Compliant Mechanisms: Principles and Design
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Lecture - 40
Two case-studies using Feasibility Maps technique

Hello, we are discussing the third design technique which is based on Feasibility Maps which is in turn related to the spring lever model and we already discussed how to construct a spring lever model for a given compliant mechanism and how we can construct the feasibility map for given user specifications. In the last lecture we discussed how the selection process as well as a redesigning process works. Today we will consider two case-studies to illustrate what we discussed in last lecture regarding selection as well as redesign.

So, let us look at the two case-studies and again the key words here are the feasibility map technique and designing compliant mechanisms by selection and a redesign.

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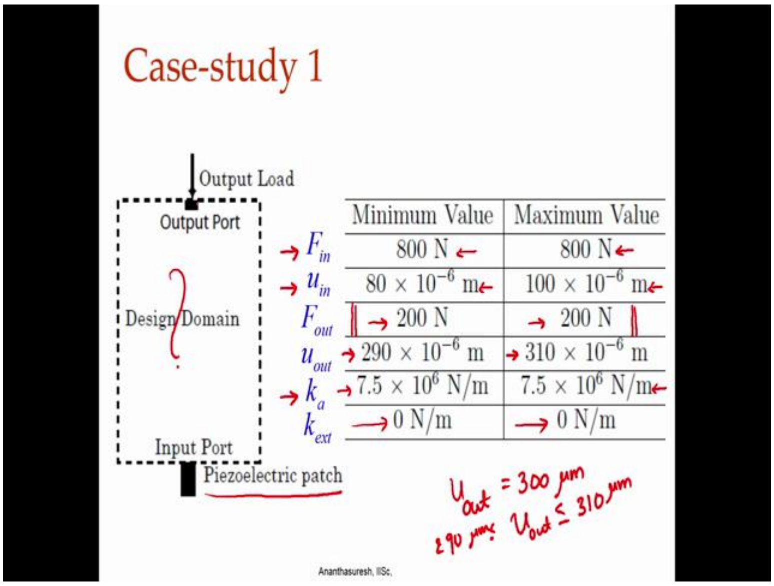

So, here is the case study one which is an example that we had used as a motivation in the first lecture that described this technique of using feasibility map where we have a Piezoelectric patch which has its own stiffness which is what we called k a which is the actuator stiffness and this piezoelectric patch can give some force which is our input force and it also has some stroke which is the input displacement. And all three of these we have let the user specify a minimum value as well as a maximum value there is a lower bound and upper bound.

So, for example, this actuator can provide input force of 800 Newtons since we want precisely that value we put lower and upper bound to be the same. And input displacement 80 to 100 microns. So, the 10 power minus 6 meters there is a range, there is a input lower bound and an input upper bound on the displacement. And k actuator that is fixed here so we just have specified the same number for lower bound upper bound that is perfectly possible when you have a fixed value in mind you can specify lower and upper bound to be the same value. Then the output port we have indicated how much force is there that is 200 Newtons precisely that is what you have you put the same number and how much displacement you want? Let us say you want 300 microns we specify lower bound to be 290 and 310 because you can live with 10 microns less or 10 microns more if that is the case when you have in mind you ought to be let us say 300 microns, you can enter that to be anywhere from 290 microns to 310 microns if that is what you can tolerate, if you cannot we enter the same value for both of them.

And then there is also external; k external which in this case is specified to be zero meaning that there is no output spring there is only output load there is no output spring; sometimes there may be only output spring, but there is no output load. In this particular case we have output load which is specified here, but there is no external spring, so zero zero.

Now when you have specifications such as these we want to know whether there can be a compliant mechanism that can give this that can use this actuator be within the restriction that we have shown here and deliver the output as it is desired here whether such a mechanism is there or not. The first thing to do is to do a little bit of analysis; analyze these specifications user can ask anything first you have to see whether that makes sense or not, how do we check?

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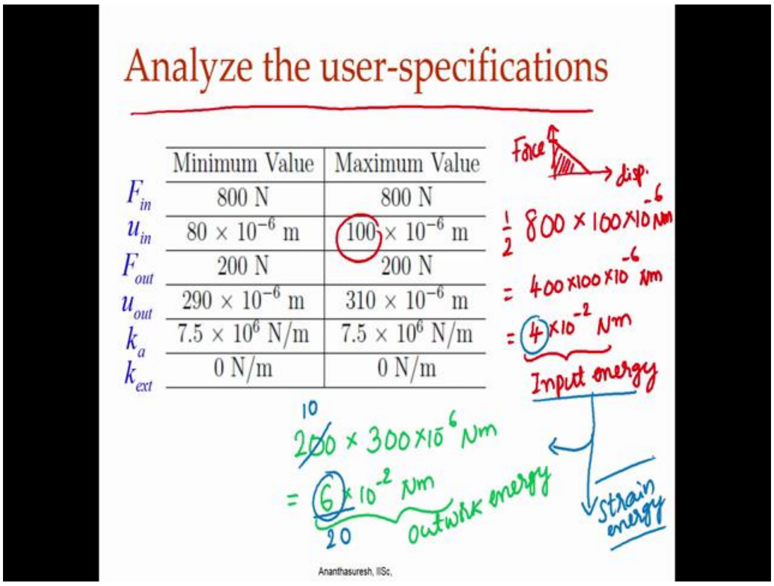

Let us say we have F in equal to 800 Newtons and output displacement let us say we take this 100 microns 100; 10 power minus 6 usually this piezo actuators would have the force if I call this indicate that on the force axis and then this is a displacement access; if we have that then it will go like this it will be 800 over there and then become 0 over the stroke.

So, the area under this input energy we have to divide by half; if you do that it will become 400 into 100; 10 power minus 6 the unit are Newton meter; because you put these all in Newton and meter unit is; that means, that what do we get here 4 into 10 power minus 2 Newton meter; that is what we get here.

And if you look at the output; so we have output this is the input energy; that is what our actuator is able to deliver over the maximum displacement of 100 microns. So, now, let us write the output here. So, F out is 200 Newtons and let us say nominal is 300 microns, 300 microns this is Newton meter that will be and it is not half because 200 Newtons will be acting were assuming all the time throughout the range of motion. So, output moves by 300 microns; it would be working with this force 200 Newtons all through this 300 micron. So, what I get will be 6 into 10 power minus 2 Newton meter. So, this is output work or energy; clearly this is not going to work because output is more than the input. So, we have this output 6 4 10 power minus 2, it is not going to work. So, immediately we can say that this specification user does not work; this is an obvious thing you can do energy calculation like this and then say that it is not going to work.

But the point here is sometimes when a user specifies all this lower and upper bounds what might look possible based on the simple energy calculation like this actually might not lead to a particular mechanism. So, that is where we bring in our selection map with the feasibility map as well as showing compliant mechanism within that feasibility map and then see if a mechanism in the database will work or not.

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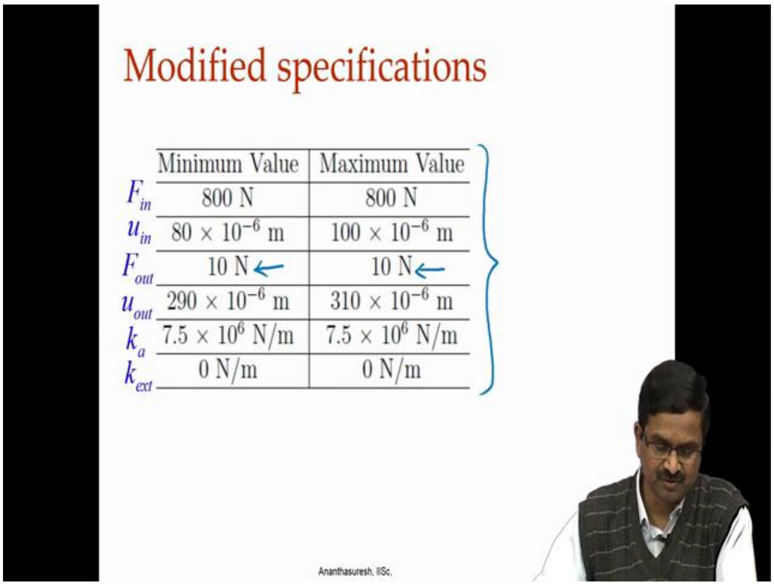

	Minimum Value	Maximum Value
F_{in}	800 N	800 N
u_{in}	80×10^{-6} m	100×10^{-6} m
F_{out}	10 N ←	10 N ←
u_{out}	290×10^{-6} m	310×10^{-6} m
k_a	7.5×10^6 N/m	7.5×10^6 N/m
k_{ext}	0 N/m	0 N/m

So, now what will do is to proceed with this example let us decrease the force, now what was 200 Newtons we decreased it to 10 Newtons rest of it stays the same; 800 Newtons input force over 80 to 100 microns of input displacement output is only 10 Newtons now and output displacement is again nominally 300 microns, but it can be plus or minus 10 microns. And then we have actuator stiffness 7.5; 10 power 6 Newton per meter no external spring force.

Now, if you have these specifications now we can see that what was 200 we made it 10 that is we reduced it by a factor of a 20; that means, that we have plenty of input energy. Now 6 by 20 is what we have there is have 4 into 10 power minus 2 4 is there. So, we have plenty of input energy and part of that energy can be used to deform the compliant mechanism; that is input energy can be split into output energy and strain energy for deforming compliant mechanism that we are going to design.

So, this technique is all about before designing we can make some inferences about what we are going to design. So, we can take this input energy which is 4 now this is only 10 the factor of 20, so it will become 6 by 20 and whatever 10 power minus 2 we had done earlier. So, it is a lot of left out energy that is 4 minus 6 by 20 times alpha minus 2 Newton meter that is available to be used as strain energy. So, we analyzed simply and realize that those specifies are not good now we have something that make sense just simple accounting of input energy and output energy, but it is not enough for us to say that these specifications are actually possible with a real compliant mechanism.

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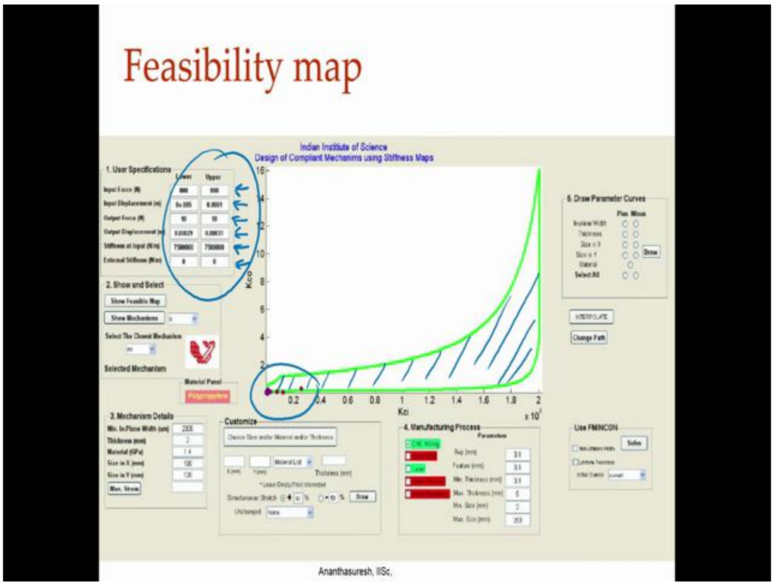

So, for that what we do is draw the Feasibility Map. So, whatever numbers that we had we have put them all here there is 800, if we zoom in we will be able to read and then displacement, we want output displacement output load 10 Newtons and input displacement, output displacement, spring constant, k external, all of them are indicated here, if we zoom in you can find out all there.

Now, we got the Feasibility Map. So, these all that the thing that is bounded by this green curve feasibility map. We also have a number of mechanisms that are plotted in this K ci versus K co plot.

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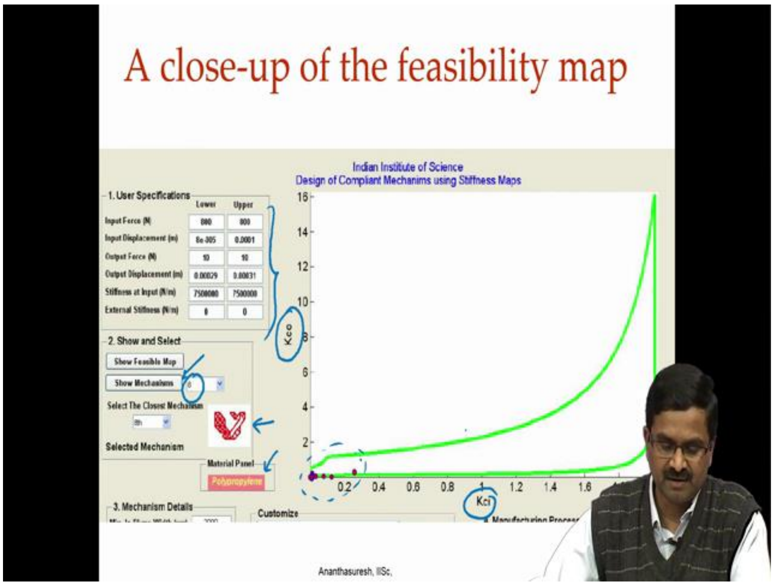

So, what we have here if I zoom in a little bit. So, here we have K co and we have K ci and we have the feasibility map now hopefully you can read the numbers that are entered here - 80 microns 200 microns of input displacement, 80 Newton of input force and all of that. So, we now have we can see some of the mechanisms also there and we can actually click this button and then say show mechanisms in this case we are saying show first 8 mechanisms if we count at in there is some overlap; there are 8 dots here. There on the boundary we have to see available inside; with that inside they definitely satisfy the K co and K ci values, but n value also has to be checked. So, if you look at and we can also see that mechanism is shown and what material it is, there are more details as was there in the previous slide. We are looking at only a close-up view of a part of the feasibility map window.

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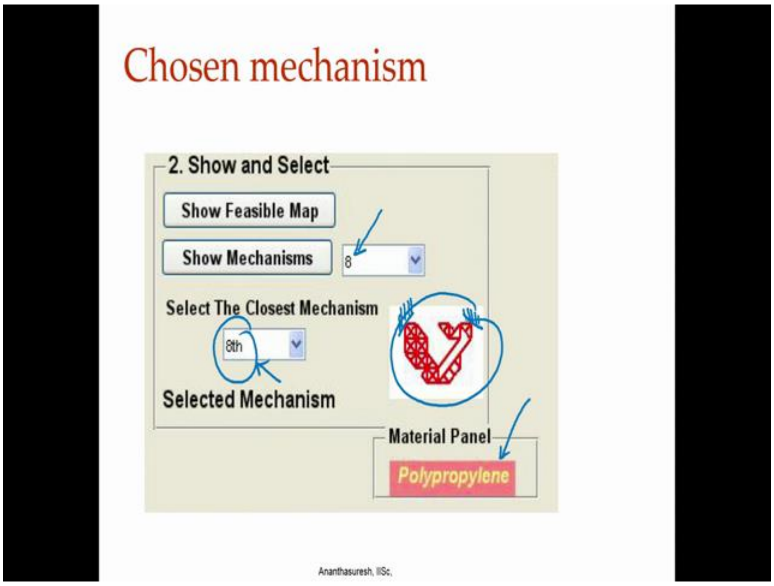

So, now the selected mechanism you can say. So, as I said we have 8 mechanisms we wanted to show we can show more as many as you want to see, but these are the one that is going to be closest to feasibility map are inside the Feasibility Map. Inside feasibility map posture will be there and then I think that are closer, if none other inside feasible to map it will show the 8 mechanisms whose points on the map are closest to the edge of the boundary of the feasibility map. We select the mechanism 8th here by clicking our by choosing here then the mechanism will show up there and that will have a lot of information about that what material it is, how does it look and even do an animations we can see how it going to be here this particular one is going to be fixed here and here, the user has to know all this because in this technique as we had noted earlier we are not going to let the user specify where it should be fixed. In fact, our argument is that many times user might not have any preference as to where to fix user is interesting input output port and there may be a preference for where should be fixed after the main functionalities served.

Now, when you show a number of mechanisms user can say this is what I like is I do not like or maybe this is too difficult to manufacture and things like that, based on that one can choose a mechanism of interest. We can see the animation and 3D model and all of that; you know what material I will see what manufacturing processes can be used to make the compliant mechanism is also there in it.

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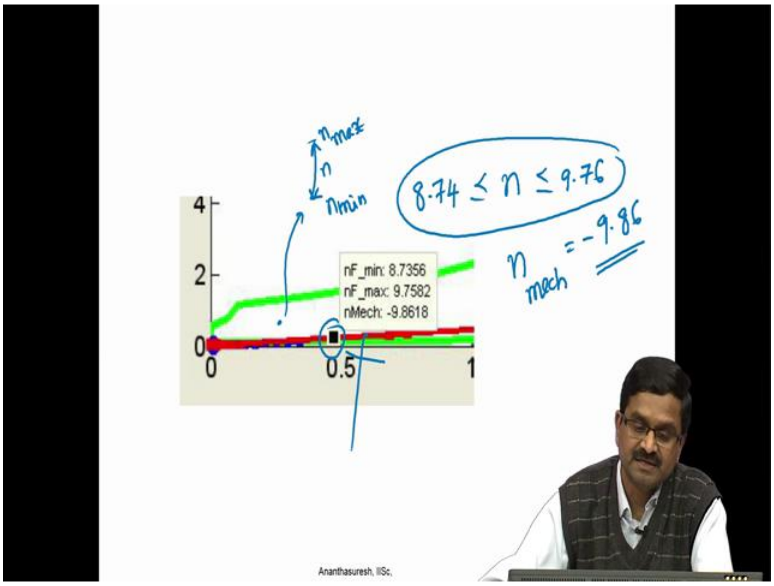

In this particular case when we zoom in and look at a point that is somewhere there which is slightly inside just inside, but very close to the boundary, but there is a problem n value if we can read this is n minimum and maximum that is what we had said any point inside the feasibility map will have a corresponding range of values for n.

So, this one we have a range of values for n there will be n min and there will be an n max. In this particular case min is 8.74 and max is 9.76; there are 2 different places it does not matter, but n of the mechanism that we have chosen happens to be minus 9.86 even if you ignore the sign which you should not because mechanism has a sign for n positive or negative; if it is negative it is an inverter that is input and outputs are opposite directions; if it is n is positive then form the same direction. Here 9.86 is clearly outside this range so this mechanism is not suitable for us. So, we can find that there is nothing else inside.

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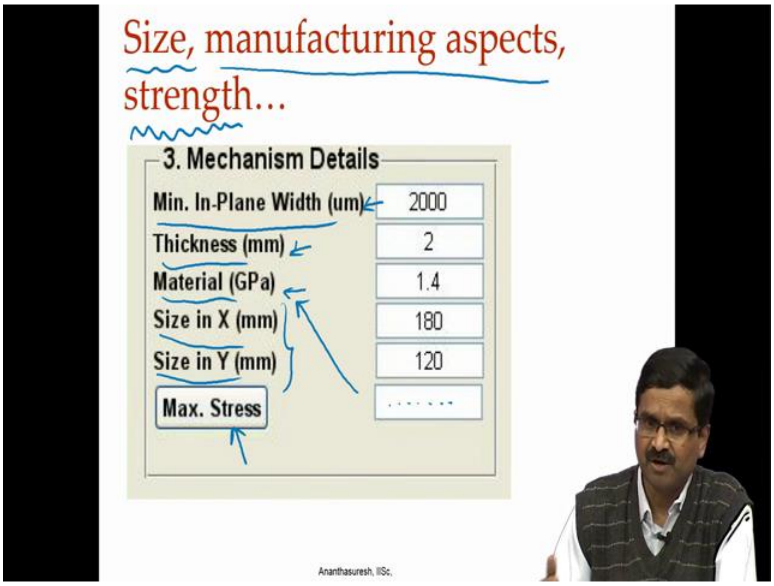

Then what do you do? That is when we try to redesign it, what we do is we try to change a number of things that we had discussed earlier. We can change the In-Plane Width thickness, material size in x, size in y all of those we can change as we wish and then see if we satisfy K ci, K co that is very inside the feasibility map and at that point whether n lies within the range correspond to that point because every point in the feasibility map K ci, K co Stiffness Map or Feasibility Map we will also have n because what we are seeing is only a projection of a 3 dimensional volume containing the feasible values of K ci K co and n. So, n will be rare there, that n has to correspond to or has to agree with the n of the compliant mechanism.

So, we try to change and we put some limit is of these we can change thickness, material and all of that and try to see, now as you can see the size is taken care of because Size in x and y we can put some values whatever unit is that the user wants to be consistently using manufacturing aspects because we have indicated the material and thickness and In-Plane Width all of those correspond to the manufacturing processes and strength as well because any time you click this button maximum stress in that interview gradually interface the stress value be displayed here. We can compare the strength of material correspond to that materiality that you have chosen we can see whether it is satisfy or not. So, everything can be accounted for in this particular method.

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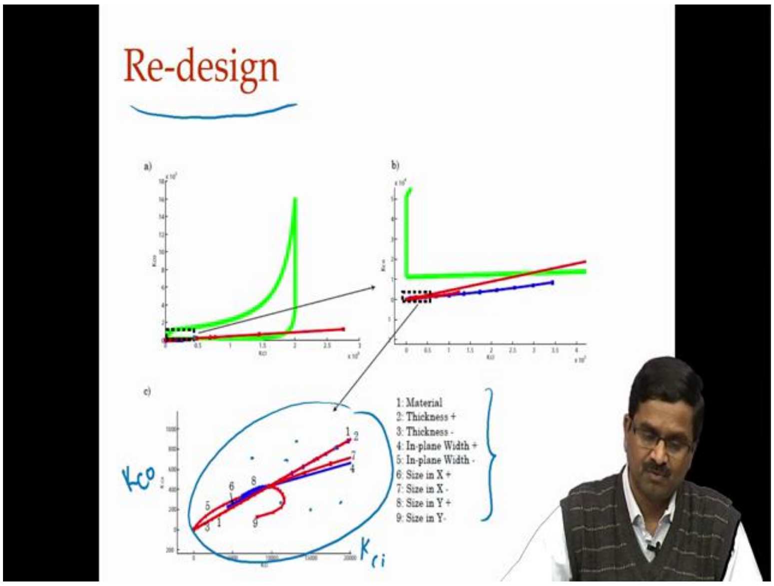

So, now with those things we can go to the redesign. So, redesign here means that the point that was there was not satisfied. So, we construct some parameter curves; parameters are here we can change material, thickness plus means that it can increase sickness and then see what happens to K ci, K co and if you click on it you would also know what n value will be there and then thickness minus means that you are decrease in the thickness and then In-Plane Width increasing or decreasing, Size in x increasing or decreasing, Size in y increasing decreasing or simultaneously will increase size and x and y, some of the decrease the Size in x and y. All of those things will be shown like curves that are shown here and they are all in the K ci, K co maps x axis you have K ci, y axis you have K co and of course, anytime you want to click and you will find out what the range of n is.

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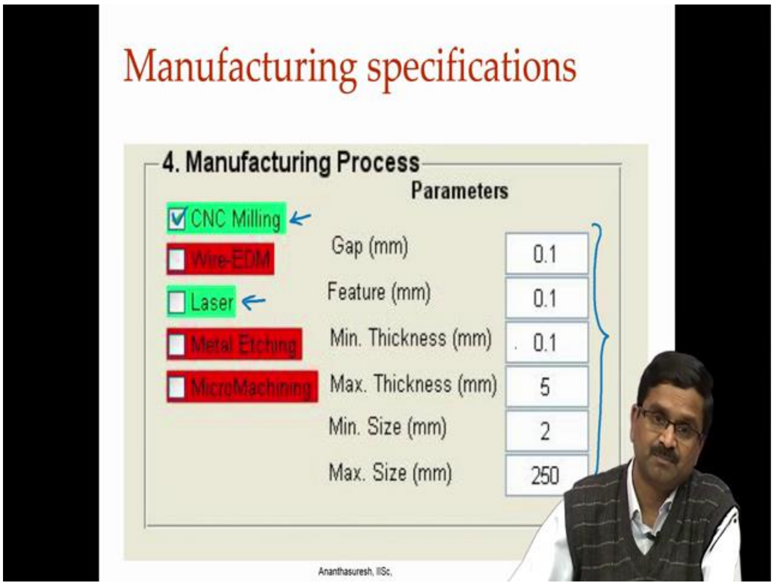

So, until it is satisfied keep on changing when you do so in the window it also shows for any mechanical chosen in green which are possible process is. In this case Laser Micromachining and CNC Milling are applicable whatever people who stored the mechanism in data base know with what manufacturing process is that mechanism can be made, indicate that in this particular case c and c one is c milling is chosen and there you can enter in millimetres in the particular case the gap; minimum gap that can be done, minimum features that can be done minimum thickness that process allows maximum thickness also because silicon in micromechanics, micro mechanisms will not allow very thick structures there is a max thickness also they (Refer Time: 18:58) beam in always and the minimum size and maximum size depending on what process you are using, you can enter all those manufacturing process parameters and then try to change them.

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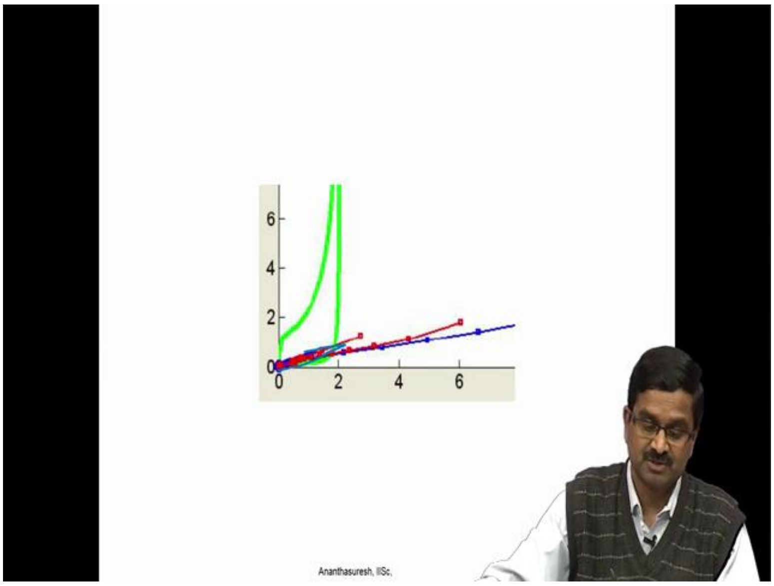

So, we started somewhere here go somewhere and then comes back. So, you can basically use it like almost like a game if you will, it is like a game where you start somewhere it is not satisfied move along one of those parameter curves and see if you enter the visibility map. If you entire check and value there n will have a range, if it is inside the range you are done if it is not change again from there draw parametric curves and you can do that.

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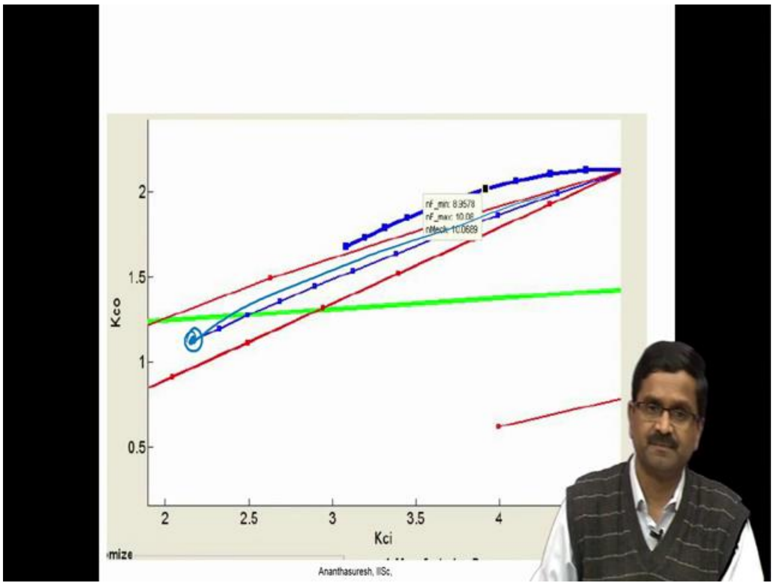

So, in this case something like that is shown you are started inside somewhere when there and then draw the curves and come back. So, you are at some point.

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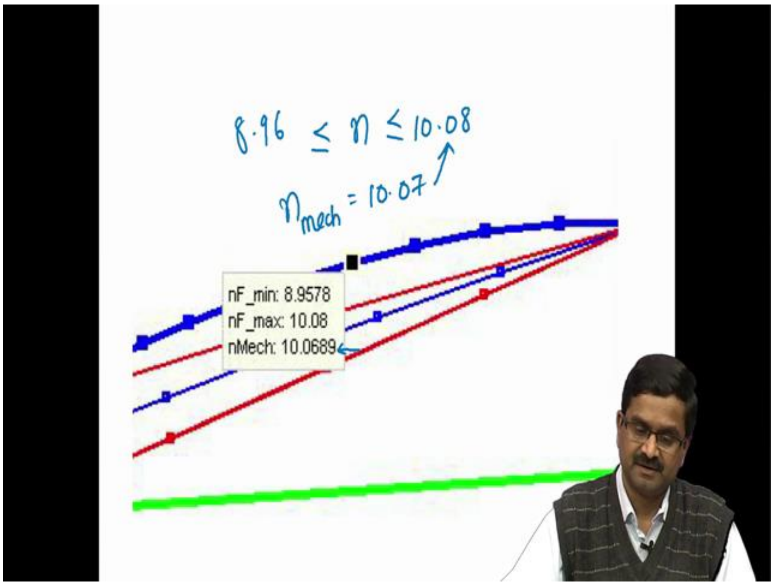

At that point if everything is fine meaning that n is within the range which it is so here you can see n min if I write, minimum value of n for that point is 8.96 maximum is 10.08 and n of the mechanism is 10.07 almost close to the maximum, but nevertheless it is in the range it is done. So, we have a solution we have a solution to the user specifications that are given that is how we redesign.

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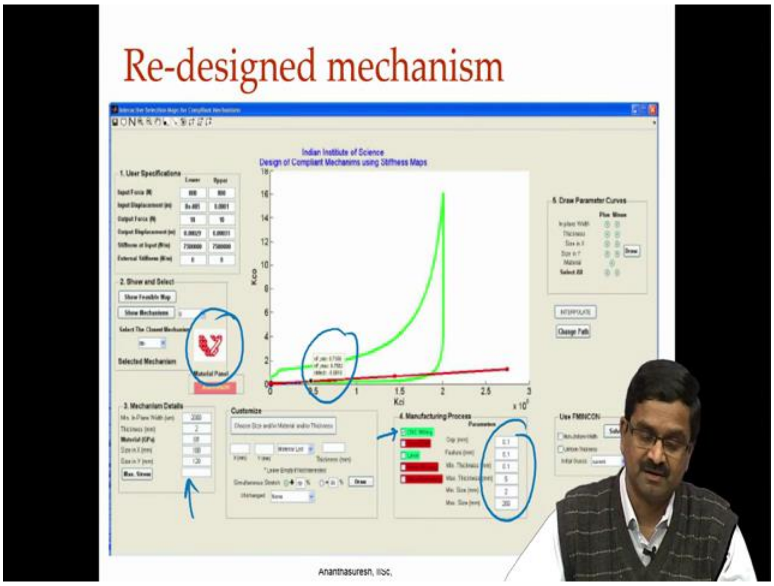

So, the redesign mechanism we cannot see unless you zoom in that information is there, you got inside look at the mechanism and what process is suitable for this, what are the manufacturing parameters and what is the maximum stress; all of those can be found out from the user interface by clicking a few button; software buttons it is not real button.

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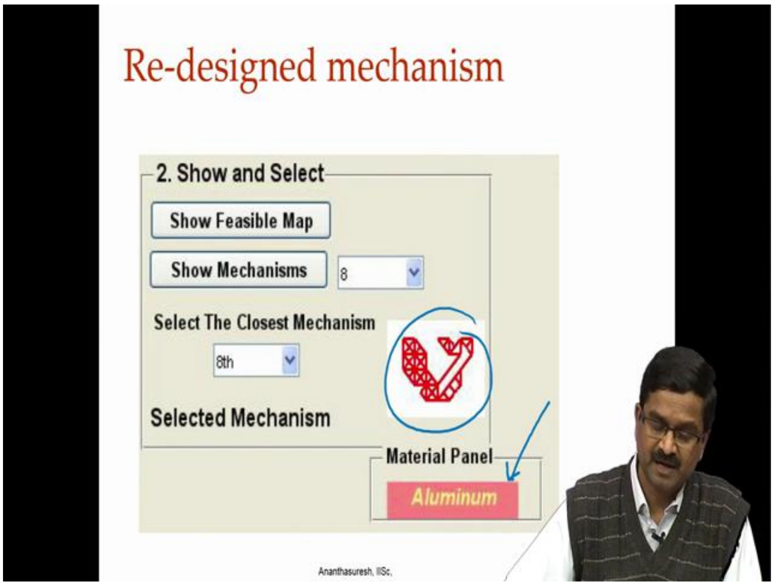

So, we have designed the mechanism. (Refer Time: 21:00) mechanism you can look at it now the material has changed to aluminium, (Refer Time: 21:04) it was polypropylene, but we change the material to the parametric curves and got that mechanism looks like this you know where is input and where is output and we get proceed with it, that is how this method works.

Now, let us take something going from meso scale like a Piezo Actuator or macro scale let us go to the micro domain; where we look at a Micromachined Accelerometer previous case study where the Piezo Actuator something output has to move it is more like an actuator where compliant mechanism is acting like a transmission. It takes the actuator and transforms the input output features suited to a particular application that is what a transmission that that is what we got.

Now, let us look at another study case study, a second case study where we look at a sensor; if you have a sensor how do you make it more sensitive through mechanical amplification is the purpose of this sensor; it is an accelerometer which measures the acceleration of a body on which the sensor is mounted.

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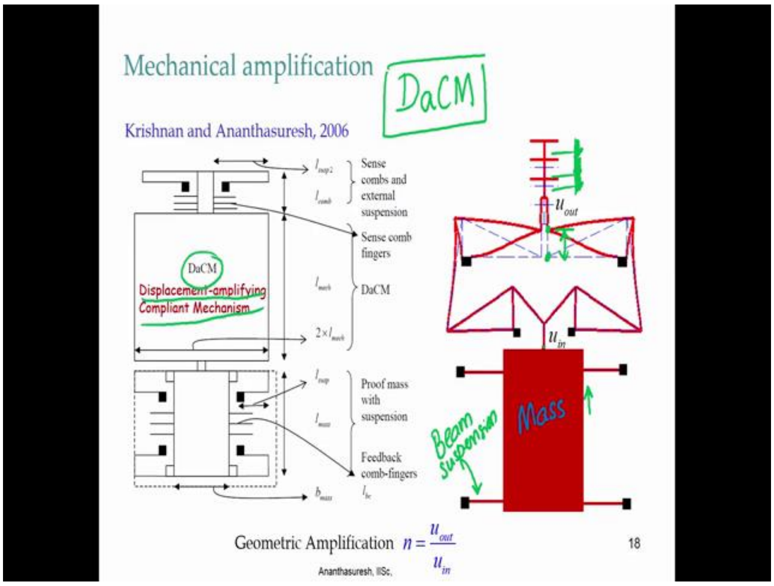

So, it is shown here usually accelerometer will have what is called a proof mass there is a mass and there is a acceleration it is going to deform it is going to deform and there are these beams which we call a suspension; this is the beam suspension it will move and you can measure the displacement electrostatically. But what we say here is that instead of (Refer Time: 22:46) electrostatically sensing over here the movement of the mass in the direction we amplify it here what was here has now moved to here.

So, it is a lot of displacement from here to here where input has not moved much at all, when output moves a lot here is where you can put the (Refer Time: 23:08) fingers and measure the change in capacitance. So, your sensor becomes that much more sensitive. So, you are trying to look for what we call a DaCM; Displacement Amplifying Compliant Mechanism that is DaCM Displacement Amplifying Compliant Mechanism as it is written here is what you want to design and for this also we can write first specifications.

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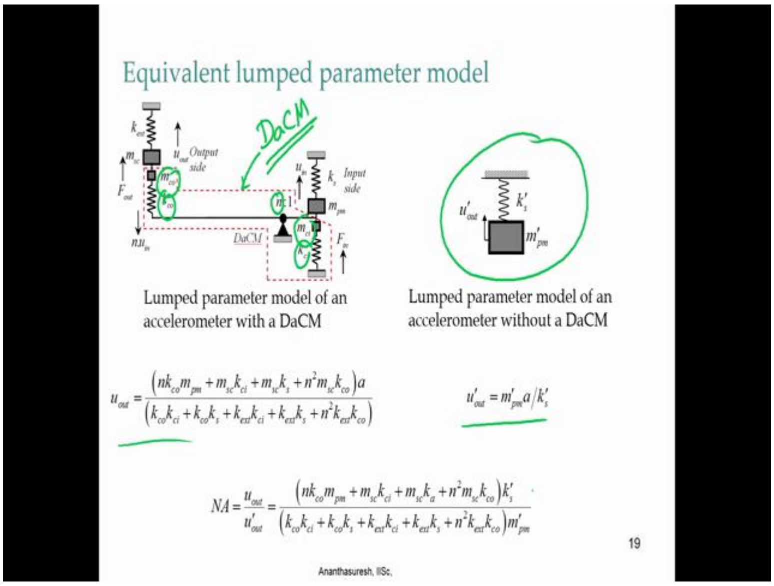

So, before that let us also remember or remind ourselves about the spring lever model where we have again K ci, n and K co. As we will see in the next lecture we can also talk about m ci and m co - input side mass inertia, output side mass inertia. Right now today we are going to discuss only the static applications relatively accelerometer.

So, what this slide shows is that just like a structure can be represented using a spring and a mass a compliant mechanism can be represented in this case DaCM Displacement Amplifying Compliant Mechanism can be represented using this spring lever model and the two equations u out and u in and net amplification there is a particular definition we look at that later. Anyway there you say analytical model for the spring lever model and we are using that along with the concept of the feasibility map.

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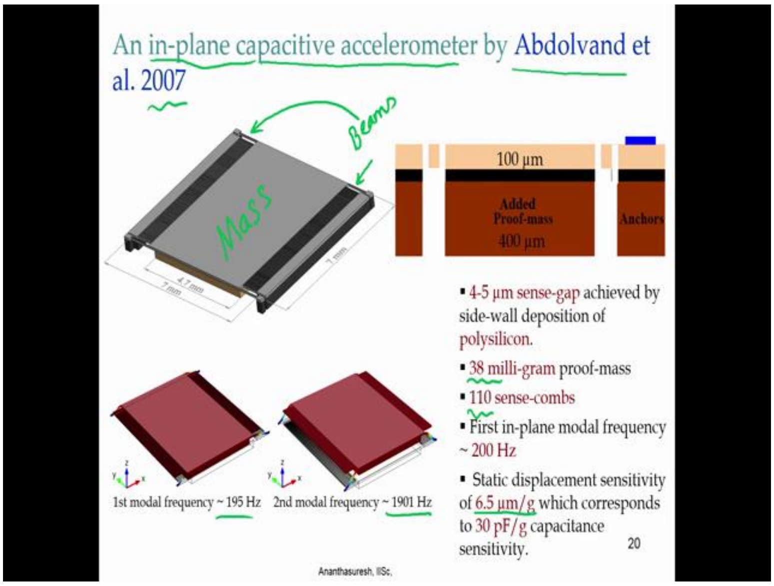

So, in this particular case what is done is that if you take an accelerometer in this case some researchers Abdolvand et al 2007 had published an in-plane capacitive accelerometer that basically looks like this these are the beam - this is the beam suspension you can hardly see those very small and there is a (Refer Time: 25:16) big proof mass and there are some frequency which will come to later because that is dynamic consideration that is not static and there are some thickness and so forth. The proof mass has to be 38 milligram and 110 sense-combs fingers that relates to how much capacitance is there, frequency, static displacement sensitivity 6.4 micron per g that is if there is an acceleration due to gravity of 1 g then the proof mass should move by 6.5 microns and the capacitance is 30 picofarad per g that is what we get the (Refer Time: 26:00).

Now, for these the (Refer Time: 26:01) we can calculate the equivalent input force and then set aside how much input displacement may be there how much output force - output force is not there here because just a sensor; it just moves and capacitance detected. A little bit of electrostatic force, but you do not worry about it is not put force there is an output spring because that suspension will add a little bit of stiffness and displacement the more than many year because for given g if it can move by let us say 1 micron then you can resolve much smaller through capacitance then you can actually get it fairly accurate value of whatever you going to measure.

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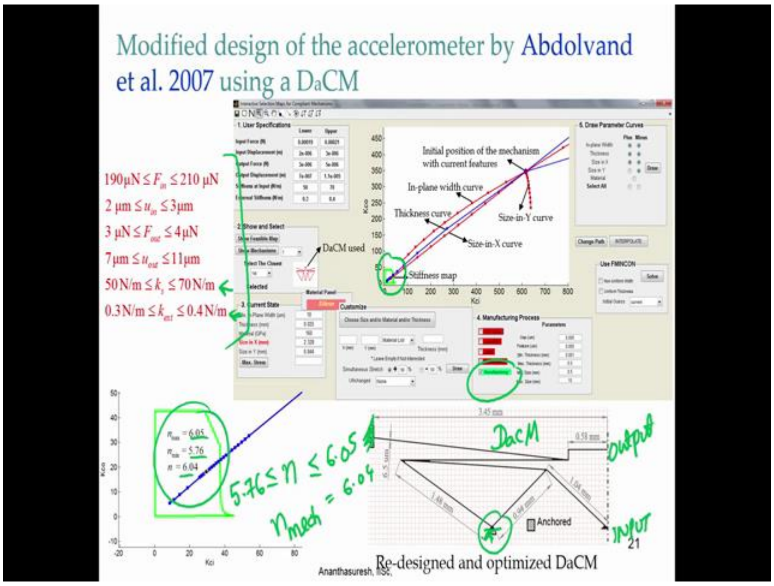

So, in this particular case what we have done is we have extracted those in terms of the specifications F in is 190 micro Newtons 210 micro Newtons that is 1 g acceleration times the proof mass n g basically and then input displacement is asked to be between 2 microns and 3 microns then F out is 3 micro Newtons to 4 micron Newtons and then output displacement 7 microns to 11 microns and there is k a that is actuated 70 Newton per meter and the 0.3 Newton per meter to 0.4 Newton per meter is the k external that is for stiffness that you have for the output side; with those things we can draw the feasibility map again if it is very small and if that is not satisfied most often it may not be in terms of n also then you try to do this parametric curves and try to get what you want.

So, here we have that feasibility map another mechanism 6.04 n max 6.05 n minis 5.76 clearly n is within the range; let me write that in case you cannot see there - n min is 5.76 whatever the unit is in this case n has no unit and 6.05 n mechanism that satisfies that inside the feasibility map is 6.04 again very close, but the method is finding something that is possible with n value not just K ci, K co you have those and here is the mechanism, mechanism looks like this it is fixed here and it is fixed here and here is where the input is and here is where the output is - it is DaCM Displacement Amplifying Compliant Mechanism. We can see that is fine sometimes having an anchor inside like this may also cause problems, but there are ways to deal with it they can choose and in this particular case is also showing that Micromachining is the only possibility for making something like this because user would have put in such information into the software.

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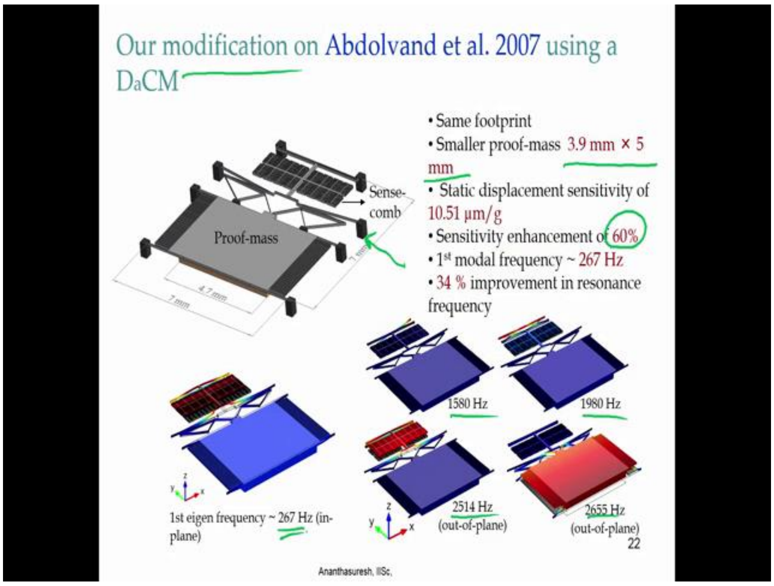

And we modify that Abdolvand's Accelerometer by replacing compliant mechanism in between the proof mass and the Sensing Mass. When you do that we actually see that for the same footprint that is 3.9 millimetres 5 millimetres static displacement to 10.51 micron per g unit auxiliary of gravity sensitive improvement of 60 percent over up till advance design. So, you can take the best acceptor that is there and make it better by adding a DaCM Displacement Amplification Compliant Mechanism; we will talk about that in another separate lecture later on detail the purpose here is to show that we are able to design an accelerometer or rather a compliant mechanism or DaCM Displacement Amplification Compliant Mechanism for a given application here application is an accelerometer.

So, we can do later the analysis frequency analysis and so forth and later on when we discuss the dynamic equivalent of SL model which we call spring Mass Level model SML model then we can actually look at the frequencies that simulation shows and the frequency that that experiment give there is a difference one has to figure that out.

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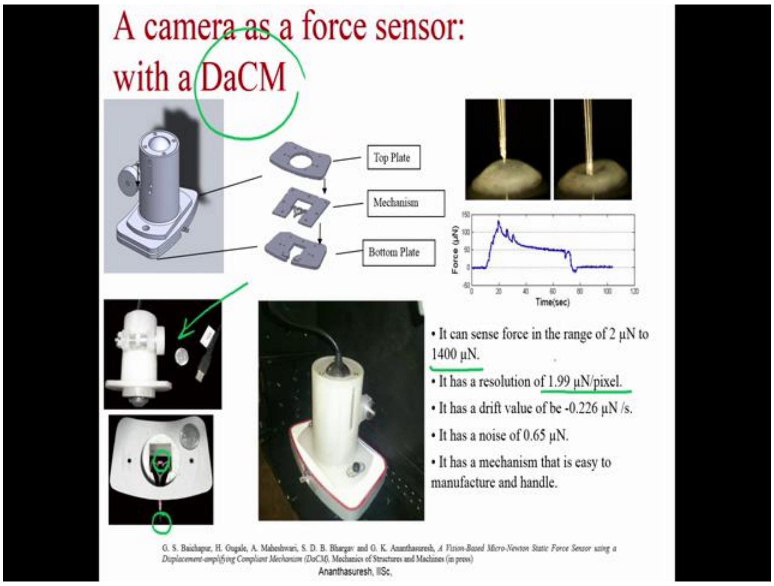

There can be another case study which we are not going to discuss in detail, but we will take it up later where again another DaCM, but here there is no put force, there is an output spring. It is simply a sensor that has a probe which you can see here a little probe a small force applied will amplify the displacement over there that little red thing and you want it to be large enough to picked up by digital microscope. So, digital microscope is here and that (Refer Time: 31:22) displacement we can calculate the forces; with this we could do a resolution of 2 micro Newtons per pixel and with a range of about 1.4 milli Newtons or rather 1400 micro Newtons force is what we can detect that range the resolution of 2 micro Newton per (Refer Time: 31:44).

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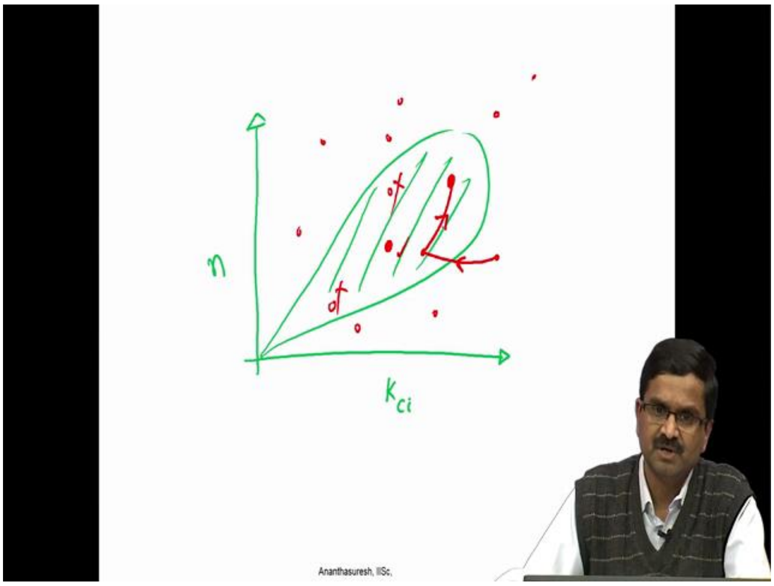

In this particular case since there is no output loader force; K co does not matter. In fact, what we will see later on is in this case feasibility map will be order 2 parameters we can just say here is K ci and it is n because K co does not matter when there is no output load, no output spring here also there will be a feasibility map and we can put all the mechanisms inside that.

So, there could be some inside, some outside no matter how it is we can detect that if you say this let us this one the n value matches that is taken n value does not match you throw it away, n value does not matter throw it away. So, you can keep on going like this until you get what you want sometimes you may have to change parameters curve let us say from here it comes along one and that n value does not change again go along another curve and finally, end up here that is what discussed in last lecture through case studies we will illustrated this. But it will also get a demo of the program where you can see how it is done both in MATLAB as well as in java, there are 2 versions a supplementary material will have access to these programs

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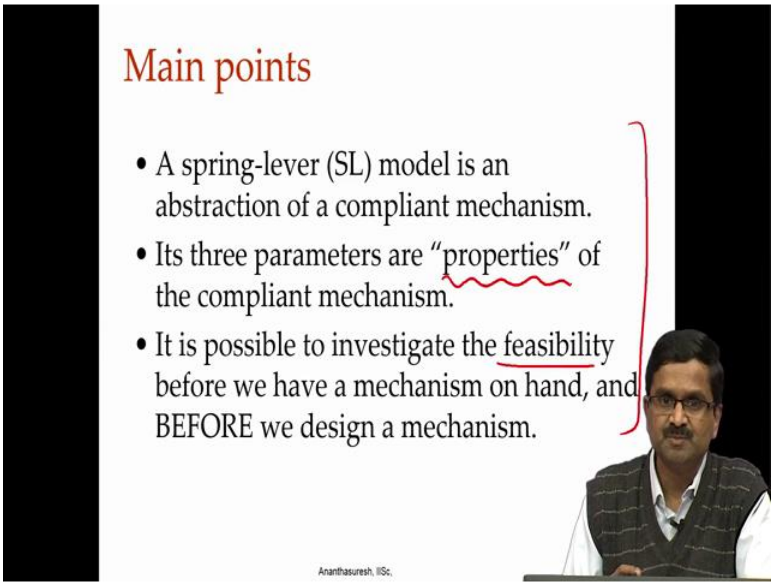

So, to recapture the main points there is exactly what we had done in the previous lecture we can investigate the feasibility of a mechanism before designing it and after that we can select and redesign it and what are important here is to note that there are this properties of complaint mechanisms which are spring lever model parameters is what we are looking at.

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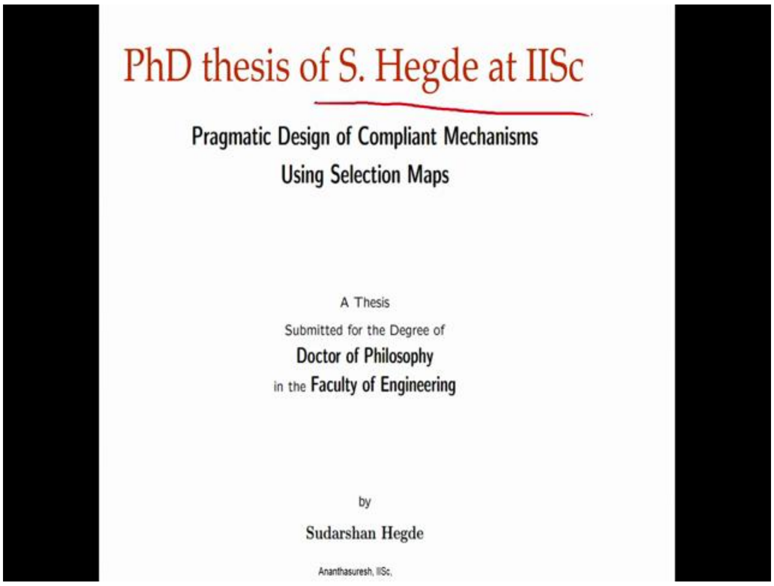

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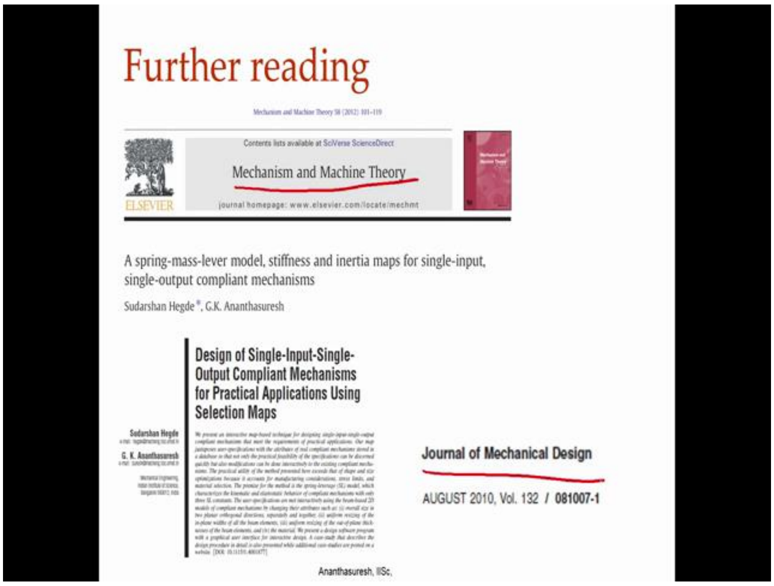

So, the PhD thesis of Sudarshan Hegde is the basis for this method that he had developed this method as part of thesis. So, that is available to you and you can read that or to the papers that Sudarshan has written one in Mechanism Machine Theory another one Journal of Mechanical Design is also available for further reading on this topic.

Thank you.