Compliant Mechanisms: Principles and Design
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Lecture- 52
Comparative analysis of different methods for designing compliant mechanisms

Hello, this week we have been discussing design methods, in fact for the past few weeks we have been discussing the design methods that are developed for compliant mechanisms. We have discussed six different types of design methods; today we will compare all of them. In fact, will add one more which you had discussed earlier using a compliant mechanism kit that is another way to design intuitively by comparing all of these, one gets a chance to discuss the proves and cons of each method. So, that for a given application the user can choose the appropriate design method for designing compliant mechanisms; so it is a comparative analysis that will do today.

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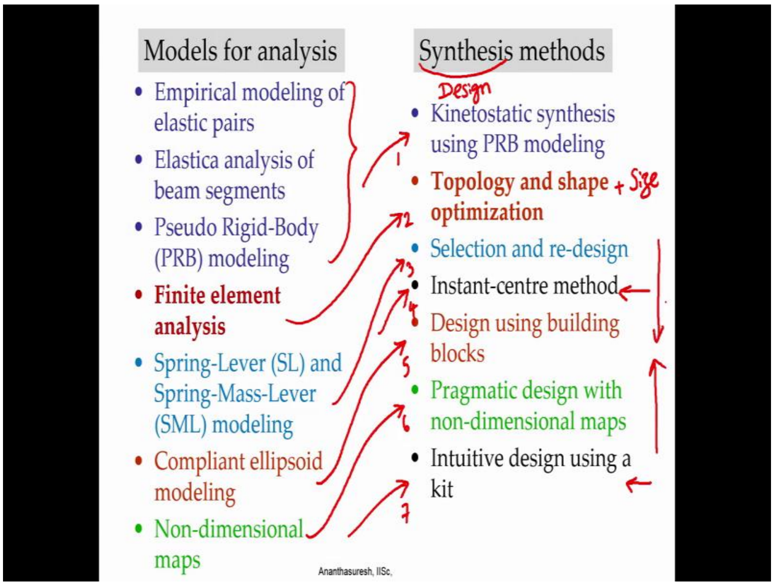

So, we first summarize all the methods that we had discussed, so this is done in a way that we can see in order to have a synthesis method are design methods. So, here synthesis and design we use them as synonyms, so designing is creating something that is not there that is exactly what synthesis is. So, here we call in them synthesis methods there design methods nevertheless. So for each design method a particular model for analysis should be there because compliant mechanics are entities, for that matter any entity if you want to design, if you want to do it systematically you would need to have a way of analyzing them that is away of evaluating their performance.

So, corresponding to each synthesis method there is a model and that is what this slide captures and they are color coded, if you see the first three models of analysis that is empirical modeling of elastic pairs and the large displacement analyze using elastic and this pseudo rigid body model, these three give us a design method which is shown here, which is kinetostatic synthesis using pseudo rigid body modeling. So, where we use empirical modeling of elastic pairs meaning narrow sections which behave like joints, but they are joints which some stiffness. So, that is one model that we had discussed and then we had discussed large displacement analysis as well where the beams under go very large displacement and rotations.

And for that we had discussed the (Refer Time: 02:53) base solution and based on these two and some incites that where obtained in the old papers, we have the pseudo rigid body modeling which is a link between rigid body linkage synthesis methods and compliant mechanism synthesis methods. So, that there is a model there actually three models and compared to that we have a design method. Now if you go to the next one, we have finite element analysis which is a model for analyzing de-formable structures and compliant mechanisms are such deformable structures, related to that we have in the frame work of structural optimization we have things for topology and shape optimization I should also add plus size also or parameter.

So, for all of those things we have a model which is finite element analysis. One can also use boundary element method, but mostly finite element analysis is used a farm widely used. So, there is a model there is a corresponding design method and then we also discussed this selection and the re design method where we had used a database of compliant mechanisms out of which we can select something. So, for that also we had used a model, if you recall we had discussed spring lever models or SL models and spring mass lever models SML models. So, SL models were used for static analysis SML models are used for dynamic analysis and now we can use this SL and SML models and also develop a design methods which is based on selection from a database and also modifying the one that is closest to the requirements, we can actually redesign that and an act database to database become richer.

So, that was that design method also needed a model and then we recently also discussed this concept of compliant ellipsoid modeling or stiffness ellipsoid modeling and then there was a transfer force concept that we had discussed in the last lecture. So, all of those models for analysis now become amenable for design and that was design using the building blocks and little before that we had also discussed this non dimensional maps from which we could develop a design technique which was what you called up pragmatic method meaning that you can consider not just the main functionality of motion and force and energy transmission are the kinematic functional requirements.

In addition to that we can also look at stiffness and strength and buckling and natural frequency and so forth again using a database we could use this non dimensional maps then we can go across the length scale; that is it can be a macro one as big as a an aircraft wing and as small as micro or nano scale structures or even (Refer Time: 06:16) as we had mentioned once, so for all of those things is non dimensional analysis the really helps.

So, we have the six different models and then we have six different methods that we took. So, now we also had discussed along the way a an intuitive design method using what is called a kit, so we had that also and I left out this instant centre method because there was no corresponding model for it, which a concept instant centre method is a concept that is very well known in the kinematics literature based on that intuitive design methods; design method and intuitive design using a kit is something that is prevalent for making structures we borrow that and use it for compliant mechanism also.

So, in a way if we include the instant centre method also we have seven different design methods. So, we have so many; one may ask which one do I use for a given situation and that is why we do this comparative analysis to see what is positive about a method what is not so good about a method and basically analyze the strength and weakness of each method and let us do that in the reverse order that we have here this order going this way but we will go the other way, so starting with the intuitive design which we are already seen.

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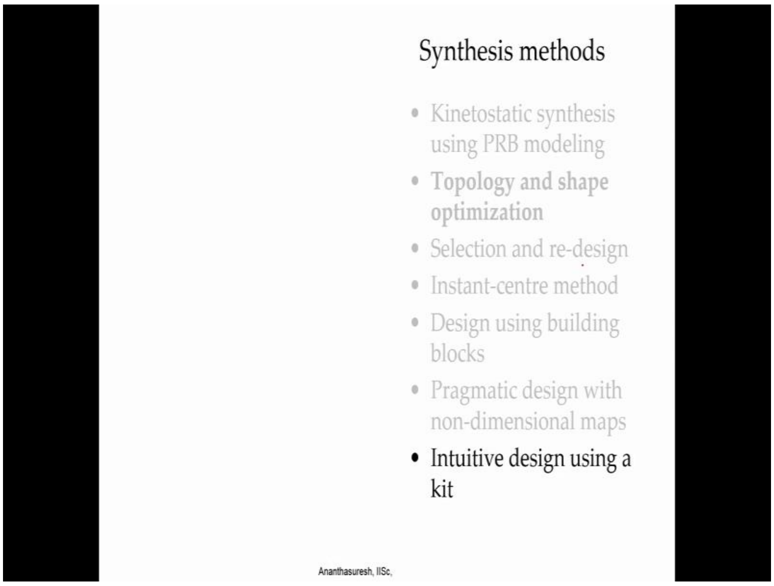

So, we can look at that intuitive design using a kit of parts which has a two types there are beams and there are connectors.

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So, let us watch this one minute video where it will become clear as to have it could be done.

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So, you have this connectors and you have this beams; you can stick them in different directions and they will be tight lag snap fits and you can bend them once in a while and put them together and it will act like a real compliant mechanism. So, now we are using symmetry here making two parts, now input output, you fix where you want and go ahead and do this.

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So, it is a functionally similar to the compliant mechanism that is shown over here, so continuing.

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So, this is something that assembled using the kit, various beams and see how it moves when you make a device out of it.

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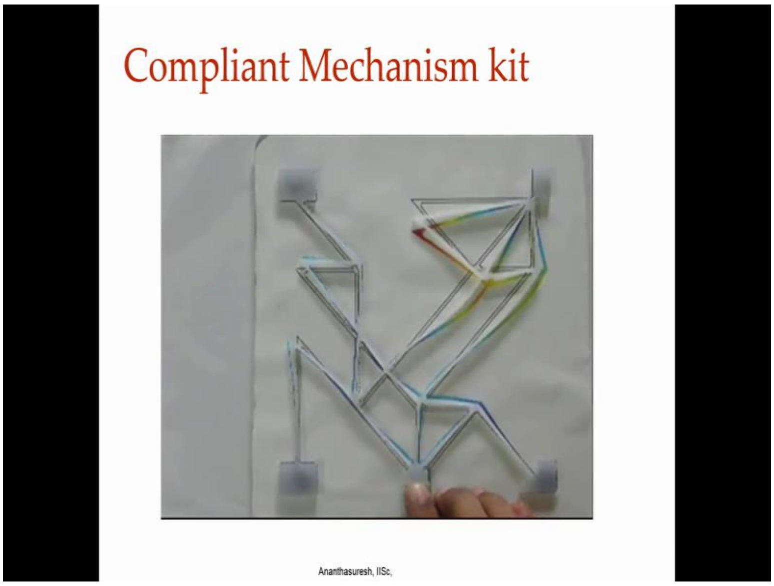

It will more exactly the same way like it is shown it is a c n c mild proto type, it also moves exactly the same way what see the color one is finite element analysis, large displace finite element analysis.

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And these actually bistable, once you give a kit what people you could do is something that is left to their imagination, it is a bistable leading edge of aero foil and these a trailing edge.

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So, it is preloaded while assembling itself you can go work constant have a state and that is a very nice thing for this things.

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Some are these are described in this mechanism machine theory paper that we are already discussed.

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So, this is one way to design is somebody has intuition to do it.

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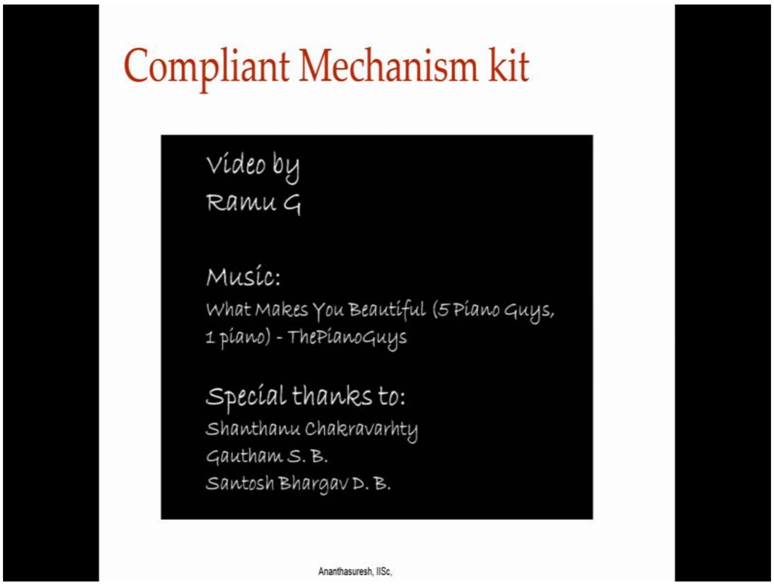

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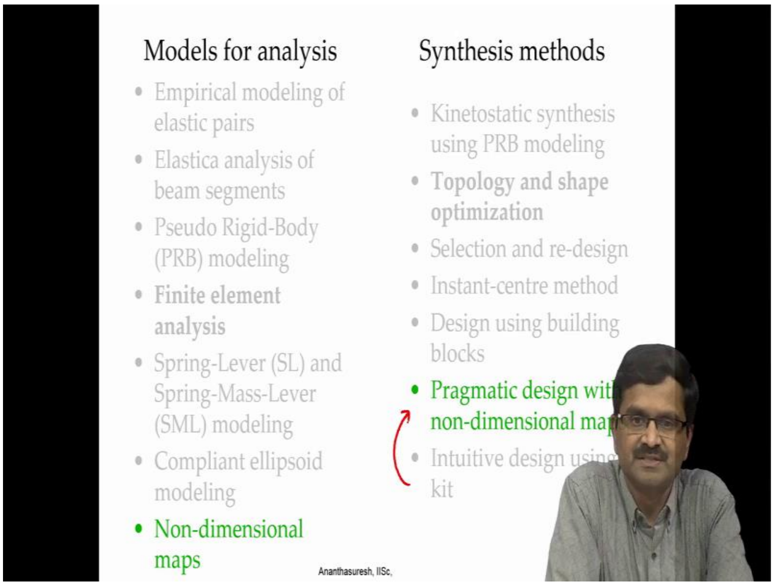

Now, let us look at another method going from again from bottom to top, so we go to this one which we called it pragmatic because a number of things can be take into account here.

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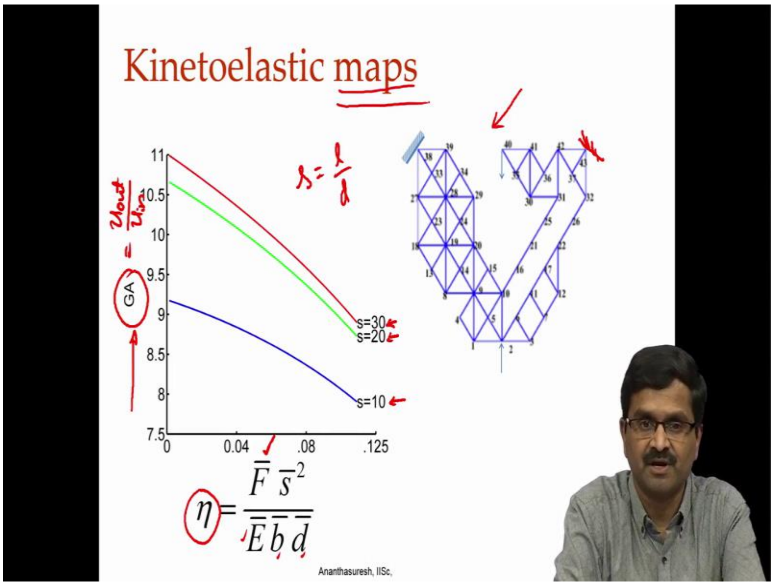

For this the model was we needed to have this kinetoelastic maps, we had discussed that this non-dimensional quantity which emerged from cantilevered beam analysis and then undergoing large displacements, where we noticed that, if you parameterize in terms of this slenderness ratio as many non-dimensional quantities here what is shown is a geometric advantage that is u out; u out; output displacement divided by u n; for different allies of s we can draw this curves.

And this non dimensional performance quantity can be anything that one wants, it can be maximum stress in the structure, it can be natural frequency, it can be multi axial stiffness as we had discussed at length. Area of those can be put their and for different values of s if you plot them against eta then you actually see what are the limits of the particular compliant mechanism are particular topology.

Here if you have compliant mechanism with this topology, if you keep the proportions constant then these curves will be there and depending on what force you have and what as you would choose and what material you choose, what cross section dimensions you have; you can choose the appropriate mechanism by the way here; s is l by d, a characteristic length of the compliant mechanism and d is the depth or characteristic depth of all the beams segment that are there in the compliant mechanism. So for these things you can look at the charts understand this one has 11, it does not have more than 11, unless you increase the value of s and once you choose a particular s how does it change as you vary force, it will tell you what rate it drops and all the information is here.

If you have such a map for a number of compliant mechanisms which exist now and 100, one can easily have. In our lab we have about 85 and some more coming, so when you have all of those in these maps you look at it, you can actually design very easily and these are non-dimensional, so when go across the scales, but only thing is here you have to select a mechanism from a database, so this does not all of you to create new, but even if you have a new one, you can draw these maps and learn more about that particular compliant mechanism that you have, so this is one way of designing across length scales.

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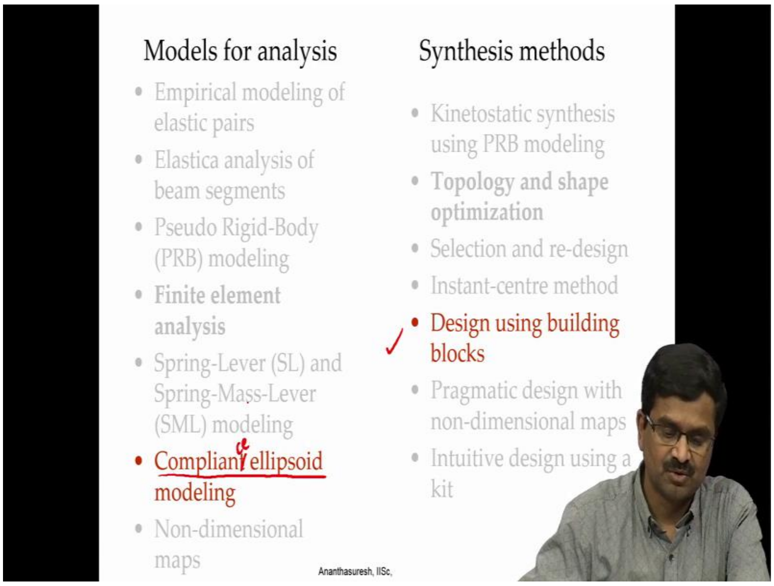

Moving on to the next one which is design using building blocks where we needed this concept of compliance ellipsoid.

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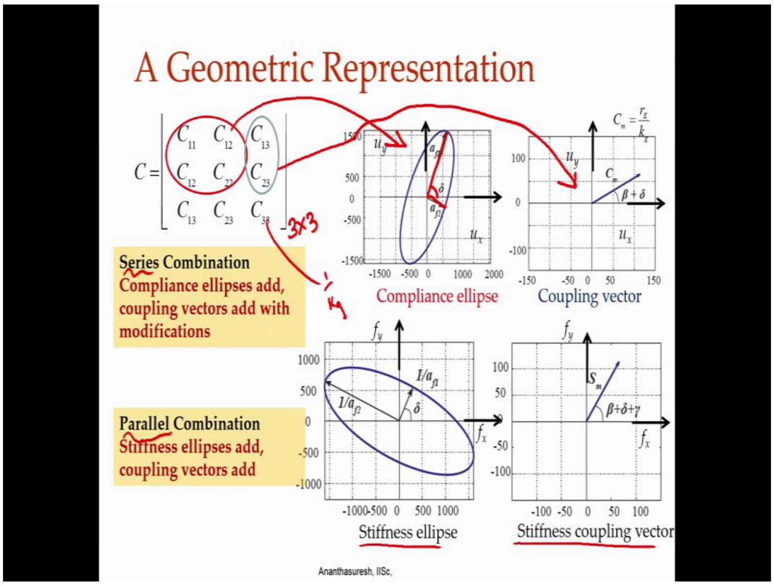

So, there we had talked about this in 2 d; 3 by 3 compliance matrix that relates wrenches and twists that is forces and displacements. So, each part this part gives those extreme compliance in the orthogonal directions on the orientation of that is given by this one and there is also coupling vector which defines the center of elasticity is given by that and then there is this rotational stiffness which is one over k g are that is see three threes one over k g and then we can similarly look at the stiffness ellipse also and stiffness coupling vector.

So when you have this concepts understood; then for different compliant segments where there is a complaints ellipse and stiffness; ellipse and coupling vector for both of them you can add them in series or parallel to make more complicated compliant mechanisms.

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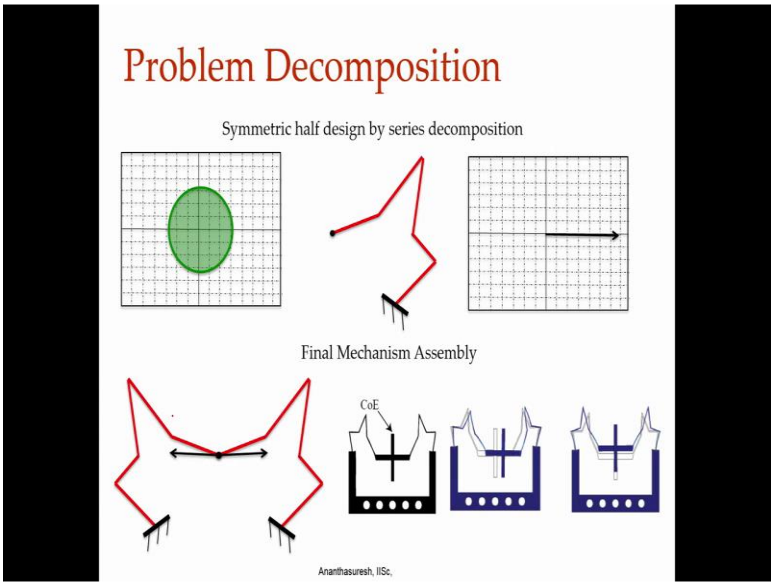

And you had seen in example where we look at this complaints ellipsoid are in this 2 d case ellipse on the coupling vector and if the target is something until it comes we keep on adding and then see that for doing something like this, you would need a lot of intuition because you should know how to add these elements one by one.

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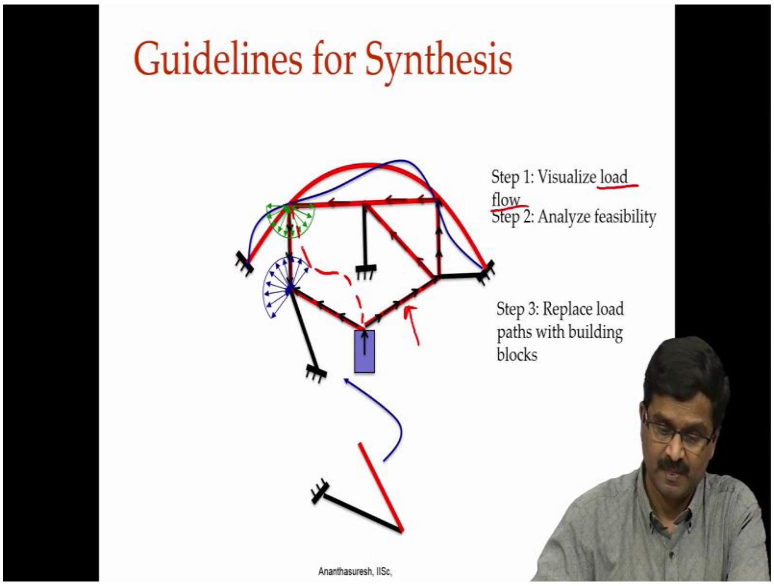

So, let us I am here and I want to add the next one; I should know where to add, what direction, how long all of those should be there for the user and since interactive user may get experience with time, but these something that requires that kind of intuition in order to design using this method.

But generally product design when you decompose the functional requirements which you could do and then develop these methods and another one we had discussed recently is this load path method. So, we had to use the load flow or force flow and how we can get to this, again to predict this how this force flow or load pack is again you need to have intuition once you have it, you also need to have intuition as to if you want a particular load pack, what compliant segments will these suitable for let say I have I want a load path from here to here of this kind; I should know what segments, compliant segments will give me this particular load path. So, it is also very intuition base method and very powerful because you can do very interesting designs with this method.

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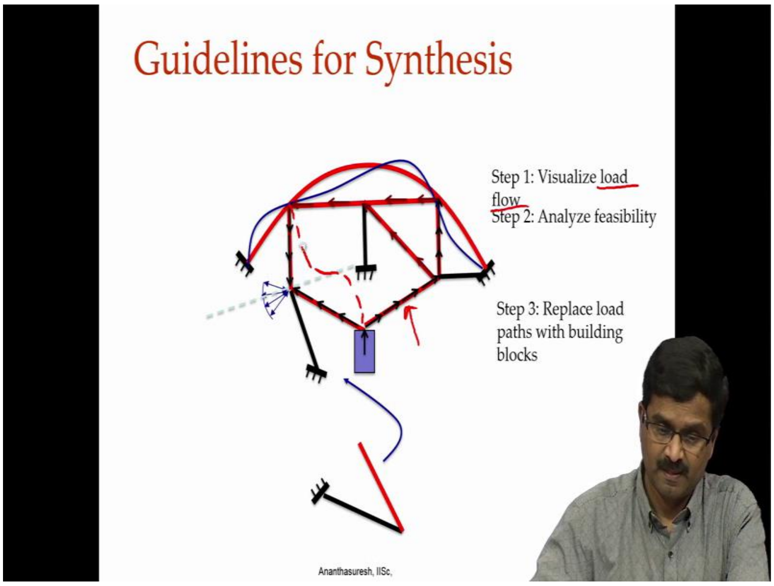

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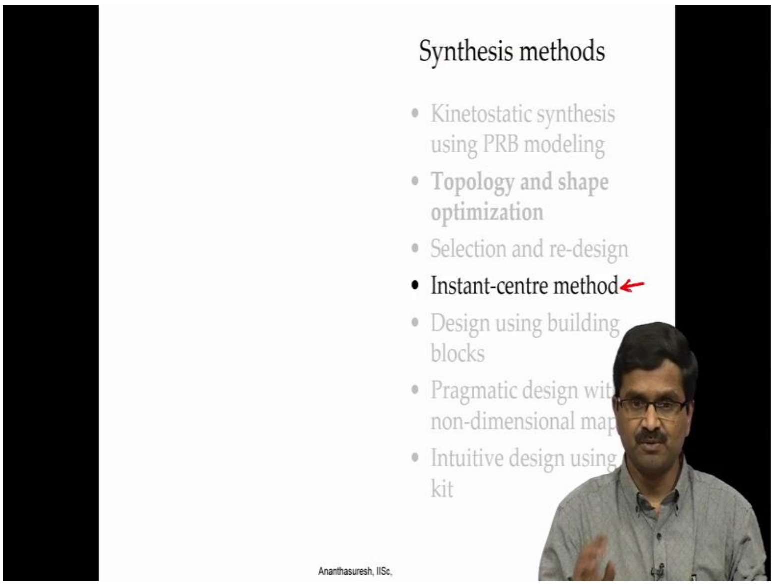

And now the instant centre method, which we had discussed is purely graphical method one can also do it with some numbers.

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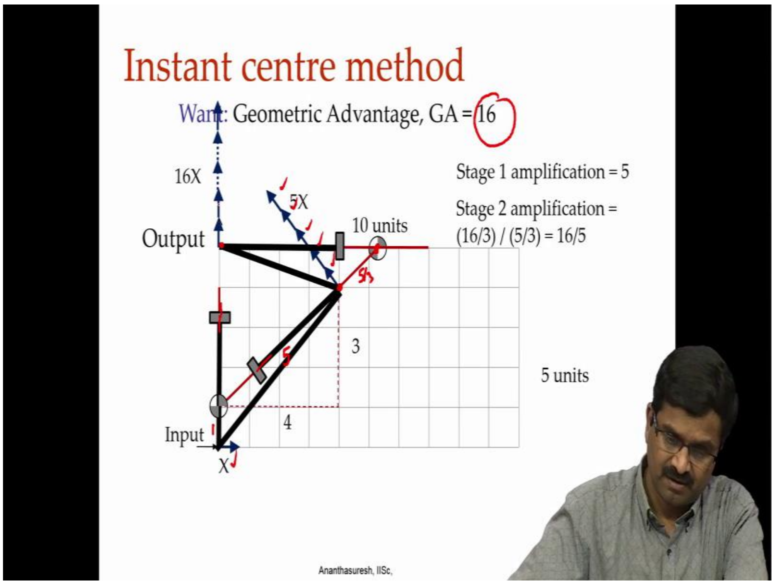

So, what with taken up was a problem where you have input and output, you have a target geometric advantage of 16 and it has to fit within this thing, you can actually do that for this proportions 10 units and five units. So, you could do that by choosing intermediate direction and find in the instant center between input and the intermediate point and that will give you because this is a instant center which moves by 1 unit, this will move by 5 units because this is 4 and this is 3 and that is by pythagoras theorem 5, so we can see that if this is 1 unit or 5 unit; that will move by 5 times.

And then we make up the mechanism where you fix this; does not really matter you can fix it anywhere on that line and then go to the next one because that gave you 5, if you want 16, we have 16 by 5 still. So, for this we extend the same line over there, we get the nu centroid or instant center not centroid; instant center and look at how much we get here. So, if you see this will turn out to be 5 by 3 that is from here to here, from here to here it is 16 by 3. So, we get the 16 amplification from here to there, so 16 by 5 and then 5 both of them can multiplied into sixteen, so we can make up the rest of the mechanism for it. So, have x at the input, 5 x over there and in 16 x in the output.

So in order to design using this method, again one it is to have intuition where it is very simple graphically, it is all instantaneous right at the time you can actually do this.

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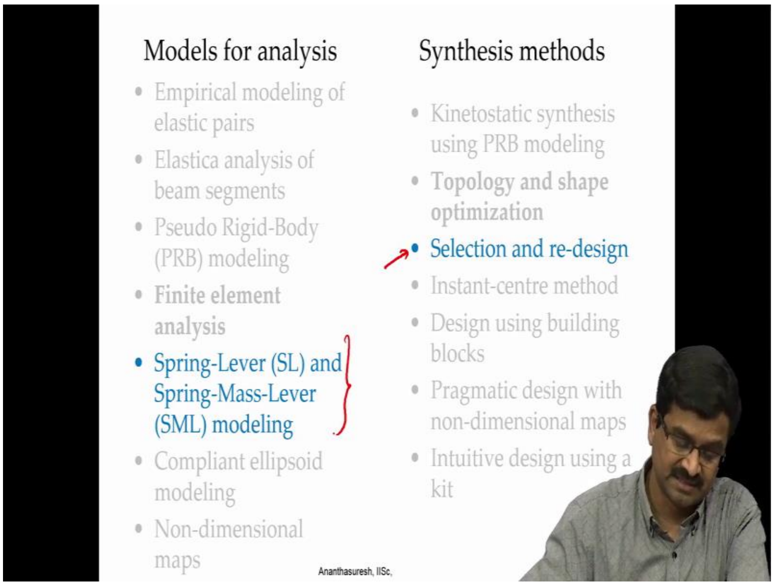

Moving on we also discuss this selection and redesign the corresponding SL and SML model.

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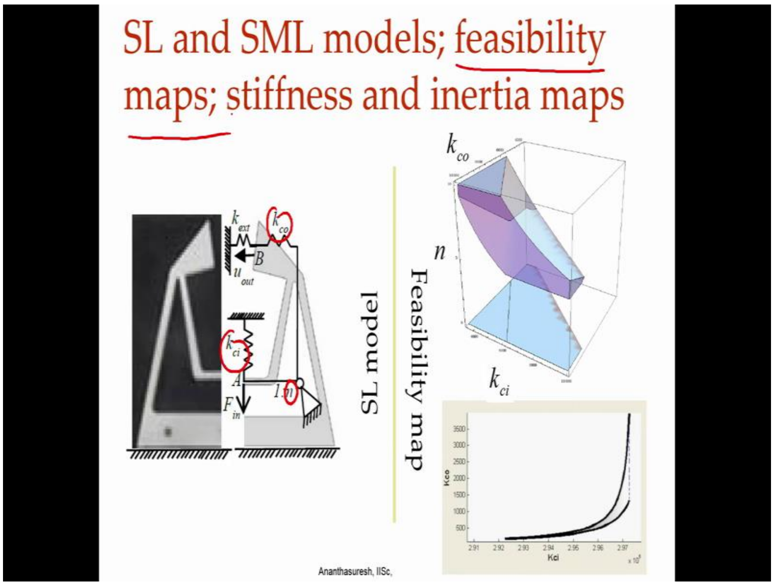

So, here a compliant mechanism is represented using a spring and lever model, we use lever here because the input and output there is usually an amplification or de amplification. So, we need to indicate it at a lever and we had said that there is a K ci and there is K co and there is inherent amplification between output and input which is n. So, these for statics and you can put mi m ci and m co that is inertia, so the input output site and that those 5 parameters will define a compliant mechanism and you can draw these maps which we called feasibility maps for given uses specifications.

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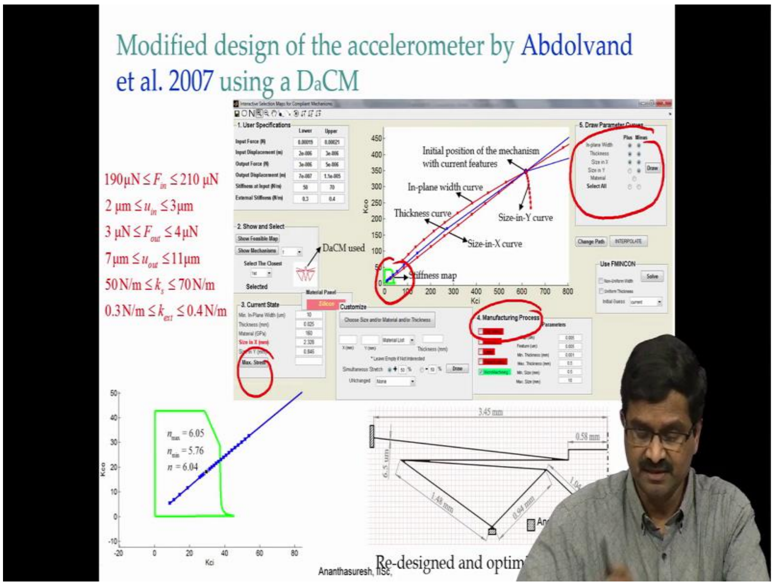

And will that need also demonstrated how to develop a software for doing this when user specifies the requirements with upper and over bounds on input force, input displacement, output force, output displacement and there is k a or k s which is the actual the stiffness and then k external which is (Refer Time: 19:48) work place.

Once we have those we can actually enter them, look at the feasible space in this case that little thing is the visible space then we also show the mechanism in the same plot and then we can choose the one that lie inside the feasibility map and also redesign if something is not inside the map and it has to be brought in there are ways to do that by looking at various parameters here and then varying them and it also takes into account the maximum stress any time we can check and manufacturer ability that is why it is a pragmatic method everything is taken into account in this method.

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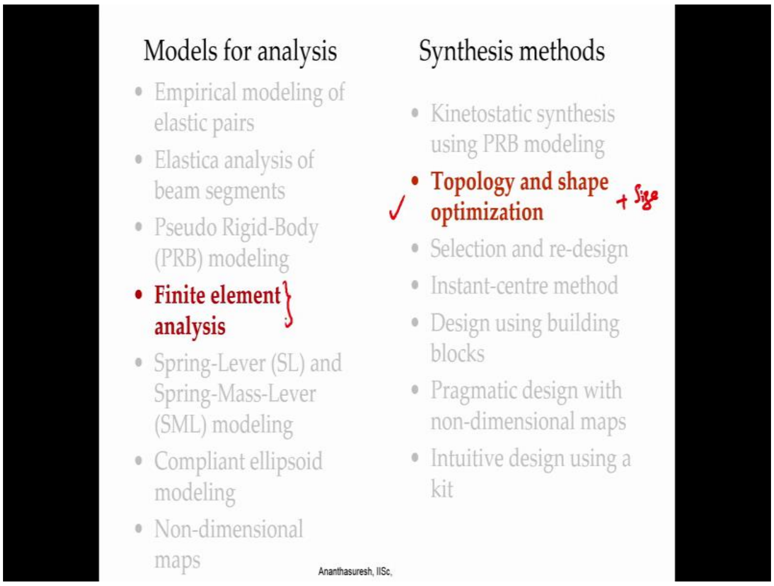

So, we could actually design the entire mechanism here then we move on to topology shape and size or parametric optimization for that finite element analysis is the truth.

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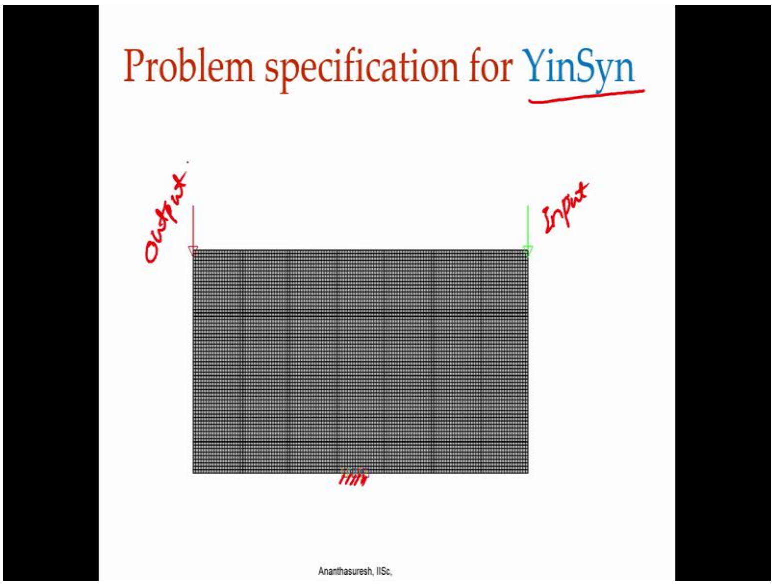

So, here we had looked at lot of theory and also solve some examples using this software called YinSyn which is (Refer Time: 20:54) software. If you apply input force over here and the expect output force over there, it gives you that; it only support here. In fact, it will try anything this program does give the reciprocal program developed by as it is as well.

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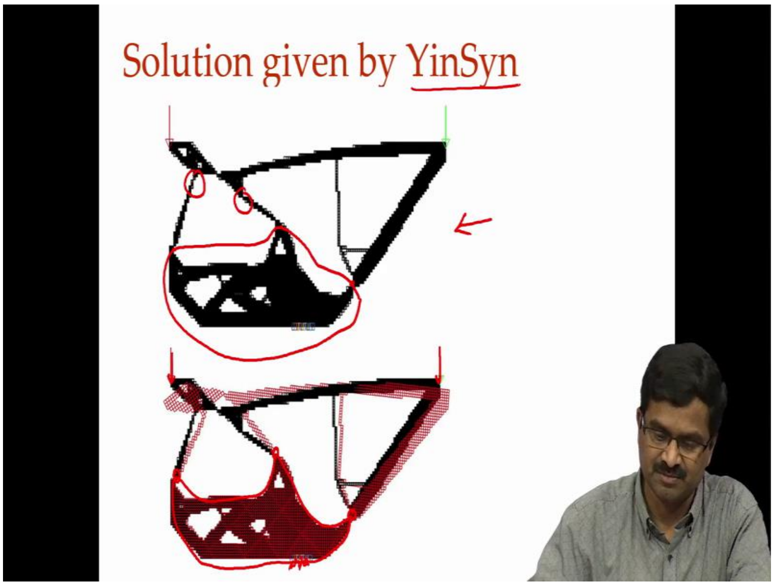

This particular one looks like this and it actually very cleverly made this all very rigid and took essentially the pre words little further from the fixed one here and the input and output. So, basically here what a user gives is nominal input and everything comes out that is strength of this method, so topology does not need to be assumed. But then you get this, what look like point flexures and that is a problem and sometimes manufactures could ability could also be an issue not with today's 3 d printing, but even with that we do not want to have very complicated things, it does tell you it; it gives you intuition, in fact, this is the method that gives you intuition that you do not they should will not have.

So, here we are saying that we fix it here and we have force applied, let us say at this point and we want displacement in this direction. If you say that it tells you; you first design a stiff part of it like that there is a stiff part with does not deform much and have more locations where you can actually fix such a thing, it tells you where to put those locations also tells you and it essentially as we had discussed it is basically 1 4 bar here another 4 bar eventually it can be interpreted like a linkage, we do not have to assume something, so that is strength of this method. But including strength consideration is natural frequency, buckling all of those become a little t d s; especially the manufacturability constrains become little involved with this method, it also takes a lot of effort for linear analysis there are method, there are software YinSyn is one of them.

But if you take large displacement, it is actually quite difficult to make this program to work for any situation. For linear there is no problem at all, you will also get a solution some a solution that is meaningful is solution that gives you some insight into the problem that one has on hand, but at the same time what you get might be very difficult to manufacture and all other considerations may not be easily met by this method this is one of the early methods that are there for compliant mechanisms.

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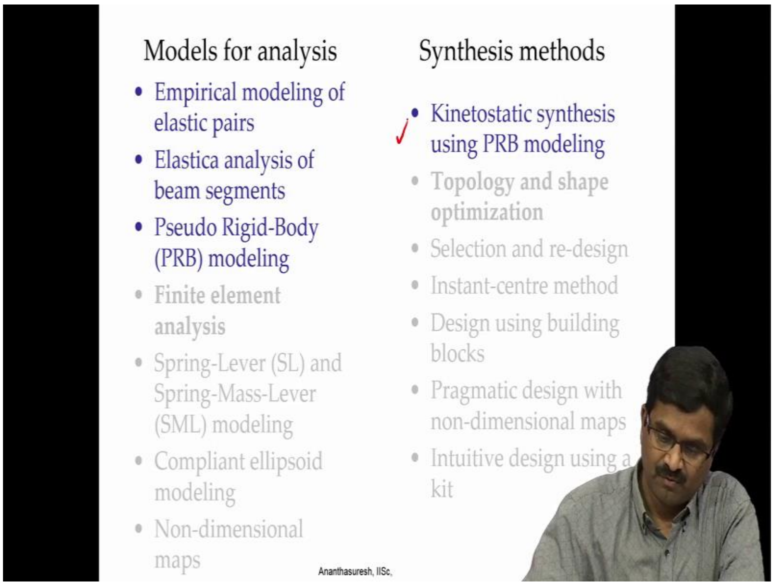

And then we come to the earliest method, which is design using the pseudo rigid body modeling.

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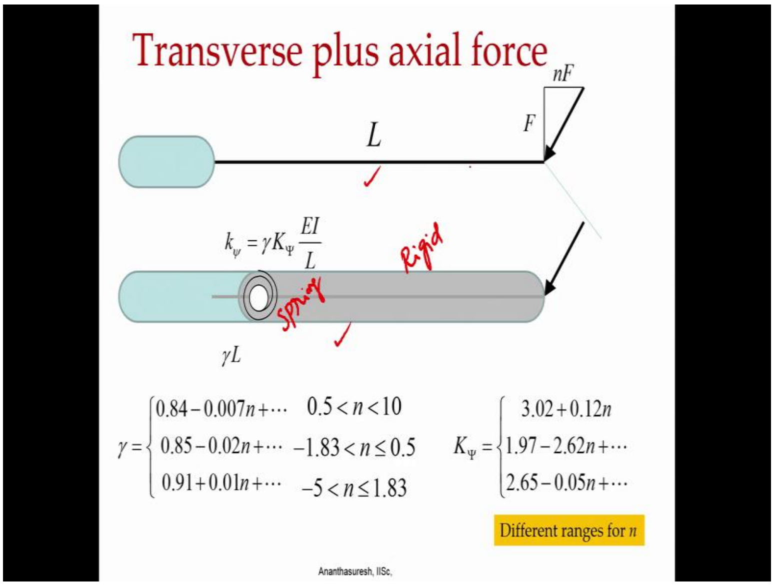

So, here we use lot of understanding that we have about how beams undergo behave and the undergo large displacements and where you have a cantilever beam such as this one can be approximated as a rigid thing, so this is now a rigid; so pseudo rigid and there is also a spring, a torsion spring.

That models pretty much the behavior of the compliant beam and then we can take this joint with a torsion spring and model a compliant mechanism as a pseudo rigid body model meaning it is basically rigid body model which springs.

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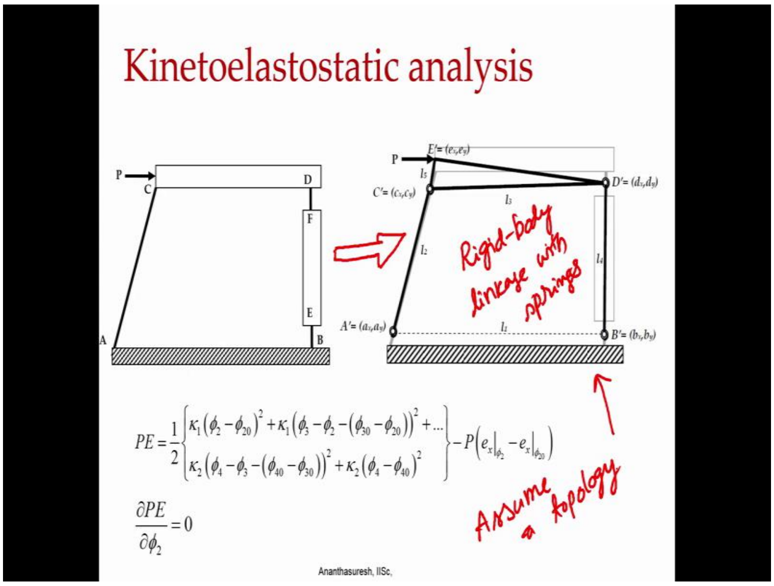

So, rigid body linkage with springs we had spent quite a bit of time on this method. Once you have it, you use once you have the rigid body linkage model with springs, we can use the synthesis methodology there are for rigid body linkages which is what we had discussed where we had the force or talk equal equations.

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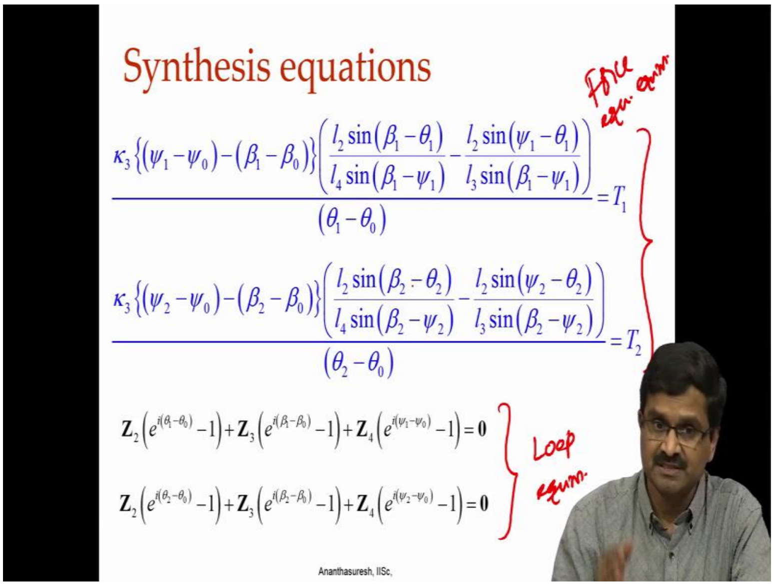

And then the loop closure equations, these are loop closure equations and these are force equilibrium equations. So, we could do that, but then solving the becomes a problem there are two issues one is that to begin with we should assume a topology, we have to assume a topology that is whether you want a 4 bar linkage, 6 bar linkage, 5 bar linkage whatever quite assume and where; whether it is a single loop or two loops all of that you have to assume.

If you assume that then you get equations and these are pretty much exact equations unlike the (Refer Time: 26:06) where we have continue models you need finite element analysis, you have to learn a lot about optimization variation methods and (Refer Time: 26:14) and so forth. Here it is all within the ambit of kinematics or rigid body linkages, but these equations are non-linear there few are in number compare to discretize equation that you would have in a finite element analysis which is the basis for the size shape and topology optimization.

Here we have fewer variables, but there are all non-linear, so such a method and also you have to assume topology and solving this equations is also not easy because you have free choices, but then what you get might have a very large length for a particular body are very small or spring stiffness that you get may be very high and so forth but the equations do take into account that non-linearity are geometric under non-linearity that exist in compliant mechanisms.

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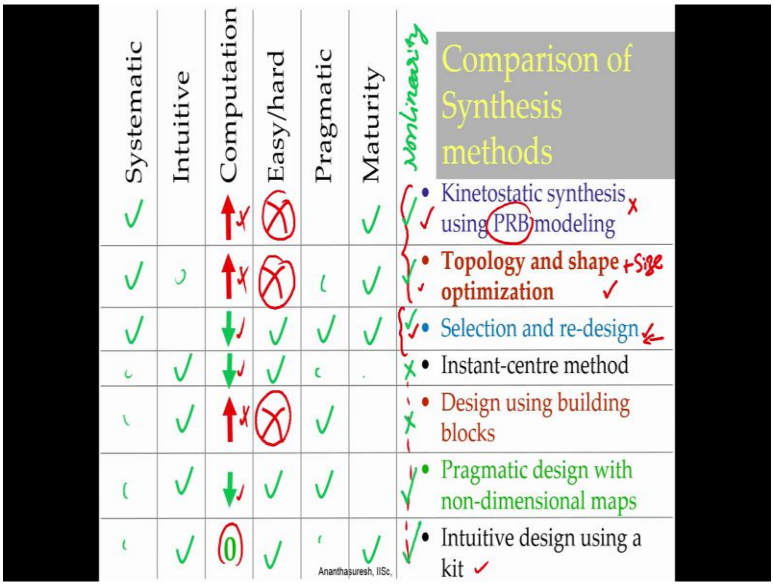

So, now let us summarize all that we discussed to see how we can compare. So, we are chosen systematic whether the method is systematic or not, whether it is intuitive that is a human designer has to use the intuition to design and how much competition is there and also is it easy or hard and whether it is pragmatic meaning that can it can take a lot of things rather then is the main functionality that is strength, buckling, natural frequency things like that also how matured is the method, how what is the level of maturity, how much is developed here.

So these my personal subjective comparison somebody else made look at a differently, so the I look at it is that, I think that the first three methods that is pseudo rigid body model base method, topology and shape optimization and I will always add size also here or parameter optimization and the selection and redesign which uses this spring lever models and spring mass lever models with their systematic there is no room for any intuition or randomness here; even in the selection and redesign because here these there is guided as to what he or she will get when a particular mechanism is chosen.

The user has the ability to specify the lower and upper bounds and then the proper mechanics in that satisfy those requirements are pointed out to be user and user can take and then systematically redesign them if it is necessary; topology and shape optimization of course, is very systematic in seeing p r b, but then here topology needs to be assumed, here topology comes out and here you actually choose a topology from a database and in terms of linearity, non-linearity all three of them can take care of non-linearity.

So, non-linearity is very well taken care of here with so pseudo modeling here it becomes a little hard, I will give a small arrow to it; it can be done, but it requires a lot more work and here non-linearity can be easily taken care of. We said that a compliant when the feasibility map will now will be curve as it goes from which original state unloaded state to the loaded state and you have make sure that the entire curve is inside the visibility map, so these are systematic methods.

The next four methods that is using this kit and non-dimensional maps and design using building blocks instants of method, there is little bit of I would say subjective judgment needed because a designer has to that is intuitive design is in the kit of course, entire left to the imagination of the user and instant centre method, they should also look at there is some guideline as to; if it is a need to single stage there is no problem you just draw the lines perpendicular to the input direction; input force then I have output for direction we are then make it is instant center, but we saw that that is not always enough because to choose an intermediate one there are number of means doing how do we do that.

So, there is something left for the imagination of the designer and design using building blocks and this non-dimensional maps, you do not know which want to look at (Refer Time: 30:39) non dimensional maps you look at you have a data base of mechanisms, but then which one actually you should use for designing, you can of course do across the length scales, but you still should use it. So, these are the once that are dependent on the intuition, instant centre method of course, that and design using building blocks also the same way because you should know how to design, that is why that based on the intuition and computation these things require a lot of computation because design building blocks when you are doing it, this transfer force load pack requires lot of finite element analysis to be done and topology optimization same thing and solving the coefficients p r b model is also lot of complication.

Whereas, other one selection and redesign and instant centre method is non-dimensional maps actually with intuitive kit actually 0 work, it is more like a again and so are the they are very low computation that is an advantage for them whereas these are disadvantages, red is bad, green is good. Now is it easy or hard, well for somebody who studies let us say kinematics and elastic (Refer Time: 31:58) analysis and everything this would not be a problem, but in general it is hard and so is topology shape and size optimization you have know variation methods, optimization theory, numeric optimization techniques and all of that sense to analysis then only becomes easy and design using building blocks you need to understand this compliant ellipsoid, stiffness ellipsoids and how these things happened in terms of addition and subtraction and so forth all that not subtraction really addition that also is not so easy.

The other four are really good because you can just use your intuition and just do that, in fact this particular one does not even need intuition. Pragmatic I would say selection and redesign non-dimensional maps, building block, methods are pragmatic because you can look at the strength consideration and natural frequency buckling and manufacturability everything while you are doing it, other methods more or less give your topology other things will be hard. In terms of maturity, how well developed they are; the first two methods are developed for a long time, so there in fact, there are software programs and can use and selection it design also we had seen that there is a software program both in map lab in a java base so there will be developed other things still need development and this one write now there is a company that actually can make it for people who are interested; this kit, but still lot more work is intend to make it fully usable.

So, this is my prospective on comparing different methods and in all of these who have to remember that the methods that take into account non-linearity are the most important once and that if I say the based on non-linearity which is not a criterion here p r b based model definitely; let me change this color to green, non-linearity which is not something here if I say whether they can handle non-linearity which is critical for compliant mechanisms, this is definitely a big plus and so is topology shape optimization, but little bit more work is needed there and this can also do that and instant centre method, it is instant centre meaning that at that moment, so it is not (Refer Time: 34:30) for large displacements and design is building blocks that also is only instant have that moment.

Non dimensional maps non-linearity is very well taken care of and intuitive design using a kit definitely because when you make a model, we can actually move them until the break and it is a very easy thing even if you breaks you can always replace it. So from non-linearity perspective these are the once that are good and I will left out intentionally all these things we thought writing because we do not want to really say one method is bad or good because all methods will good, so that is where we will leaded and they just have advantages and disadvantages.

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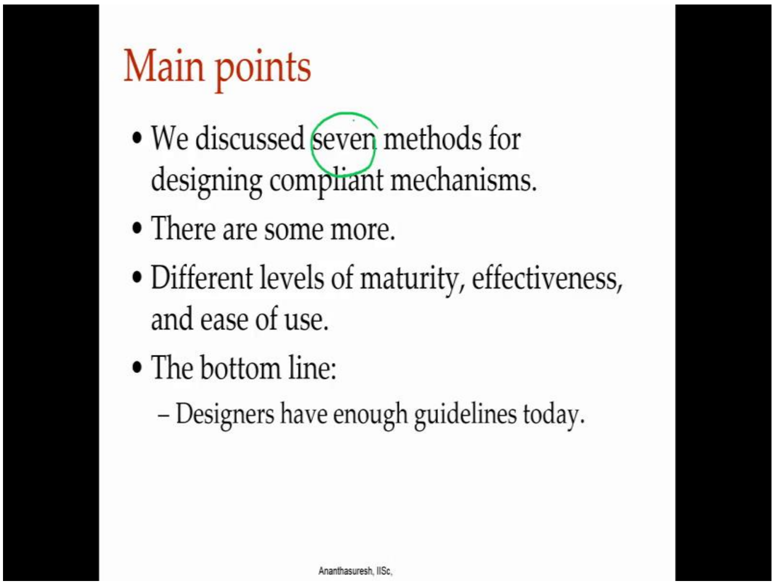

Summarize we have discussed seven different methods for designing compliant mechanisms; seven that was that is a very good thing because when this field started there went any methods at all, today we have a seven method that could actually discuss and teach in a classroom and there are some more which we have not considered here. There are constraint base methods several people are working on using screw theory which is somewhat similar to the building block method and there are a few more methods that are very specialized which you have not covered here.

And all of these have been developed to different levels and their effectiveness also various depends on the problem on hand and some of them are easy to use, some of them are not so easy to use, some of them can be automated, some of them cannot be automated for example, the method of pseudo rigid body model is not a mean able for automation because one has to use the topology has same thing leakage body linkages first you have to know the type of linkage and only you can do, but then with the features are available and the different steps involved in going that also is not something that taken be easily automated, whereas topology optimization and some other methods can be easily automated.

So, in terms of ease of use when you have ease to use software you know a difficult method such as topology optimization can become an easy to for design, but the final conclusion analysis is that there is enough for designers today which was not the case to decades ago with lot of people working on compliant mechanisms. Today we have design methods and with that we are seeing that lot more people are using and lot more applications are also coming for compliant mechanisms because there are design methods now.

So, we will end our discussion of the design methods today. And in the rest of thing we look at some more final aspects of compliant mechanisms such as mechanical advantage by stability and manufacturability materials, and finally a lot of applications where all these deign methods become useful.

Thanks.