Compliant Mechanism: Principles and Design

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Lecture – 39
Selection of compliant mechanisms for given user-specifications

Hello, today we are going to discuss how to combine two ideas that we have already discussed one is the spring lever model or SL model the other is a the feasibility map. Spring lever model is a model for compliant mechanism so that you can treat compliant mechanisms as a terminal characteristic model where they just input output stiffness there and of course, the intrinsic ratio n, K ci, K co or the stiffness parameters and n is the lever ratio and we also discussed in the last lecture how to construct the feasibility map.

Feasibility map captures the user specifications in a visual way. So, user can see how stringent requirements are or how loose the requirements are whether requirements are possible to have a mechanism, right. Today with these two ideas we will combine together to create what we can call a selection map technique for designing compliant mechanisms. So, let us look at how we do it, so beginning with the selection and redesign. Here the key words are selection redesign of a compliant mechanism not only we can select the complaint mechanism data base, but we can also redesign as per the similar specifications which is captured here with the help of a feasibility maps.

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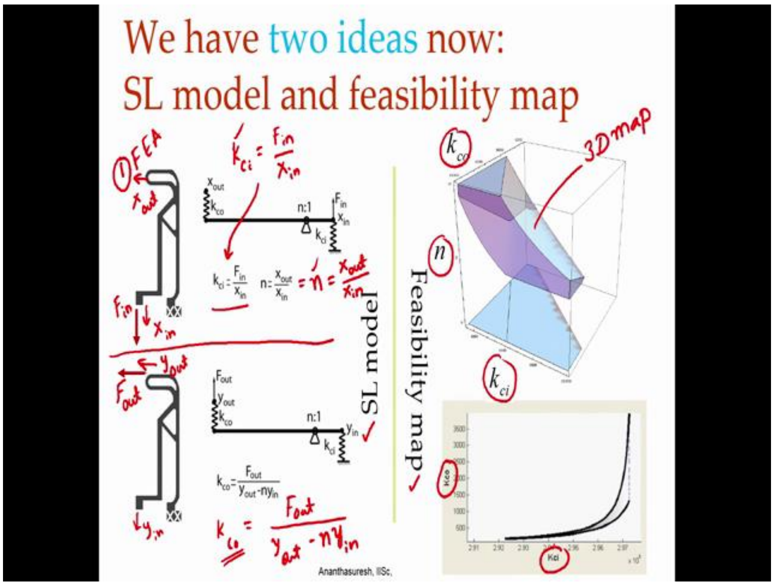

So, to recapitulate what we have discussed in the last two lectures one is the spring lever model and the other is feasibility map. What did we learn in spring lever model? We learned that by doing two finite element analysis this will be finite element analysis 1, this is the first FEA where we apply force here this is F input layer to the compliant mechanism and we record the input displacement X i n. So, what about displacement you get here let us call this X in and we also measure the output displacement in this case, output displacement will be like that let us call this X out, then as shown here the K ci inputs side stiffness can be obtained as F in divided by X in that is what is written here in small apparent and n here this is n which is X out divided by X in which you would have measured to finite element analysis. So, that is one where we got K ci and n, in order to compute K co we remove the input force instead we apply output force in the direction or in the opposite direction whichever way you want to do, we apply the F out and record the input displacement as well as output displacement.

So, there will be we are using a different symbol now instead of x we use y and there will also be a Y in here we put these two together to get K co which is output side stiffness that will is given by F out divided by Y out minus n times which we you are completed and calculated in the previous step we will get F out divided by Y out minus n Y in will give us K co also, these 3 parameters captures the static behavior of a compliant mechanism. And then we also discussed how we can take user inputs on 6 parameters, they are the input variables that is a F in, u in, input force input displacement, F out, u out, output force output displacement and actual this stiffness k a and we also had k external that is external objects stiffness from those we find the feasible values of K ci n and K co different sets that gives us the feasibility map this is the 3 dimensional map of the feasible values of this parameters.

If we project that we get a 2D map that is plotted with K ci and K c o. So, these are basically reflection of the user parameters user inputs with lower and upper bound on 6 variables.

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Now, we have these two complementary ideas we say the ideas are complementary because, what one has other does not. So, we have SL model for compliant mechanisms this is a reflection or abstraction of the compliant mechanism every compliant mechanism has unique set of values for K ci K co and n. These are like as we already said, terminal characteristics they are properties of compliant mechanism. Now we have the complimentary idea which is reflection of the user specifications we are all specified by the user it has nothing to do with compliant mechanisms, now these two complementary ideas we put together into one idea.

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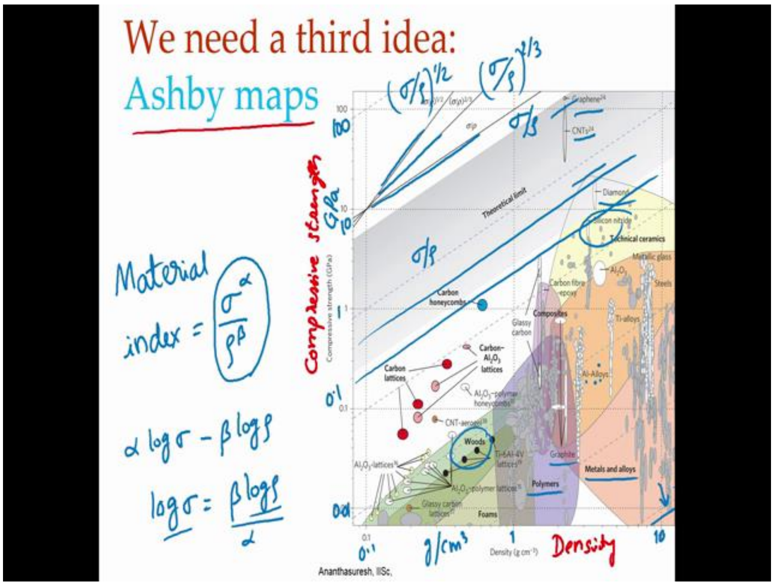

Before we do that we need a third idea and that is called Ashby maps. So, this is a Michael Ashby (Refer Time: 06:10) the Cambridge who has developed this for material selection, what is shown here is on the x axis we have density in the y axis we have in this particular case we have compressive strength. In fact in the Ashby map technique you can take any two properties and plot them in plot like this usually will log plot because, here it is 0.1 gram per centimeter cube this is gram or centimeter cube and this is in giga pascal and of course, it is log scale because gram pascal this is 0.1 and this is 1 and this is 10 log scale similarly, this is 0.01, this is 0.1, this is 1, this is 10 and this is 100 it is a log scale.

What does it show? It shows all materials that are possible that are in that that exists. So, for example, there are polymers here metals and alloys graphite or all kinds of things. So, if you plot like this similar materials occupy a space in this map. So, you have compressive strength and density for every material then it will give you aluminum alloys right, there point there combining all of them with this big orange shape which contains all aluminum alloys now the densities compressive strengths have ranges and you get this, right. So, here we are looking at the properties of materials and plot all the materials and then see there are woods here there are some silicon nitride diamond all kinds of things they are in this map we show their relative positioning with respect to pair of part of the consider in this case mass density in compressive strength.

So, this way we can plot all the materials and Ashby says once you have this you will have some criteria based on your designed requirements and that will have what is called a material index, we talks about in material index based on a performance criterion that one would want. In this particular case, we have two material properties density and compressive strength that is a compressive strength denoted by sigma densities divided by rho it need not be jut sigma by rho or sigma rho there can be an exponent there, an exponent here. When you have something like this, you would say that if you maximize this material index there is a performance criterion is maximized or minimized whichever way it is then what you do is in this map since in log-log plot this alpha and beta amongst to a basically a straight line when you write this material index and take log of this will have 1 minus alpha times log sigma minus beta times log rho and that will be a straight line here, so one will be in terms of the others.

So, if I do log of this I will get alpha log sigma minus beta log rho. So, I can write a log sigma here in that case log sigma equal to beta log rho and then it will be one over alpha. So, it will be divided by alpha right, and there could be some constant as well now if depending on what all you have in the performance criterion. So, basically a between log sigma and log group we have a linear relationship we get a straight line. So, what you have here it could be sigma by rho we have one slope and sigma by rho raise to 2 over 3 has another slope and sigma by rho raise to half is the third slope. So, you have different curves here.

Let say we take one curve let us say this is parallel to sigma by rho. So, if I want to maximize sigma by rho I basically move this line. So, I can draw lot of lines parallel to it I can say extreme is here, maybe divert is the best material for it or if you go further there is some grapheme 24 or carbon nano tubes over here, right. So, you see you they are the best in terms of compressive strength and density one of the worst you come all the way here and whatever materials are there they become the worst once or the one that minimize in that material index so, but putting all materials in terms of this map we can select material.

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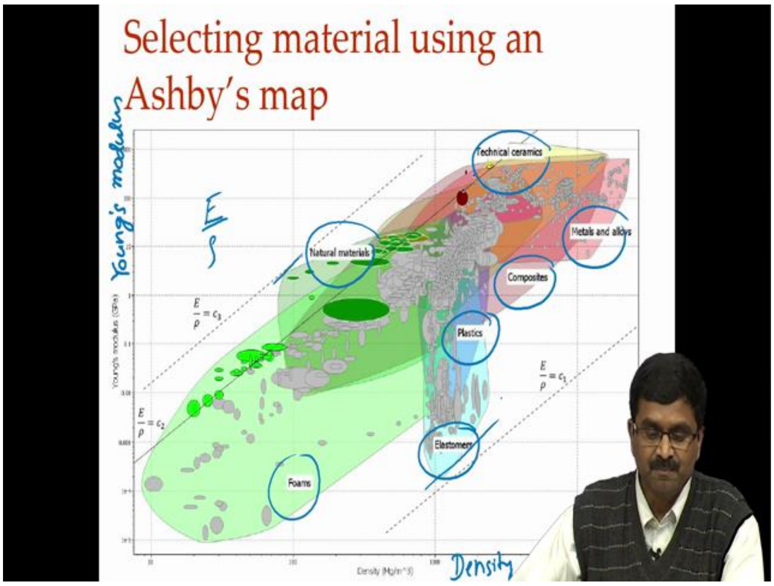

So, that to (Refer Time: 11:14) here now we have here again a two properties one is a density or a different criterion that density and here we have young's modulus again you can see how that a material clustered together. So, there are natural materials over there some foams, elastomers, polymers, composites, metals and alloys, ceramics that are all occupying different spaces, but if you have material index in this case it is E by rho then you draw a lot of parallel lines and you get the best material E by rho there that has one value one extreme another extreme is here. Based on the extreme values you can choose materials but idea is properties can be shown on a map. So, that material can be compared with one another and the best material had that the best extreme or worst extreme when I say worst, it will be minimization that is still the best when we want to minimize or the other extreme where you maximize and that is the best for you.

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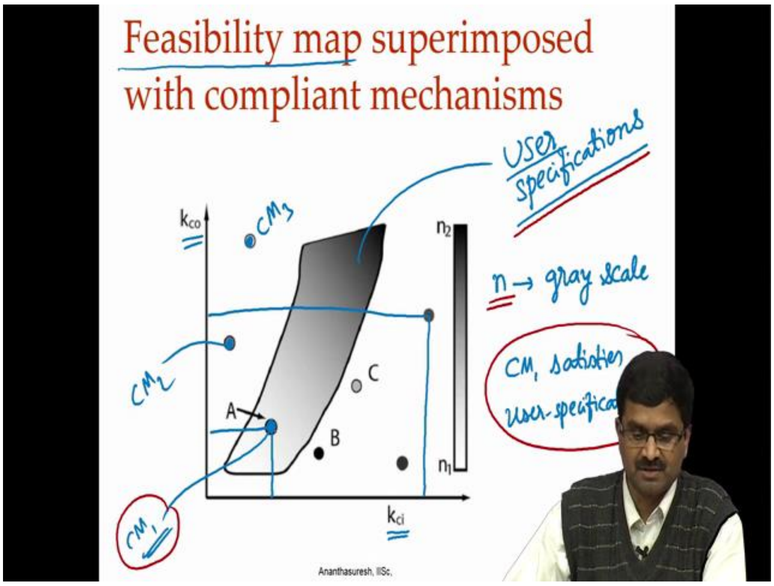

So, that is how Ashby’s map method works we use this third idea Ashby’s map and put it all together. So, idea is now in the feasibility map that we have the feasibility map here that we have drawn that comes from user specifications we discussed in the last lecture how that can be computed by solving 2 equations and 12 inequalities upper and lower bounds on the 6 input parameters, so these are the feasibility map. Now we also know that every compliant mechanism will also have unique values of K ci K co and n, now what we do is we put those compliant mechanisms in this chart now we have K ci here and then K co here and these are feasibility map projected we are not showing n, n is shown like a gray scale here. So, n is shown on a gray scale on this map now like in Ashby’s map we put all these dots.

So, each one of them corresponds to it is K ci K co every one of them. So, for the example this will have some K co there some K ci, they are the coordinates we put them feasibility map like a countries map all these mechanisms are like cities in it. Now the ideas are very simple in order to select a compliant mechanism we just see which of these compliant mechanism dots that is each dots corresponds to a compliant mechanism, this is a this point is let us say; compliant mechanism 1 and this is compliant mechanism 2 this is compliant mechanism 3 and so forth, whichever is lying inside the user specifications based feasibility map then we say that compliant mechanism that compliant mechanism satisfy the user requirements.

In this particular case this is CM 1 is inside CM 1 satisfies user specifications that is what we can specifications we can conclude here, so it is as simple as that. So, we have a map in which we are super imposing the feasibility map and compliant mechanisms, again remember that each dot correspond to a unique compliant mechanism. There could be other compliant mechanisms also by correspond to each dot there is a compliant mechanism I do not say unique, because 2 compliant mechanism can have the same values of K ci K co and n. Now when we are inside when we say inside it is not enough to be inside in a 2 d projection of K ci K co map the n value should also match, that in terms of gray scale level also it should match, in which case you take that compliant mechanism and walk away because you have selected a compliant mechanism that satisfies the user specifications.

Do we say this is the best, we do not say we only say that it is satisfies the requirements will the users wishes user specification can be tightened or changed and then see how the compliant mechanism chosen now would fair, but even then you cannot say it is the best it just the one that meets specifications. It is a different design philosophy here user specifies what he or she wants and then we draw this map by computing that is solving the qualities and the equations. Then we super imposed on it n number of complaining that we have an a data base and we have and sure, we have all these compliant mechanism in the data base they all can be shown which ever lies inside we are not only to K ci, K co, but also n value matches that is one that is selected and one can move on with it that is the principle where we are super imposing two concepts rather Ashby's map concern concept as well as feasibility map and SL model concept.

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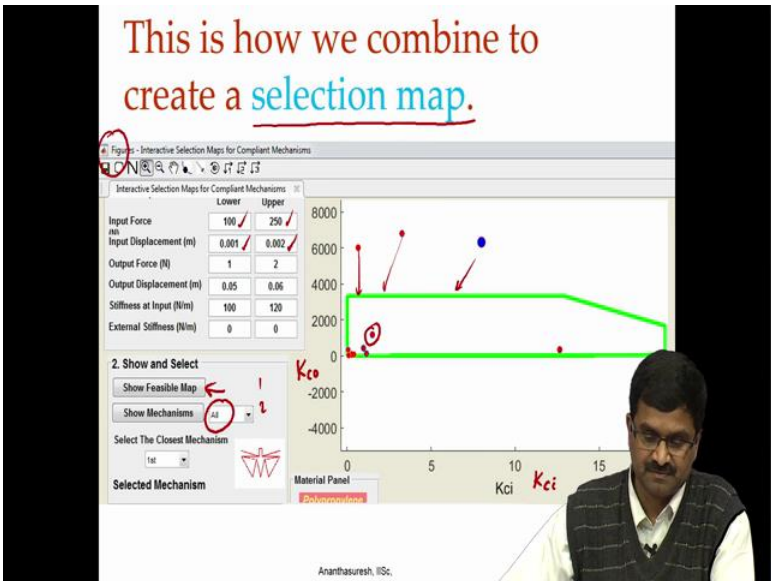

So, typically this how it looks and what we can call now selection map where we have K ci and K co this is K co and this is K ci per some specification input force some 100 250 and other 0.001 to 0.002 are displacements and so forth, output force output displacements stiffness at input that is actuated stiffness, stiffness the output that is external stiffness we can do all and then if it click show feasible map draw the map and some other n inside some other n in outside what about dots that we have in the data base. And we can ask the interactive software to show all the mechanisms or you can say show only top 1 top 2 and so forth. How do we know what is top 1 top 2? Again the program computes how many mechanisms are inside, how many mechanisms are closed, how many mechanism are far off; that is how it would rank what does that things are inside we get more better is that are outside. Outside also one that is closer to feasibility map is related higher than something that is little further or this may be the closest now this is a little be further, little further, little more further.

So, we can see all these and choose the one, we can click on something I want that and we can select it and then see the n value also matches if it matches then we have chosen or selected the mechanism these are the MATLAB, the software we can see MATLAB I can here. So, you will get that software to play with and we will explain more features of this.

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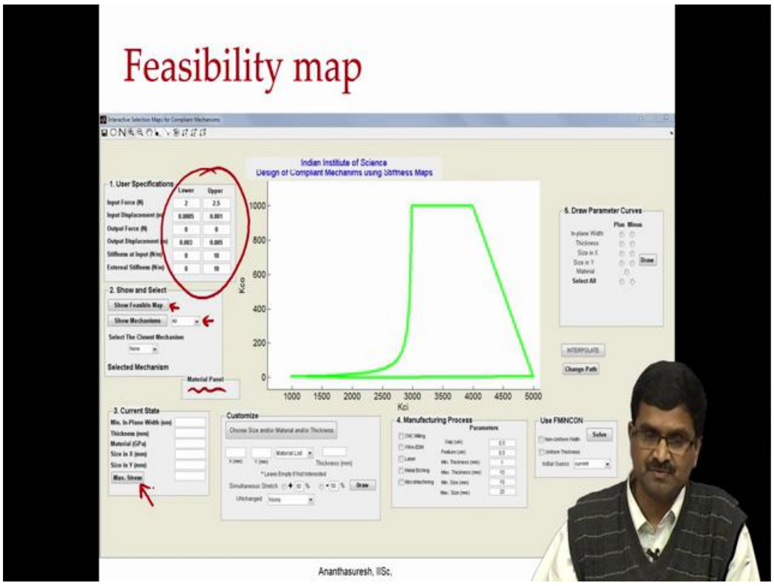

So, there are many other features, this is where we input our user would input the requirements that is F in u in F out u out actuated stiffness k a and external stiffness and then show the feasible map, show the mechanisms and we can select a mechanism that we like and look at what material it is made of and we can also learn about the maximum stress that we feel, there is a button here if you press that it will show you what is a maximum stress. We can learn a lot about mechanism there are few more things related to manufacturing aspects that we will discuss as we go along.

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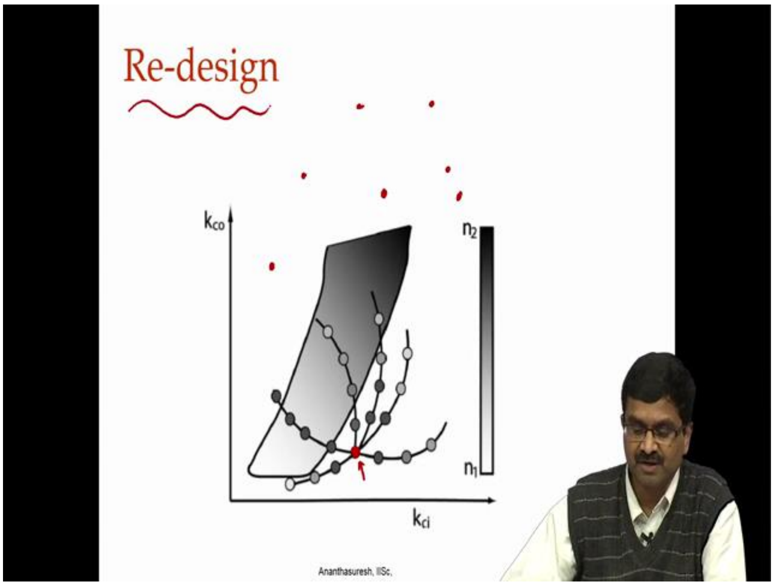

So, now given a set of specifications we draw the feasibility map and we show on the same map the compliant mechanism the data base as dots if something is inside n value also matches then you take that and then you say my requirements are met. What if none of the mechanism in the data base are inside the map what happens then if they are not inside at all; that means, that your specification because the map exist then your specifications potentially have a solution, but none of them in the data base meet your specifications what you do then you can modify a mechanic that you like to match it is specification.

Here is an example: we have let say only one that is outside which I have circled with red color here and that is not inside all others are say let us say outside for the further away none of them are the satisfying our requirements. So, they are all the outside the feasibility map, then we take the one that is closest let say this is the closest here and then try to get it inside the feasible map how do we get it not arbitrary, but by modifying it or by redesigning it.

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What are all the things we can redesign, there are number of parameter for redesigning where is a in plane width of the numbers. If we have a beam there is in plane width this width you can vary in the compliant mechanism we do not change the size just change the in plane width or thickness. So, it may have some thickness here. So that thickness over here can also be varied thickness can be varied or size in x size in y or material or all of them can be chosen and then see how that change in the K ci K co n that is, if we have a compliant mechanism and you change the width or thickness or material or the size. Size can be changed in the x direction or it can be change in the y direction or changed together x and y.

So, when you do those things a point that is outside right now will move it may move and let say I increase thickness the point may move like that because, when mechanism is made thicker it is stiffness K ci K co and n will change according point will move or it go the other way that is t minus. Similarly, we can have it for the width we can have it for the size x we can have a size y and you can behalf of the material change, that is how we can redesign it there are number of them that is what it shown here.

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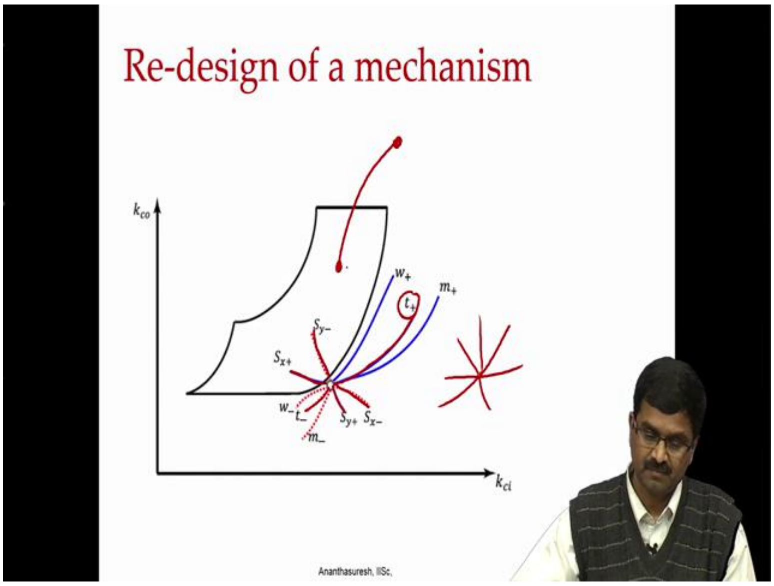

So, if I say a t plus; that means, that from where you are you will go like that, and t minus you are going the other way and similarly S x will go that way S x plus S x minus that decrease in the size increase in the size in y direction or you can change material and so forth. Every point will have lot of options to go based on this parameters and that is how we redesign you do not change the topology, we do not change the shape we only change the size meaning x direction y direction and thickness and width and material also. We can change all of them and then say how to get them inside the feasible space again when I get some mechanism inside the feasible space I also need to match n it is not just K ci k c o, but also n has to match.

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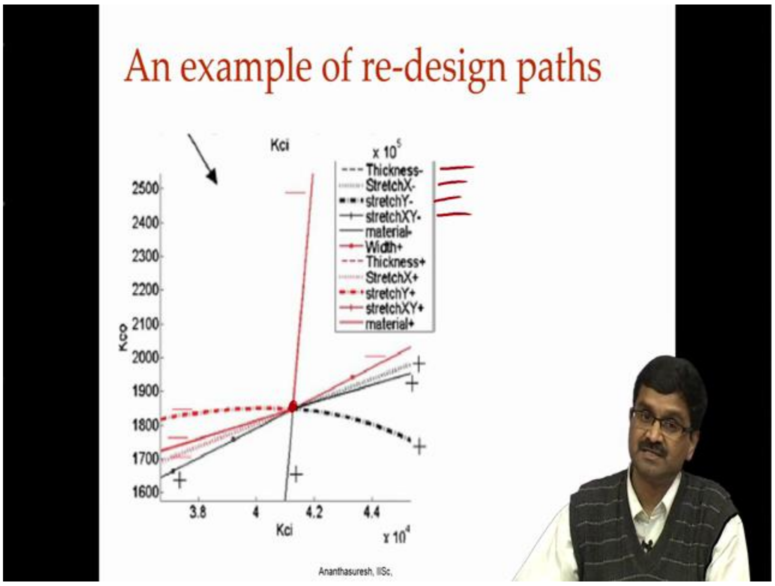

Here is a typical real example or it is an in paths. So, there is a thickness and stretch x stretch y stretch x y both stimulant you can do and how it looks how we can go from one point to other points which change these parameters. So, user can interactively explore what are all the possible things to get the mechanism inside the feasible space. So, that we will again satisfy requirements even that to begin none of the compliant mechanism points are inside the feasibility map.

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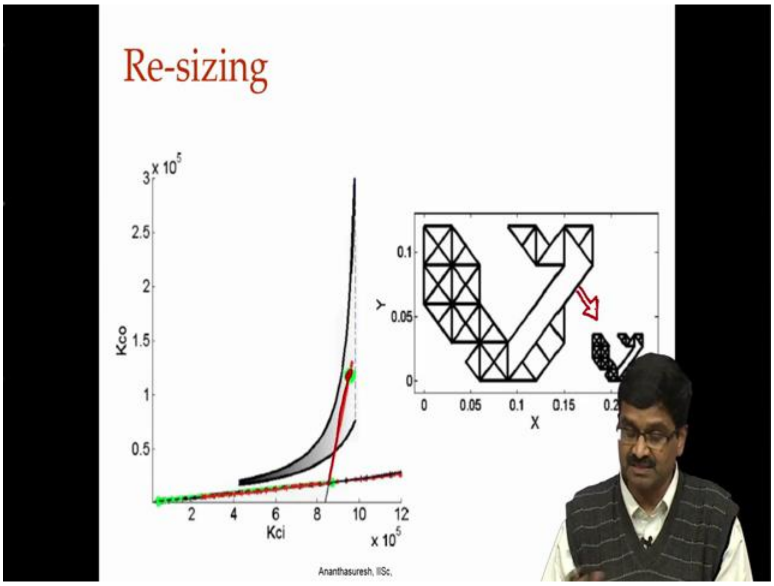

When you do it is resizing let say you are here by resizing here over there what it means let say here we are resizing in both x and y and mechanism that is like that big one will become small one or small one may become big one, we are not changing anything else within the size and then say our specifications are met.

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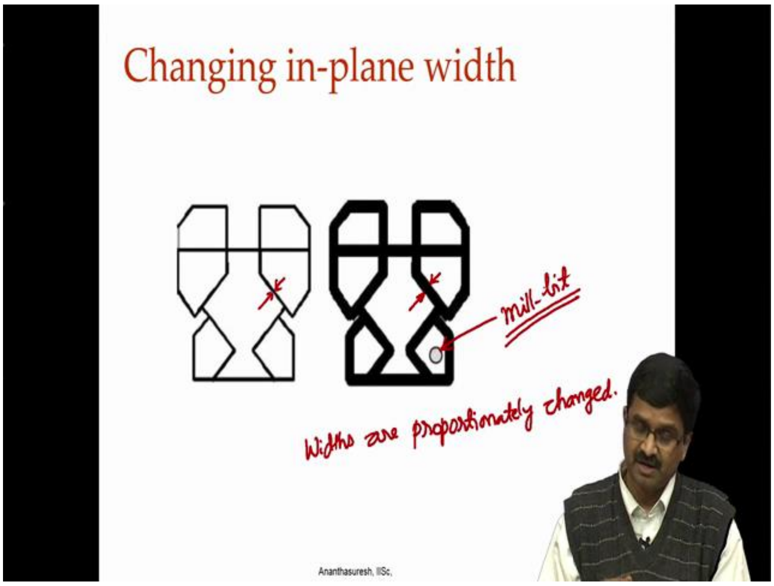

We can change in plane width. So, here this particular width is small now you here it is large, all the in-plane widths are proportionately changed. So, we are not doing everything separately which are proportionately changed sometimes you make the widths bigger sometime you make it narrower widths are proportionately changed, and the change effect on the change you can see in the map because, that point would move to another point depending on how width is changed it can be increased it can be decreased.

In doing so we can take into account the diameter the mill bit or for that matter even manufacturing process that we are using, we can take the mill bit diameter and accordingly design the compliant mechanism or redesign the compliant mechanism.

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So, we have indicated over here in this program material in this case polypropylene is indicated and CNC and laser or the process (Refer Time: 25:48) load we can look at that, and also once you choose a process let say you choose a CNC machining then minimum gap feature, minimum width feature, minimum thickness, maximum thickness and minimum size and maximum size all these parameters you can put in what can be done with that process it can be laser it can be CNC then accordingly mechanism design can be redone. So, that manufacturing aspects are obeyed and we also set strength can be obeyed, because there is a maximum stress we can keep that button anytime and then see what the maximum stress in the mechanism is.

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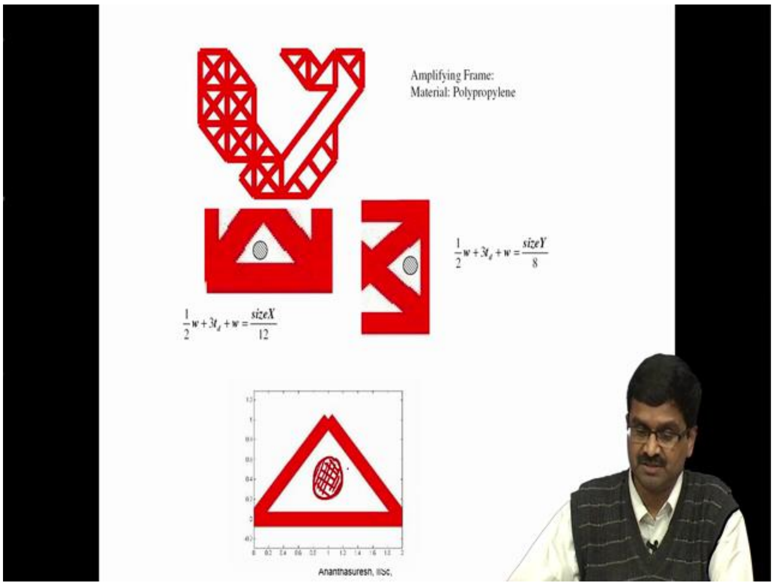

This is the philosophy, where we have the interactive thing where we can change in this case this illustrates how the in-plane width can be changed within that mil diameters, so this is the mill bit and based on that you do not want to increase the bit to more than certain value because, in width which case it will be not possible to be this if you make it a narrow and it takes care of that how large can you make how small you can make based on the manufacturing process specifications.

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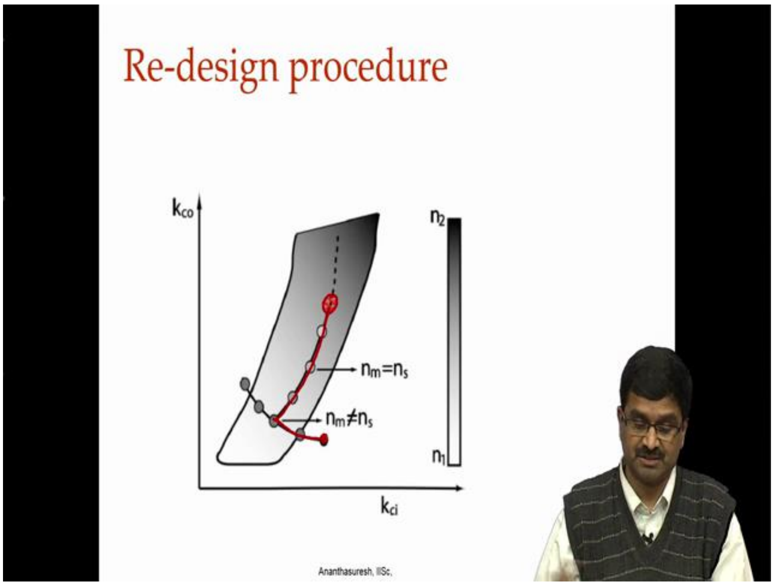

So, redesign procedure again we are outside let say you are coming and then if you go further you are going out of the map, but n value does not change you can take it a different path and where the n value can be actually changed to meet the user specification not just K ci K co n also has to match.

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In order to do this what we need is a catalogue of compliant mechanisms, that is every compliant mechanism should be shown as a dot in the feasibility map for that we need to have a data base of compliant mechanism which we have number of years of research has led to a lot of designs in our lab we have currently about 90 compliant mechanisms each with it is own individual topology and they are all stored in either MATLAB program or java script I will talk about it. So, we have a data base of that every one of them has a K ci K co n value that is putting and then shown as a point when a user comes user feasibility map is shown user can bring it a mechanism in to the feasible map if what are the inside feasibility are not satisfied again look at the mechanism and in see you will like it or not.

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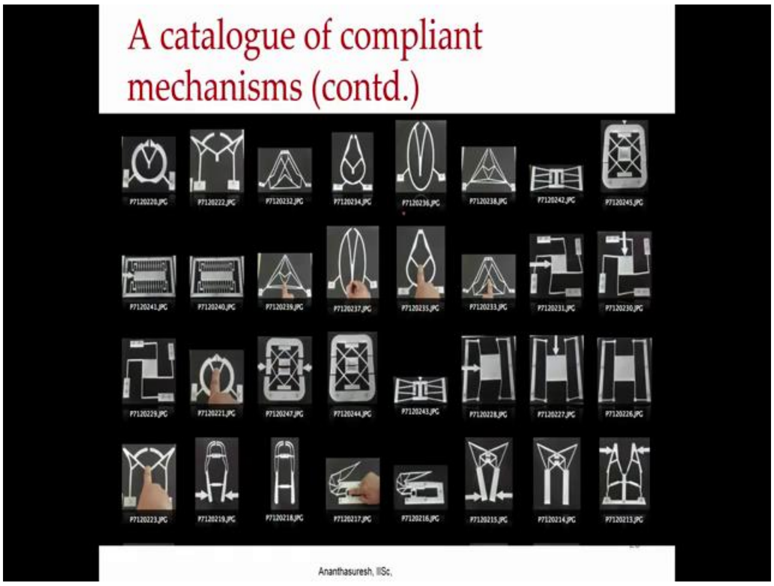

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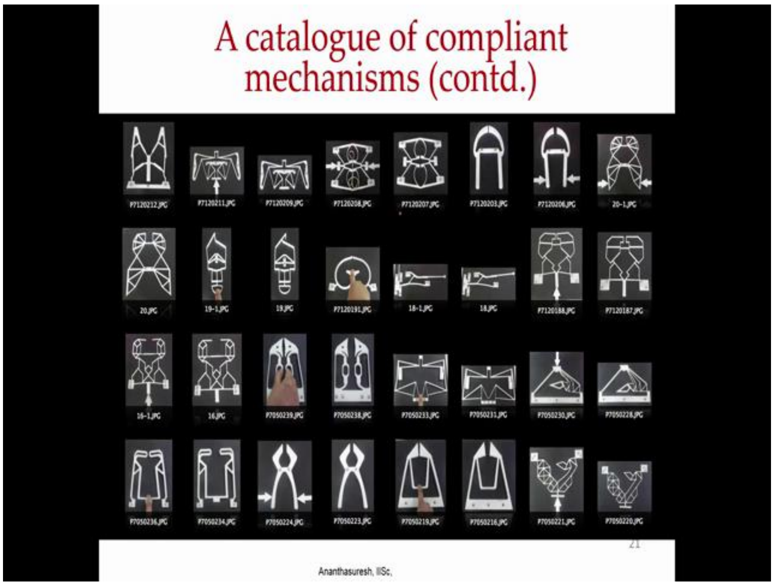

So, a number of mechanisms that we have, on the screen now; we have these four and we have many more and many more and even more.

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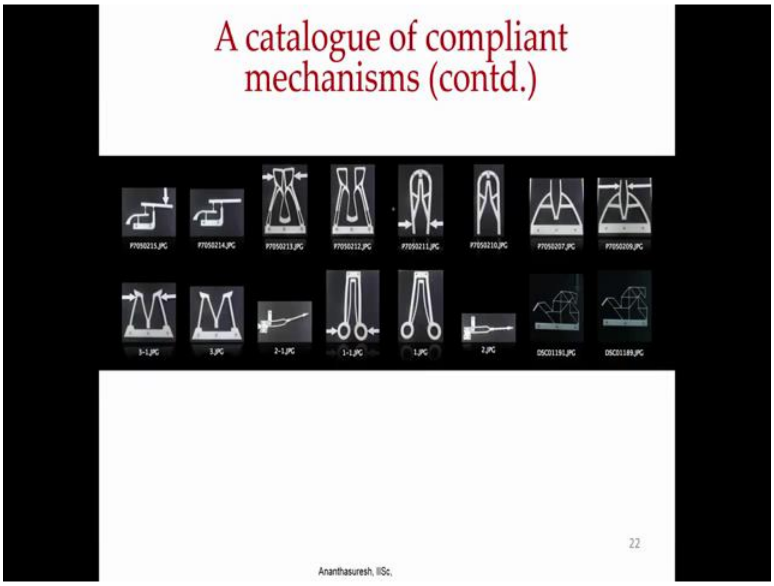

We have about 100 target is 150, but there are as many compliant mechanisms are all there and you can put them all at the disposal of the user who does not need to the much about compliant mechanism can still select what is needed or it redesign if the selection is not good enough. So, overall view of this procedure is that we start with user specifications right now we are talk only statistics.

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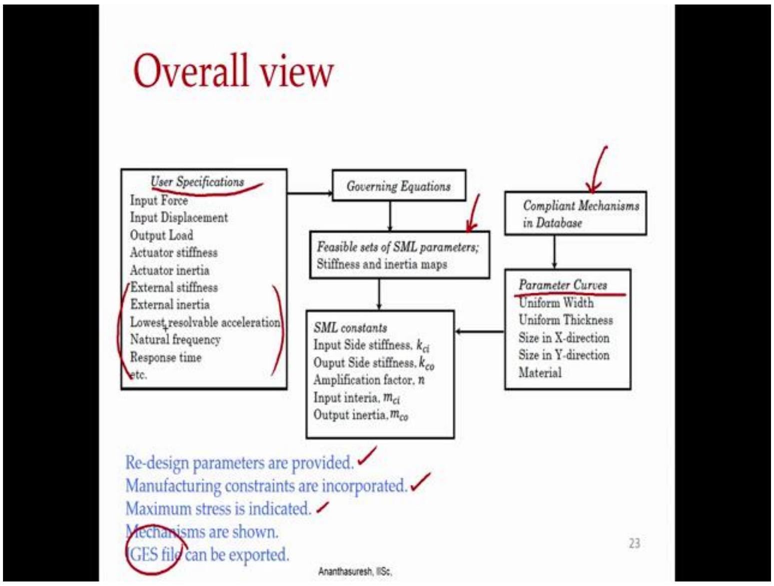

So, force displacement the input and output actuator stiffness and external spring constant that is two model the work piece with which compliant mechanism is interactive with and of course, there are a few more here which applied to dynamic characteristics which we will discuss later we solve the governing equations which we had two and we have this SL parameters. That we can put for each compliant mechanism each input specification is upper lower bounds we use that to get this feasibility map and then we get this SL parameters ranges and show them and compliant mechanism data base will show all the mechanisms and then we can draw the parameter curves to bring a mechanism in to the feasibility map to satisfy the user specifications.

So, redesign parameters are provided manufacturing constraints can incorporated and maximum stress indicated all the time press a button it will show you what maximum stress that design is; that means, that in side this user interface there is finite element analysis running all the time, once you chose a mechanism we can actually create an IGES file and actually go to manufacturing thing readily. So, it is a very pragmatic design where you have to actually select and re-design if what is selected is not good enough.

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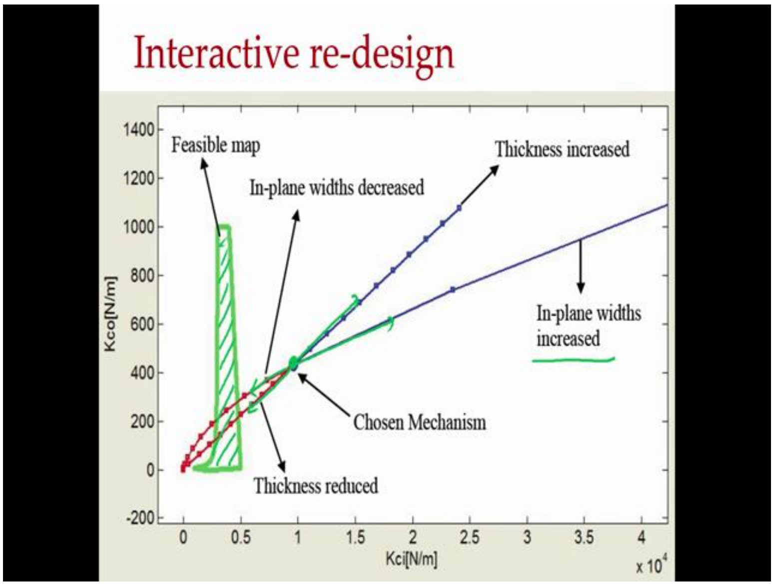

So it looks somewhat like this, where we have a feasibility map which is shown in this red here in green color here this is all the feasibility map and here the point happen to lie outside let us assume that there is nothing else and we draw this in-plane width increased. So, it will go like that in-plane width decreased will go like this and thickness increased goes like this thickness decreased goes like this. So, that way we can bring it in to the map meaning that we are modify the compliant mechanism that is closure to feasibility map to come inside the feasibility map so that n also matches, this is the interactive redesign program.

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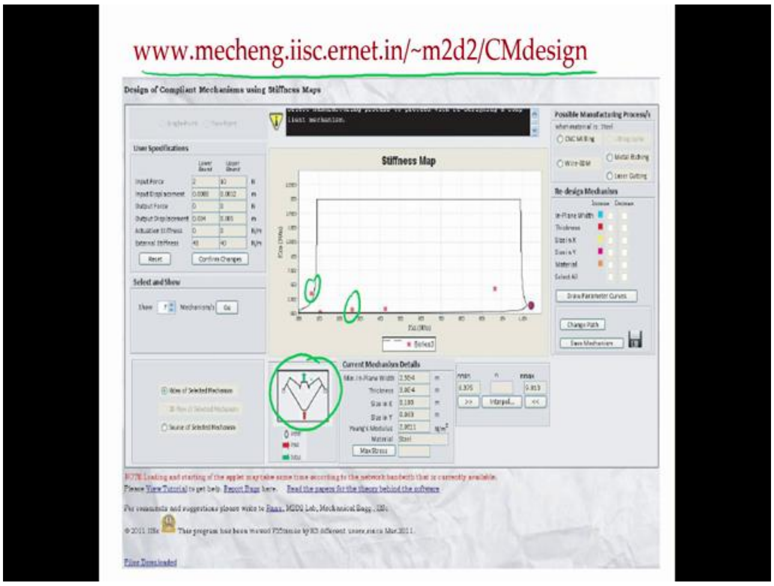

And it looks like this we also have a java version which is the URL given here. So, we will be able to play with that also in java you can just run it and you can see that we also show that mechanism. In fact, if you click some of these it also animation of the mechanisms.

So, the philosophy of this method is that user does not necessarily know where the input output point should be we just know between input output what kind of behavior is needed, but we do not say orient this way (Refer Time: 31:42) where the user sees the mechanism or looks at the animation simulation of that or even a video of a real mechanism that is in data base, then user can decide whether that is good enough for the application or not. If it is not then you can go for the other one, because there are number of them that are closed by and the one that they pick is the best one then look at the manufacturing parameters and then they redesign if necessary and finally, be a happy with the mechanism because satisfaction is the user requirements.

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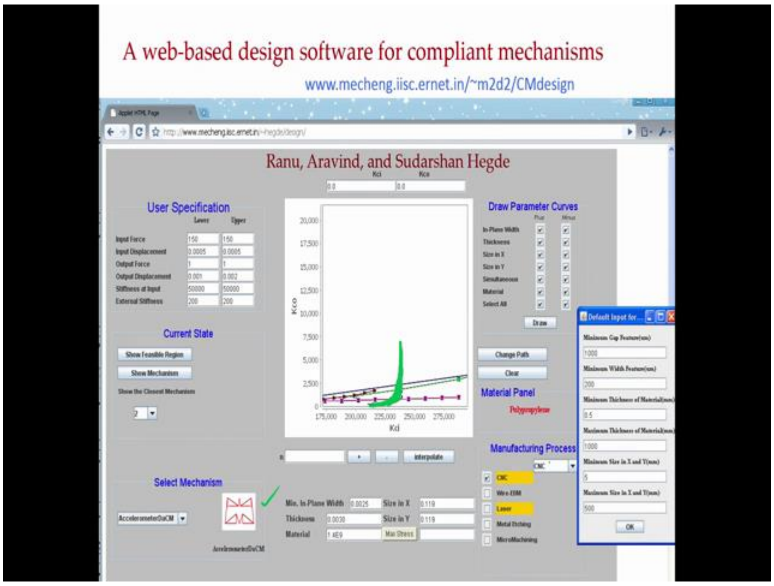

So, here this is also the java best one where we can see real example where the feasibility map is this little thing we can zoom in and out all that is possible and you can draw the parameter curves and see the mechanism and we can actually see reference also which mechanism is which reference is taken from and manufacturing parameters and finally, we can chose a manufacturing process and for that we can check where the mechanism is satisfies all the requirements.

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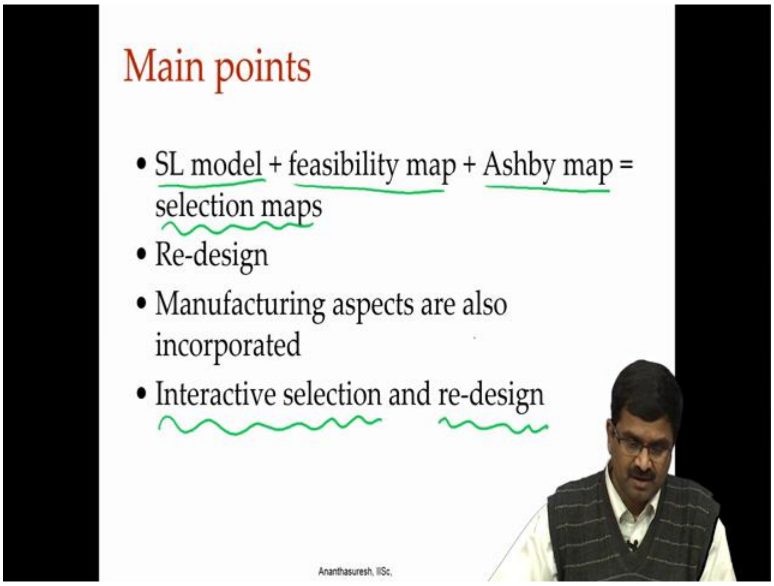

The main points on this lecture is that we have combined this spring lever model feasibility map and Ashby map together to create what can be called selection maps, we also discussed how a compliant mechanism that is reasonably close with feasibility map can be redesigned to actually satisfy the user requirements we can in incorporate manufacturing considerations such as minimum feature size maximum feature size and so forth.

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And finally, this whole thing is interactive program where we can select or we can redesign and a these 2 papers by Sudarshan Hegde in journal mechanical design and that is the machine theory are the references to read further.

Then in the next lecture we will consider couple of case studies to illustrate how this method works.

Thank you very much.