Compliant Mechanisms: Principles and Design
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Lecture – 42
Re-design of Compliant Mechanisms; MATLAB and Java Codes

Hello, this is the last lecture of this week where we are focusing on designing using selection maps, what we called stiffness maps, inertia maps, feasibility maps and using spring lever model as well as spring mass lever model, today we will actually demonstrates this technique using two programs; one built in MATLAB, other built in JAVA online one can access and try out this technique. So, let us look at the demonstration of the selection map based design technique for designing compliant mechanisms.

So, let us start with little bit of recap of what we have discussed before we go for the demonstration using software today. So, let us just write a few things down to see that we understand how this design technique is going to work.

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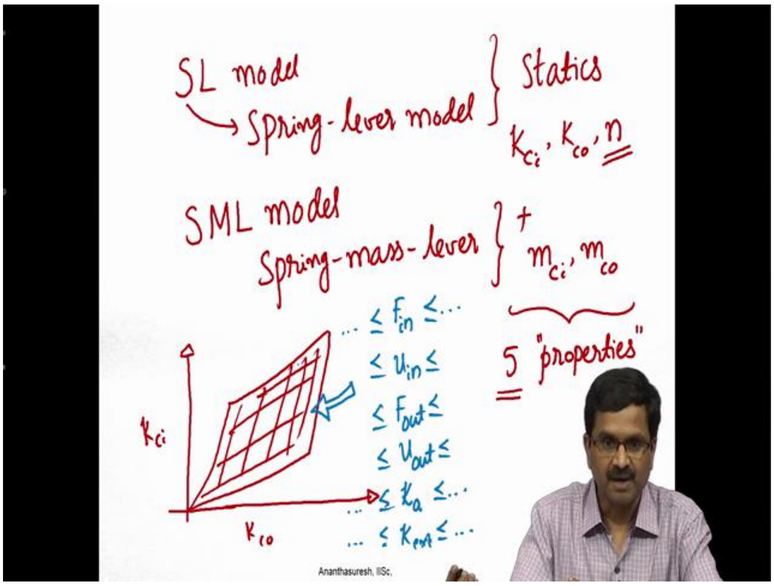

The first thing we discussed was this S L model, so where S L is spring lever model, so this is spring lever model, where we used three properties of compliant mechanisms, we do call them properties because they capture the effect of a compliant mechanism when you look at it from the terminal model that is there is a input terminal, output terminal or you can call it input port and output port. Between the input and output what happens is captured by this S L model for statics; that is static response is what you are interested in then we have K ci, K co and n these are the three parameters which happen to be in the two by two symmetric matrix that relates to the input degrees of freedom in terms of displacement to the corresponding forces or movements on the other sides, that is what spring lever model recapture more like a black box, a terminal characteristic model.

Later we also discussed S M L model, so this now becomes applicable for dynamics where we have spring and mass and lever model. So, here we add also m ci and m co. If K ci and K co are inputs and output sides stiffness parameters m ci and m co are the input and output side inertia parameters. So, these five quantities we also call them properties because every compliant mechanism as some property just as a material would have its properties for a static there are three properties, for dynamics two more properties. So, these capture what happen be in the two terminals so the compliant mechanism that as one input one output. If we have multiple inputs and multiple outputs that will be different, but for a single input, single output compliant mechanism these five properties sapphires.

Using this model and based on users specifications and this model, we drew what we called feasibility maps. In fact, is a projection where the n value is actually showed like a gray scale density in that feasibility map, so there is some map like this, so inside this map any point that you take is going satisfy the user specifications, user specifications we had a long list rather twelve in equalities we have input force and input displacement, output force output displacement and we had actuator stiffness and we had also k external.

So, all these things had upper and lower bounds, so we specify all these twelve values, so there is a lower bound, upper bound, lower bound, upper bound and so forth. So, these are the twelve ones; are the ones that users specifies, based on that we draw this feasibility map and find the feasible values of K ci, K co n. If it is a statics problem, n off course is shown like a gray density in this map; otherwise if you take three axes K co, K ci and n in the three dimensional space will be a volume that is what we discussed. Once that is there; at least the user can be guaranteed to believe that there is a scope for finding a solution for that.

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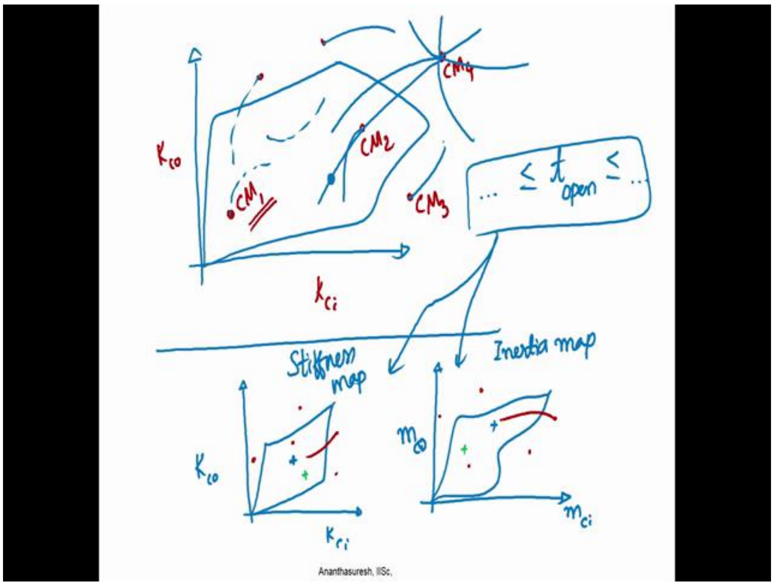

Now, what we do is we look at the compliant mechanisms and try to put them as dots in this map. So, ones we have this feasibility map drawn let us say it is something like that, this is the feasibility map. Now every compliant mechanism, now this is the let us say K ci, K co; sometimes you may want to plot K ci and n; depends on the application. So, the cremation map is a projection then every compliant mechanism will be a dot, so some may be inside, some may be outside.

Now we say if CM 1 and CM 2 are inside the feasibility map they suitable for the application, let us say CM 3 is here which is outside which does not satisfy the user's specification. So, it is more like selecting a compliant mechanism database, this is for statics we discussed that is what we will demonstrate with a software program today, in fact, two software programs we demonstrate how we can specify these twelve values here. So, there are six variables and each of them had upper and lower bounds, we can specify them and try to construct this feasibility map; we have discussed how to compute it.

Once we have that using a database of compliant mechanisms, we can get all of these complaints plotted here and then see how many of them lie inside, how many of them lie outside. If any of them are lying inside and their corresponding n value also satisfies or rather within the range because, once a feasibility map; you have K ci, K co here every point will have certain range of n values that is continuous as we have discussed and that continuous range of n, if it also matches with the compliant mechanism, so at this point there will be a range of n and the n of the compliant mechanism which is what we call property, lies within that range then this compliant mechanism satisfy the user requirements completely and we can take that.

If it is not and none of within that are inside actually match the n value also, we go to something that is not inside and try to bring it inside by drawing some parameter curves. So, we vary various parameters like the width of the beams, overall size in x and y, change material, the x and y sizes simultaneously or cross section and this simultaneously, we can generate all of that and get it inside. Once we comes inside, we may find that satisfies and again we have to satisfy n value, so we can also do the redesign.

So, while designing that we can look at the strength as well as manufacturing considerations such as minimum width of the beam that can be made using a process that you can select, we can actually select manufacturing processes and then set specify the manufacturing process also in there; those are size, thickness, narrowest beam, widest beam and smallest whole all that can be specified and accordingly we can redesign and then get something that actually comes inside the feasible phase, satisfies the all other requirements manufacturing strength of course, functional stiffness, displacement and force that can be done, this is first statics. If it is dynamics what we also said is that in addition to looking at the stiffness map, we can call it stiffness map when we are plotting K co verses K ci. Similarly, we can talk about inertia map may will be talk about m co verses m ci.

So, there will be something here, there will be something else here. Now when I click somewhere here there will be n value, correspondingly there will be n m c, m co because of the users specifications in this case, in addition to input force, input displacement, output force, output displacement, actuator stiffness and external stiffness we might also have the anemic consideration such as natural frequency or time for certain task some let us say it is a valve problem we discussed, the valve should open within sometime all of those the anemic consider can be kept and user can specify if it is like time to open.

So, t open user can specify a lower bound and upper bound, there will be more equations for us to solve in terms of now constructing these two maps, the stiffness inertia maps whenever there is a cursory if it moves from there to; let us say to another point, let us say from there to it moves here, this might move here, you have to do that may move out also right. Again we show all the compliant mechanisms on both the maps, so there will be some insides and outside. So, we have to look at all of those and do the same procedure as we have done and that way we can select compliant mechanism from a database and modify them or redesign them is something is not there we can draw this curves that bring it inside and satisfy the user requirements, so that is how it is going to work.

All of this we have discussed so far applies to small displacement compliant mechanisms meaning that instantaneously that is what the properties they have, that is spring lever model and spring mass lever model both are per instantaneous behavior of a compliant mechanism, but compliant mechanism are known to undergo large displacement.

So, we need to consider that non-linearity also meaning that if I have a compliant mechanism and I want to consider the large displacement behavior.

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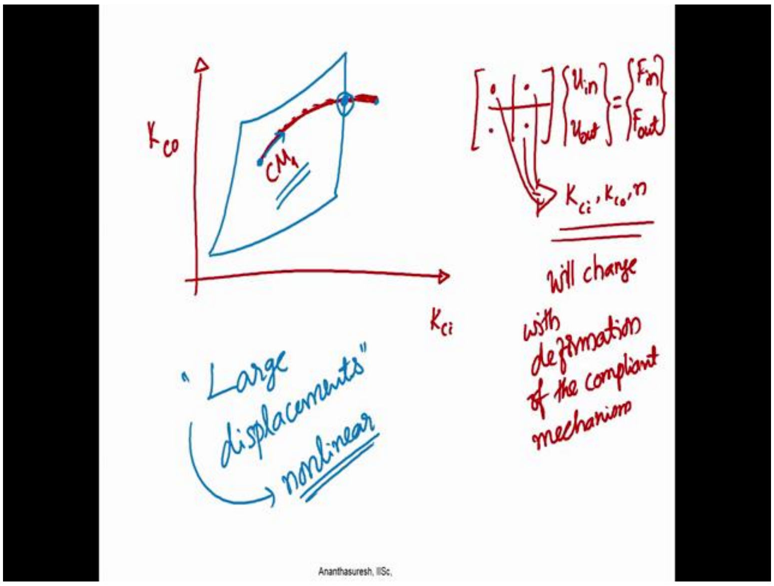

If I want to plot a K co verses K ci, it will be a single point if you consider instantaneous behavior the compliant mechanism. So, at that instance it has 1 K ci value, 1 K co value, now when you start applying more force than if stiffness is going to change, most often because of geometric non-linearity; not because of material non-linearity due to geometric non-linearity and sometimes even including contact we will have change stiffness of compliant mechanism. So, when there is a change stiffness because if again recall this K ci, K co n are nothing, but this 2 by 2 matrix symmetric input displacement, input output displacement and then that relates input force and output force.

So, these four things because symmetric matrix, so these are basically representing our K ci, K co and n. Now this is going to change because as the compliant mechanism undergoes large displacements, this matrix which we called tangent stiffness matrix are that instant what to happens because if the no force, it is under no force load free condition, at that point we have K ci, K co n. Now when we deform the compliant may the applying some force it is in a different state, at that point again we have to construct linearization to relate displacements and forces from that conflagration, so all these values will change.

So, they will change with deformation of the compliant mechanism that we are considering, so this is what we call non-linear are large displacement compliant mechanism. If that happens then K ci, K co values are going to change; it is going to go for one point another point at different points you take, these all with one compliant mechanism, they will be a path for it, there will be a locus. Now this will still be amenable for our feasibility map technique or selection map technique, if let us say a feasible map is somewhat like this then we will know that if you are starting here and as you apply more force on the compliant mechanism its K ci, K co change like this, we will know up to what point a compliant mechanism is going to be the requirements.

The user also which is specify input output distress may be for a initial to final, the final is here initial it may be they inside when you apply; that is basically 0 4's and you know that may be inside, but as you apply the force; K ci and K co mechanism are going to change, it may end up here. So, it does not satisfy, but up to what point we can satisfy will be able to know, so the concept of selection maps with stiffness maps, inertia maps both are feasibility maps, we can now draw a curve corresponding to each compliant mechanism if it is consider large displacements.

So, this concept of selection map base technique does work when you have large displacements are read it as non-linear behavior, it will still work. The difference is that each of them will not be a point, but they will be a curve, that may be curve like that this may be curve like this, may be curve like that, this may be curve like that. So, the things are going to change each element will have and you have to work in the same way same thing inertia and stiffness maps as well, so the concept works for large displacements also.

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So, what we will do now is these are the two papers that we have repeat in refer to in this week's lectures. We can read the case studies that are there, we had one lecture on the case studies as well. Now let us look at the procedure of designing compliant mechanisms using this technique; by using; a software. So what we will do is, we will first look at what is implemented in a java program, so I have a recorded movie of that this is available to you as part of this course because you can actually take it from the online u r l; universal resource locator, but just look at how it works.

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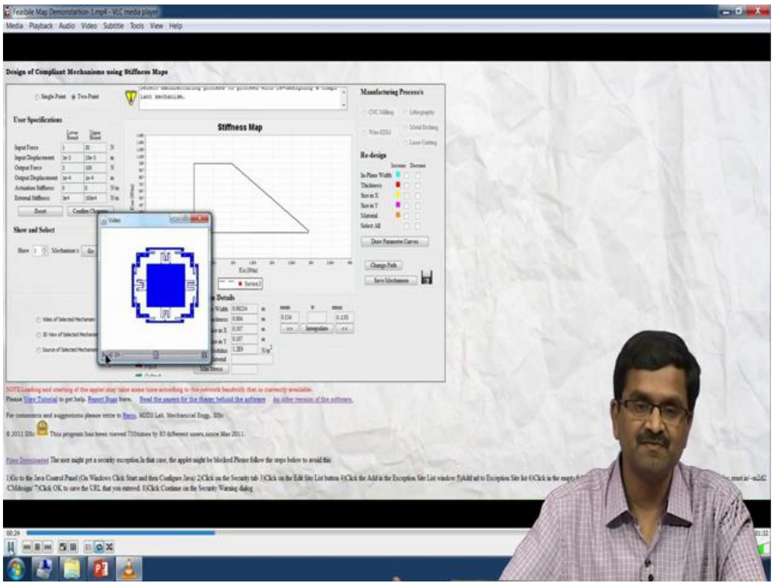

So, this is a movie, so first I have to pass and show you what happens. So, first let us start, so when you start there is small print here, but we can to read on the screen there is single point and two point, what this means that single point means that in a compliant mechanism there is a database of compliant mechanism, in all of them there are input points and output points all of them are already proscribed. At the input point because there all 2 d, there will be two degrees of freedom there is a x displacement and a y displacement.

So, if your input output are both at the same point, then at a single point you choose there may be applications where you want input, output both to be at same point, but in different direction; that is you are pushing in one direction, it will also get pushed other direction, so this is your input that is your output. In the 2.1, there are of course two different points and you can choose input at one point output another point in whatever direction one prefers. So, the most often it will be two point compliant mechanisms so we can click that and select it. So, that is the first thing to do and then what you see here in this little block here, it has the six parameter to be talked about input force in put displacement, output force output displacement, actuators stiffness and external stiffness, lower bounds, upper bounds. Units are indicated here, but one can follow their one's own consistent unit system.

So, I will just run it now to see that one can enter all these there already entered and then if we say confirm changes then it would actually draw the feasibility map. Now confirm changes we clicked now it actually draws the feasibility map from the other lines are not feasible, but you actually get a feasibility map by zooming out we can actually see the feasibility map that is here K co and K ci and we have a feasibility map drawn. So, if we change any of these numbers feasibility map will change, in doing so we are solving those twelve inequalities upper and lower bounds under six parameters in the two equilibrium equations pertaining to the spring lever model, it is all done first static this program is only first static applications, so we have the feasibility map drawn here and then you also see a little dot here that is actually because we are selecting one best mechanism which is inside the feasibility map or closest to it, we can change the number over here to see more and more mechanisms.

So, if it is there, so that will be visible and if you double click on it; it will open a window where that mechanism will be shown correspond to that point we said there is a database and you are showing the closest mechanism that is in the feasible space or closest to it then you double click on it the mechanism design will be insight. So, you can see the animation at this point user can see whether that is suitable for the application or not and if you select some more let us say 20 year port some more mechanisms are shown.

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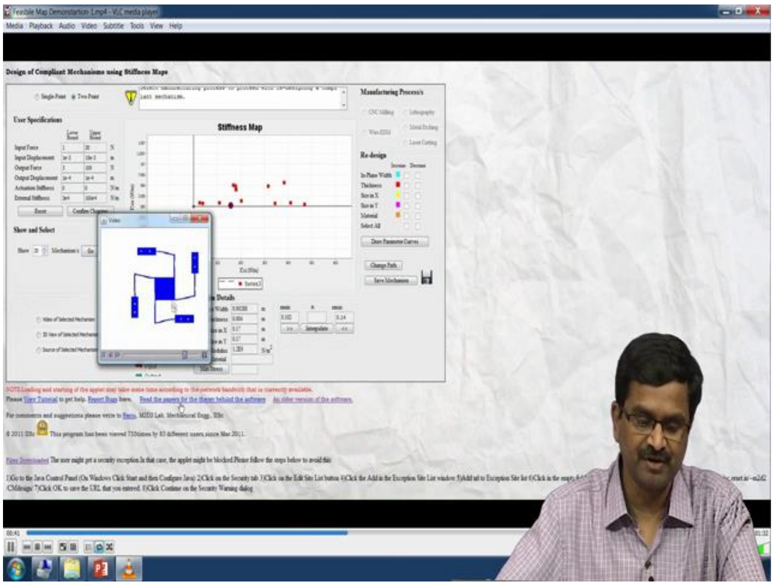

We can zoom in and select anything else that want to one see; how does it look because many of them are inside, so it is a different one now, they are different; it is a suspension here so a different one shows. So, you can choose these mechanism then see which one of them lies; remember that all of them have two different points improper can be interchanged, once you have database, you can have multiples ways that you can look at; input output can be reverse and that may look like.

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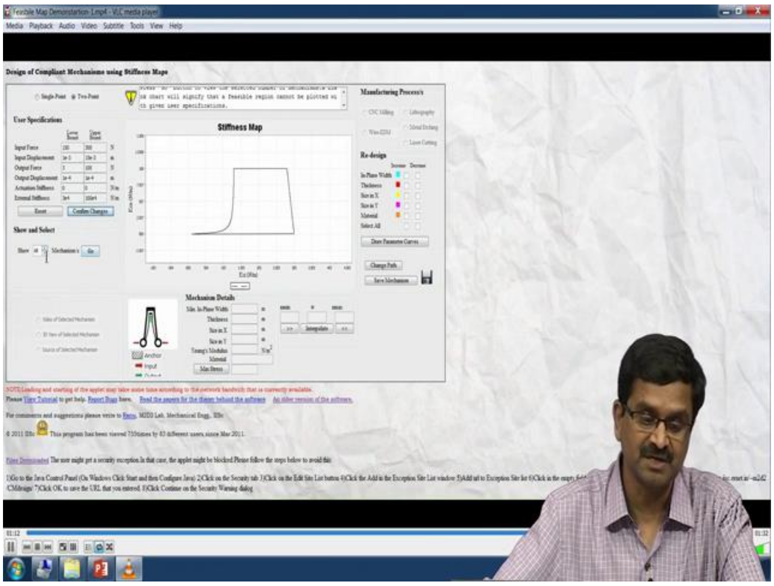

We can change the numbers as it being done now and then confirm changes if you do then it will redraw the feasibility map, we can see that the shape changed because numbers are changed. Again you can mention how many mechanism you want to see where they lying inside or not and look at the mechanism and see if it is n is satisfied or not, it is a different mechanism now. The animation tells you where it is fixed, whether how fixed points are there in a mechanism and all of those details one can take. So, is the game being shown that two point confirm changes with something goes back to specify; we started out with and that is how we can do this mechanism, so we can change the specifications and work with it.

Now what we will do is look at the redesign as well, now we see user need to simply enter this specifications and then feasibility map look at the mechanisms and look at their animation and then see whether that mechanism will suit the particular application or not and choose the mechanisms, if none of them satisfied we have to go for redesign that is what we will show these are redesign.

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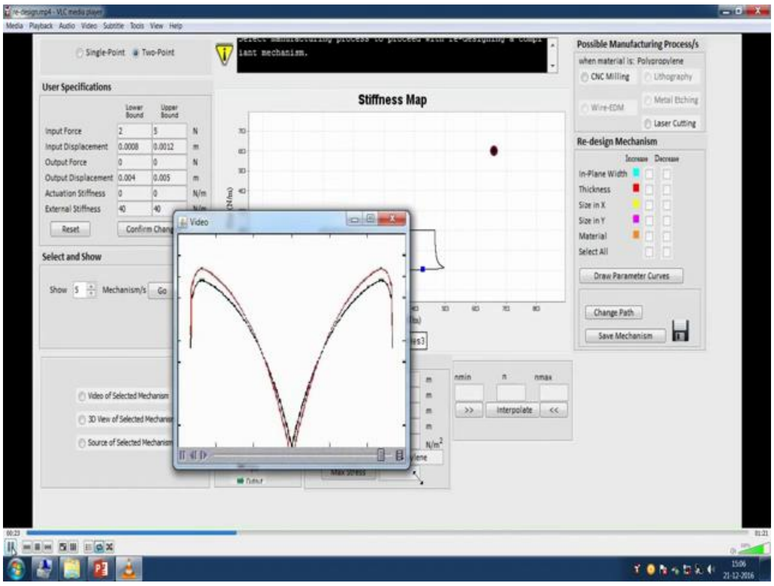

Again this is 2 point there confirming changes got that and look at the mechanisms, all mechanisms everything will be shown here 5 is entered, so some of this dots appear and you look at the one that you like just to bring, you like it no whatever reason this mechanism looks a little sketchy, but after all it is in database; that means, that somebody as enter it is valid compliant mechanism and that is lying outside the feasibility map, we need to bring it in by changing that is what we will see in this movie clip.

So, you can see how it deforms and now we see it to bring it in; we choose CNC milling that is what we have. So, look at that we have chosen CNC milling, other options are wire e d m, lithography that is micro fabrication then metal etching, laser cutting which was then CNC milling, it opens a box like this where you can put minimum gap, minimum width, minimum thickness, maximum thickness, minimum size in x and y and maximum size in x and y can enter all of those values in this units that you are consistent. Once you “ok” it will be change this parameters we have now in plane, width, thickness, size in x size in y material and all of them at once, if you do it will do that now will continued with the video clip. So, in this particular case we are choosing, decreasing the size then that particular thing will have, decrease the size going away from feasibility map.

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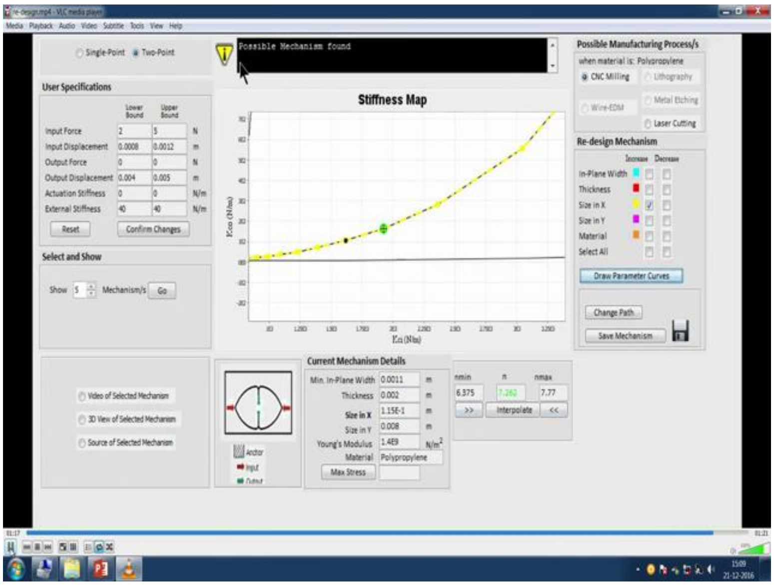

You realize that decrease in size is not on option for this particular case, then you change may be increasing size would work, instead of that let us increase size then it goes the other way comes back in the feasibility map these exactly what we mean by redesign, we are not redesigning the topology entirely, we can see what mechanism it is, here this is the mechanism and we are increasing the size of it and try to get it in to the feasibility map. We not do to anything more of course, when this locus is being drawn, lot of finite meta analysis are being done within this environment; this case if the java and environment and it is just getting you into feasibility map after that you have to match the n value also.

So, now if we click any point on that redesign curve; now you see in this particular case n range minimum is 6.34 and maximum is 8.64 and the mechanism point at that thing has 8.68, maximum is only 8.64 whereas, you have 8.68 and that is in red color meaning that n does not satisfy. So, we have to explore more along that curve; it is a redesign curve, if we go somewhere else; now it suddenly became green. So, maximum here is 7.77, these only 7.26; minimum is 6.38. So, now, we have green, you are done; you can take that mechanism on walk away, so that is how it works of course, we can look at maximum stress and look at the mechanism one more time how it looks and so forth. So, that is how we do the redesign of the compliant mechanisms in this technique.

What we will do now is, we will switch to a MATLAB version and look at that, so that

MATLAB version; online version with the URL given to you; you will be able to access it and with MATLAB version you will have more control, if you want you can even change whatever you want, add more things to database compliant mechanism that is integrated the program and play more with it.

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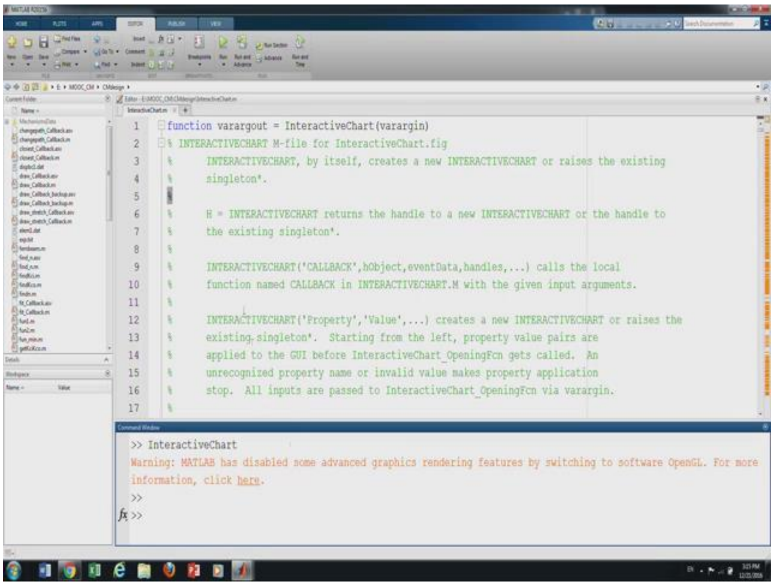

So, let us look at the MATLAB version of this same technique, so in the MATLAB version; we have a program as we can see it is actually called interactive chart, that is what it is because this whole technique is interacting with the user right from the beginning and user want specified numerical quantity values and that is a distinctive feature of this technique, user can actually specify the values and try to run. So, here if I go and say run this program then it will come up with this the chart.

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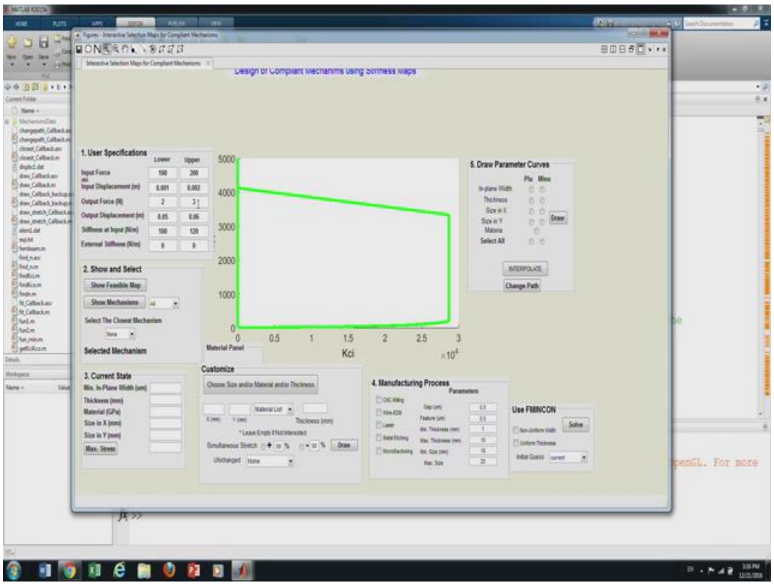

So, this window what we saw in the java program similar structure where input here and showing mechanisms and so forth, let us say I change this value; it is now 250 if I change to 300 and then say show feasible map changed and I can let us say decrease it, I will decrease it to 150. So, input is between 100 to 150 things here, if I say feasibility map, it did change something happen here, so shape changes. So, we can enter the values the way you want, let us say output is now 2 and 3.

Let us say; I will say 2, if you say precise you have only 2 Newton’s of force, then you can put 2, 2 in input output and show the feasibility map, now it becomes more or less rectangle here it will little curved. So, if you want to zoom here, there are zooming zoom bottoms here for this graphics window we can actually see the zooming there and just like in MATLAB, this actually based in MATLAB, and we can actually look at that double cliff bring you back to this. Here there is no external stiffness if you want to put external stiffness you can put; let me 100 and 120 here.

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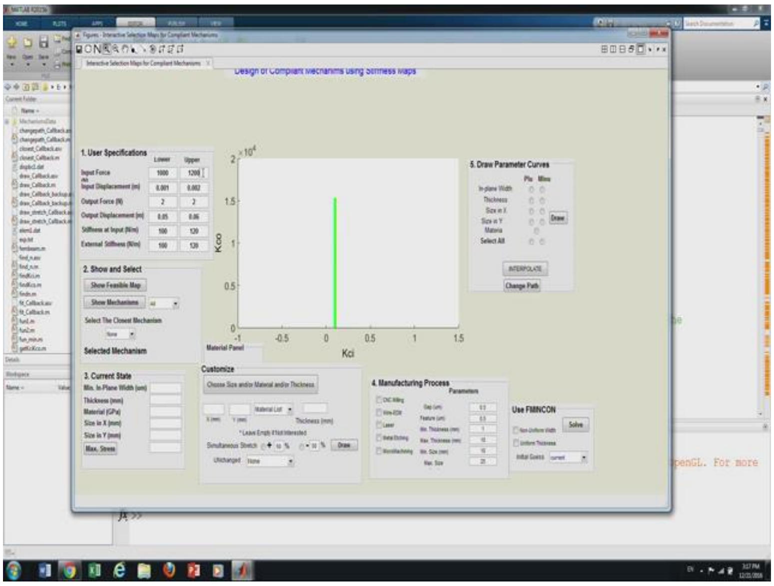

Now, say feasibility map suddenly is goes with or rather it will become, in this case very small may be have to zoom in a lot to see that otherwise just a line so; that means, that this specification may be little too harsh, that is just a line is a feasibility map and then K ci is something like 0.21 and K co is very very large because in order to have external stiffness to be handled, you need to have very high stiffness on the output side became 10 power 4 that is 20000 or rather 15000 here; there are this is only 0.1 because input displays like that. If I increase the force let us say, so in order to count over like that let say I go from 1000 to 1200; that is I am using a different actuator, let me put that feasibility map, now something comes the shape is more interesting.

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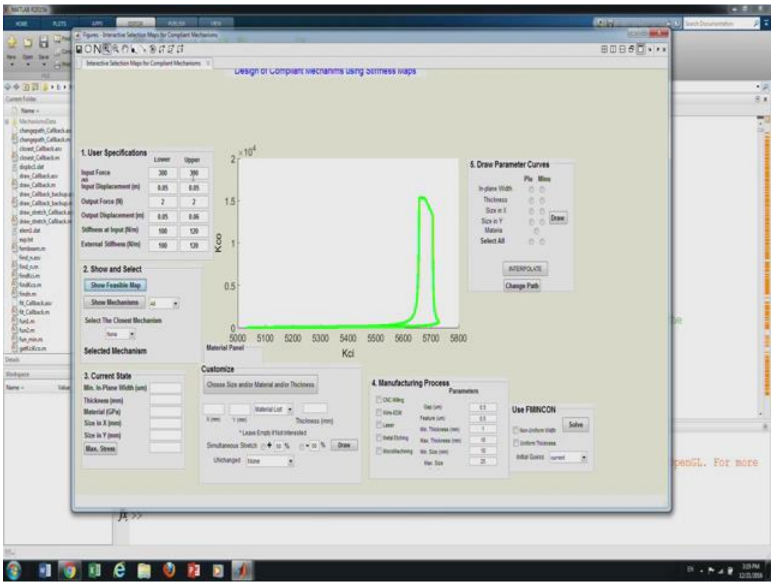

So, now we can see that if your output load is more output stiffness is more unify the feasibility map has reduced mean satisfy specifications cannot be met in practice. Now, you have to use a different actuator, now that is what we have done different actuator, but displacement let me increase that also, let me make it instead of 0.001 which is the millimeter, so now let me make it a centimeter and I would say anywhere between 1 centimeter 1.5 centimeter, I have an actuator; let say that directly comes from the actuator, then feasibility map if you show you changes.

So, now I get let say little ambitious I want; it is a more displacement, I want 2 centimeters right precisely input, output, lower and lower bound, upper bound or the input displays an output 0.02 here I still get, in fact little wider things. Then I want to see how much displacement can actually have because the actuator stroke will be there, it is a 5 centimeters feasibility map with even wide in it right, giving more displacement actually getting it better. So, then I would see what happens if I use a smaller actuator like say I put only 500 Newton's, now 500 Newton's to 600 Newton's all that specification are compliant. So, there flexible in a way that there is elasticity in the value that user can specify, so if I see feasibility map, still find then I could see what is the smallest actuator that I can actually take may be 300, if I take 300 what happens with the map. So, now it became narrower, so we can see that as I change the values; what is the; actuators?

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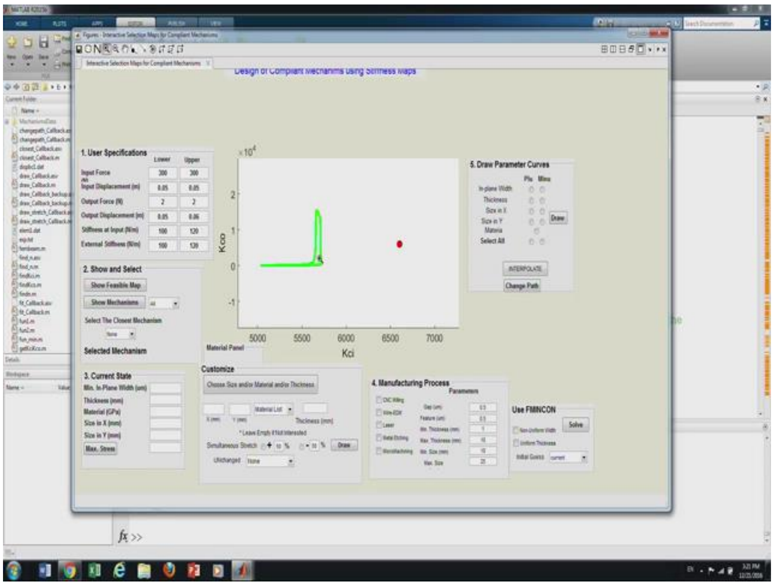

Let us say that if I show compliant mechanisms, show mechanisms now; we have to see that they are all somewhere they have to reel is zoom in now either thing, so we have to see where the map where always be at origin. So, you have to zoom in a lot meaning that whatever we have in the database do not have.

So, let me keep; now we see the map here little green one, so nearest compliant mechanism is over there. So, if I can use these draw parameter curves and get it inside, if you want to go with a smallest actuator. So, here while designing compliant mechanism, we can design it for the actuator the users chooses and there are other features that we saw how to get it in to the feasibility map by changing this, the manufacturing process is you can look at the stress as we go a long and manufacturing process we can customize and do the size also we can choose what is possible and get that here.

So, this MATLAB program gives a lot of flexibility and the more things you add into a database, the more the chances that for specification that users enters there will be a compliant mechanism that is readily available for that application, suitable application if not we can change it and get it in there. Once we get that we can add it back to the database and make the database richer. So that is how this technique works.

Thank you.