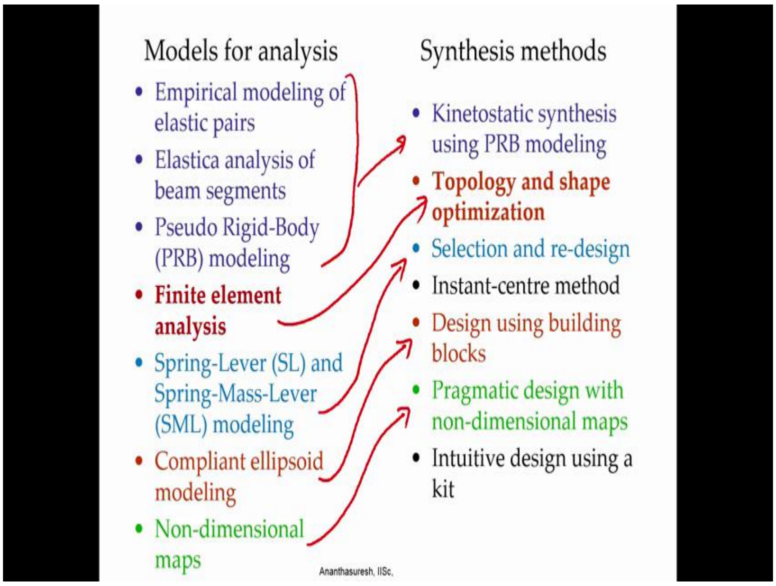

And we also said that for every design technique there is a corresponding analysis model. As can be seen here which is colour coded you this empirical modeling with elastic pairs, elastic analysis that large disc analysis of Bishop and Decker and Fishwick. And the pseudo body model and their corresponding synthesis technique. Finite element analysis, we have that spring-lever model spring-mass lever model we have the selection and redesign using stiffness inertia maps, when compliant ellipsoid for building block synthesis and non-dimensional maps for this pragmatic way of just designing from non-dimensional maps the kinetoelastic maps. So, we have all these models and then design techniques we discussed all of these in detail.

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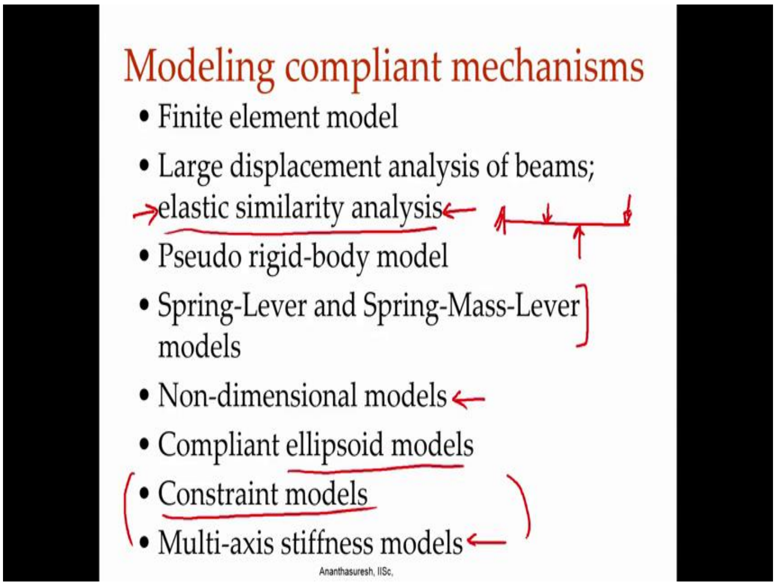

And it is important to remember the different modeling that we use for compliant mechanisms. One of course, is finite element method that is you know given. Any solid modeling software can generate the model and then you can take it to finite element software you can analyze you can do elastic or deformation analysis. But, that alone is not enough we said, so we have to gain insight into compliant mechanisms number of times that we need that insight.

So, we also discussed this large displacement analysis of beams and in that specifically the elastic similarity analysis. The elastic similarity analysis enables us to, if there is a load that is easy, but what if there is another load here or another load here. So, we discussed the geometrical interpretation of elliptical integrals there is a parameter called phi and we discussed this also. There is actually a lot more to be done here if we revisit this technique, a very powerful technique this elastic similarity analysis.

And then of course, we discussed the pseudo rigid body model and how it can be used in analysis as well as synthesis. And we discussed spring lever and spring mass lever models with which we can actually select a mechanism database using the stiffness and inertia maps. And also we will discuss the mechanical advantage; this became useful to talk about the sensitivity of the mechanical advantage to the work piece stiffness. So, spring-mass lever model or spring-lever model helps in more ways than just designing.

So, you get some insight non-dimensional model for a compliant mechanism captures the essence of compliant mechanism all it is characteristics whether it is static or dynamic can be captured here. And one can know about a particular compliant mechanism by just looking at these kinetoelasto elastic maps.

And then ellipsoid models that is also very powerful technique to talk about stiffness and compliance; how it varies in different directions for a compliant mechanism. Design of compliance is all about how you constrain the stiffness so that when you apply forces it will deform the way you want. That is the essence of any machine design technique. Basically, you want when one or two actuations are applied your machine will move the way you want that is exactly what we want to do with compliant mechanisms also. You have to get the stiffness designed in such a way that when we apply forces it will move the way you want. And that is what these ellipsoid models help you do that, where you can take building blocks and assemble.

And we also, well we did not discuss it something called constraint models. It is somewhat similar to this multi axis stiffness that we discussed in the context of the beginning of the course. We wanted to say that elastic pairs are nothing but they have high flexibility in one direction, very high stiffness other directions, later on when we came to non-dimensional models again this multi axis stiffness came how did we non-dimensionalize this. So, there are techniques where people use this multi axis stiffness models as well as constraint models to make the mechanism move in certain direction by pre posing these constraints using elastic segments. We did not discuss that whether a few design techniques along those lines, where they use screw theory and this constraint based synthesis

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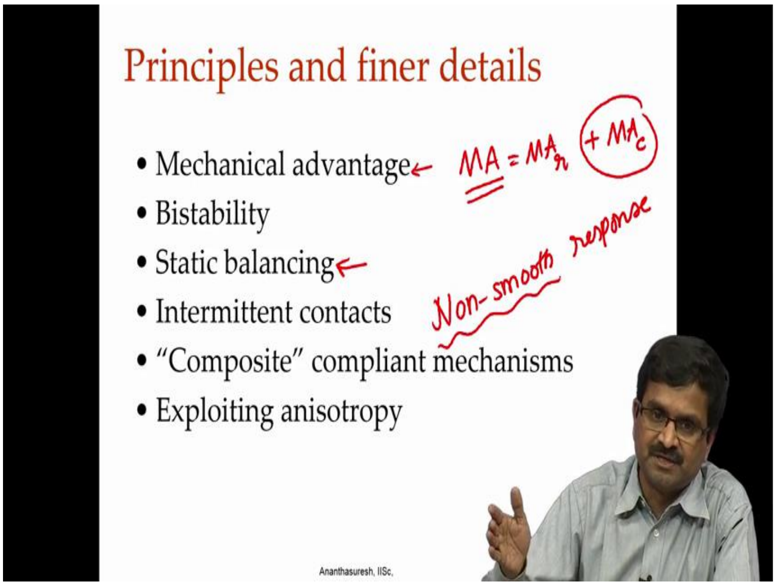

What are the principles in finite details that we discussed? Mechanical advantage and mechanical efficiency is important aspect we discussed a very few types of mechanical advantage and how mechanical advantage varies with the work piece stiffness. And that is the most important aspect and we also thought that this discuss that mechanical advantage has a rigid or kinematic part and there is a compliant or elastic part.

And usually we said it is negative, but if you preload it and do something clever we can actually make this positive so that mechanical advantage compliant mechanism can be higher than it is equivalent rigid body linkage. That would be game aim here because complaint mechanisms have lot of advantages, but we do not want to lose out on mechanical advantage efficiency because, part of the input energy has to be used to deform the compliant mechanism. That loss is necessary evil we do not want to yield to that there are ways to overcome that.

And then we talked about bistable compliant mechanisms. Bistability, bimodal bistability, multi stability all of those things are very non-linear force displacement characteristic is non-linear and number of applications are there in it, very interesting phenomena that we discussed. We also did the static balancing. This also goes back to the mechanical advantage and what drawback compliant mechanisms have. We remove the drawback by doing static balancing. Similarly one can do dynamic balancing which we did not discuss.

Static balancing we did discuss in three lectures. How to balance them so that you can treat compliant mechanism as a spring and use rigid body linkage or to a compliant mechanism you add extra segments or zero free length springs to make it statically balanced. So, that is something that we discussed which is important to make efficiency or mechanical advantage compliant mechanisms remain high or as high as possible rigid body linkages.

We discussed intermittent contacts how it can give non-smooth response from smooth input. This is also an interesting extension of compliant mechanisms to achieve non-smooth response from smooth input without having any control or anything. So, that is one thing that we discussed. And then we also discussed this composite meaning more than one compliant can be put together it will still be single piece compliant mechanism, but very complicated functionality can be obtained. And with smart materials which we did not discuss in this course we can actually make them work with this smart materials which themselves are somewhat compliant and interesting things can be done with that.

Also we discussed how people are trying to exploit an isotropy of materials now to get interest in compliant mechanisms that are not complicated in terms of topology shape or size, but they are complicated in terms of materials. So, as a designer you have control over two sets of variables: one is geometry other is materials. Geometry we discussed a lot, but now if you have interesting materials you can also do interesting compliant mechanisms.

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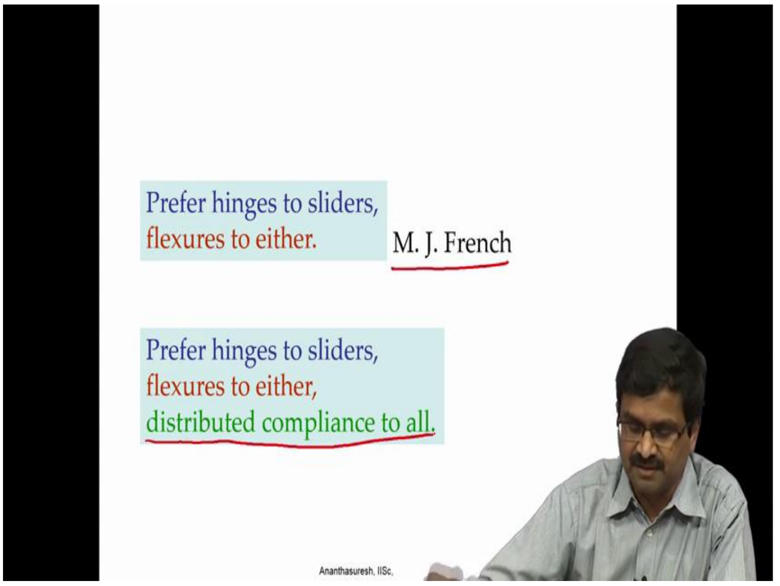

So, one principle is that Michael French we said that at the beginning of the course had said prefer hinges to sliders and flexures to either; meaning that he was in favor of flexures, flexures meaning elastic pairs. We extended that this green line is highest where we say distributed compliance to all, that is you do not use hinges sliders flexures just make everything distributed compliance slender beams or slender shells. So, one can make these many varieties of compliant mechanisms.

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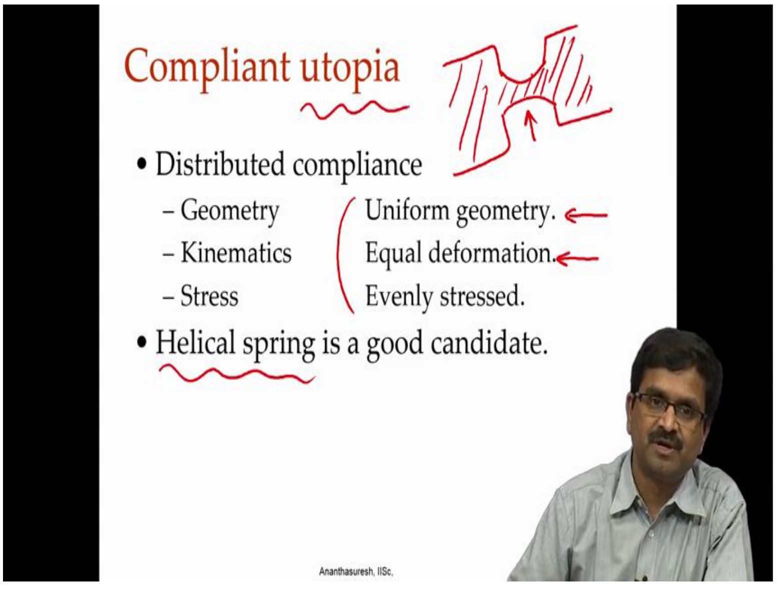

We also talked about how do you characterize distributed compliance. We said that it should have uniform geometry manufacturing becomes easy things give you confidence when you look at it. When you have narrow flexures like that with the relative rigid parts your eyes will always be on this that is going to break; that is going to break even if you well design. Of course, the range of motion will be limited when you use this you know flexures.

So, what we want to have is distributed compliant mechanisms where the geometry is more or less uniform or some variable width profile or thickness profile. And whatever that is your deformation should be more or less equal throughout the mechanism. So, it should not be that one thing rotates a lot and other things do not, that is what happens in rigid body linkages. Rigid bodies do not deform there is no relative motion between two points, but where the joints are there that is what gives is the motion. We do not want that, we want equal deformation everywhere.

And then stress strain should be evenly distributed. And we said that helical compression spring has all these characteristics. If there is a compliant mechanism that has these characteristics then that is a truly distributed compliant mechanism what we can call the perfect world or utopia of compliant mechanisms.

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And we discussed a number of applications over the course. Many of them are consumer products or by stable shampoo bottle legs and the little hair clips and lots of things are there and boxes, plastic boxes; the consumer products are many. But we also discussed maybe not explicitly a few of thing that we have discussed have automotive applications and there are aerospace applications including aircraft wings and so forth.

And biomedical we had looked at few surgical tools as well as heart valve replacement things. We did not discuss a node of surgical tools, but they have number of applications especially in terms of sterilization it is important to have compliant mechanisms. When you have rigid body joints there are clearances and sterilization becomes a problem whereas, here we can.

And then other one where we did not have specific lectures on this, but we have this precision mechanisms, because there is no backlash and fiction so you can get very precise motion precision mechanisms. So, a number of applications we have discussed, and finally micro systems because mineaturization will suffer if there is assembly involved of various parts to make a thing. So, in micro systems we want to have lithography just to know things coming out without assembly compliant mechanisms are perfect for it.

So, number of applications we have discussed throughout the course. What we will do now in the next week is consider six case studies. So, we understand how various things that we have learnt can be put to a practical application.

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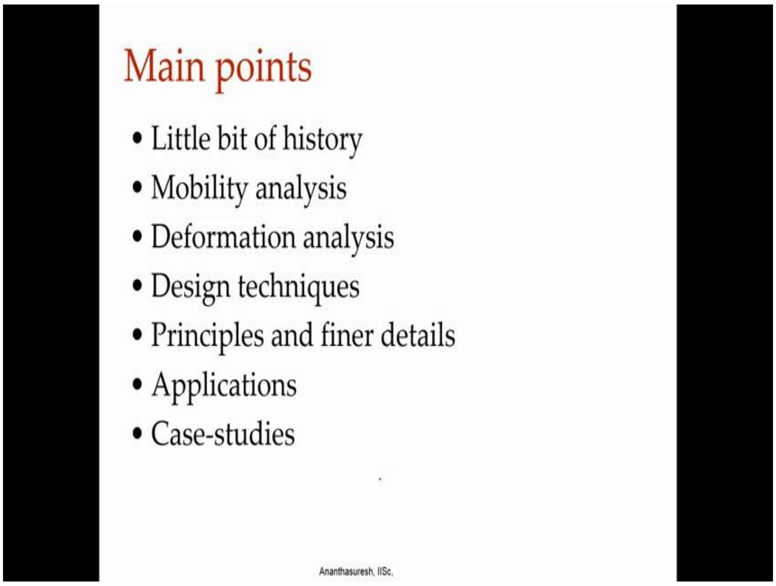

And the main points of this course again we discussed compliance in a historic perspective, discussed mobility analysis, deformation analysis, design techniques and some final details and applications. Now we will wrap up the course with this case-studies.

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Before I wrap up I would like to acknowledge all the students who have worked in my group at Indian Institute of Science, Bangalore. And all the sponsors you cannot read but if you really pause one the slide and look at people who have number of PhD students who are I have to take a pen. So, who have done their PhD thesis much of their work we have discussed and current students who have helped and also current project assistants some of them are sitting through these courses and helping a lot. And number of project assistants, they are all master students and private staff, and also my collaborators who are all here and administrative assistants so there. And I should also mention Deepika; M S Deepika and I do not know where her name in this I will write because she is the one who actually took a lot of pain to create our database that we showed one day. And Ravi Kumar his name is here and Ramu.

So, these are the people who have made a number of prototypes for us. So, all these people have contributed to whatever we discussed in these 12 weeks of lectures.

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And I will end with the note that robots are on the rise now. So, that is where people are talking now about other compliant robotics or soft robotics. I think that is one of the directions to go where robots have been. As you can see in this picture itself they are more than human; they are rigid and then joint we can see on this. They are not actually looking at making it compliance.

So, our imagination even a dog here is shown like a rigid thing and everything is there, but that is not how nature is. Nature as we go down to small sizes everything is compliant. And the virtues of compliant design are now appreciated because of various compliant mechanism researches working over almost two and half decades, last one have decades. Now robotics people are rather people are working on now are turning to make robots also compliant.

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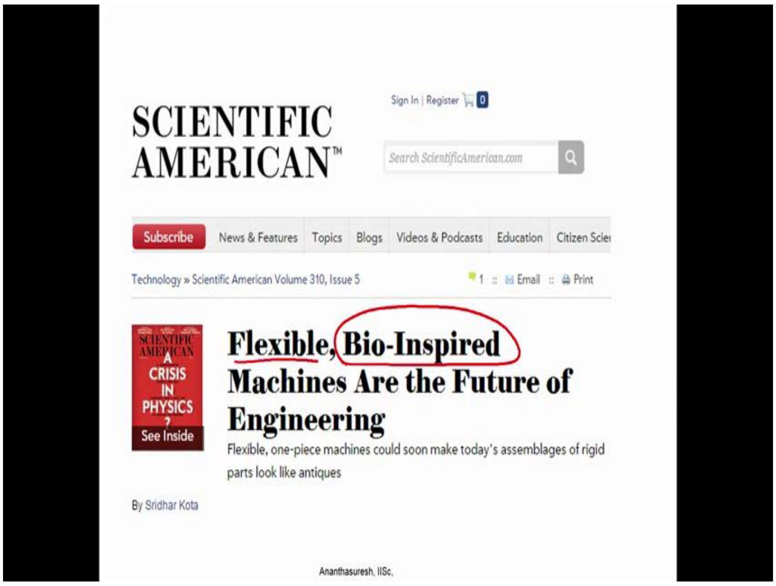

In one of the lectures we have discussed this scientific American article making flexible bio inspired that was also that are compliance mechanisms these machines are the future of engineering that is what this article calls.

So, let us end this on the note saying that those people who are watching this course will take this course, this concept of compliant design to robotics and traditional mechanisms also. So, we take advantage of compliant design which is also going to be strong and stiff as and when it is needed.

Thank you.