Compliant Mechanisms: Principles and Design
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Lecture – 57
Compliant Mechanisms with bistable Arches

Hello we are discussing Bistable Complaint Mechanisms or the phenomenon of Bistability in Elastic Systems. We had two lectures in the first lecture we talked about what Bistability actually means in an Elastic System, the second lecture we discussed one class of Bistable Elastic Systems which is Arches and we discussed an analysis method that lets us analyze Bistable phenomenon and we said that the same analysis method can also be used for synthesis. We will discuss a few applications today. So, that we understand how Bistable Arches can be used in real applications.

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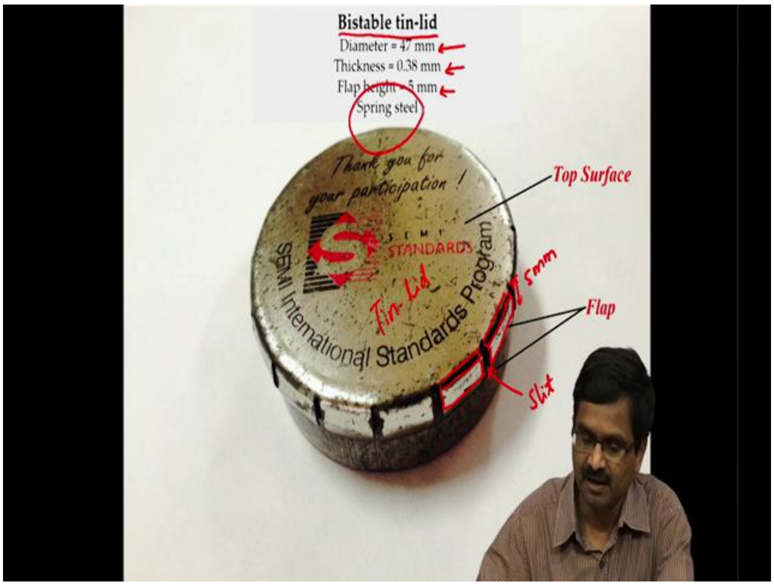

So, let us look at this application of Bistable Arches in Compliant Mechanisms and the basis for what we will talk about is captured in this Bistable Tin-Lid. So, what we see here is a tin little tin it is a small one which has all rusted and so forth still works. This lid of the tin this is the tin lid the Top Surface and there are some Flaps on the sides there are Flaps like this on the sides and there are all in a slit here. So, that there is a little thing here in between the little slit and this has a very interesting Bistable behavior it is a metallic tin but it has very interesting behavior and its diameter is 47 millimeters, thickness is 0.38 millimeters or 380 microns, flap height is 5 millimeters the height of this is about 5 millimeters, it is made of spring steel.

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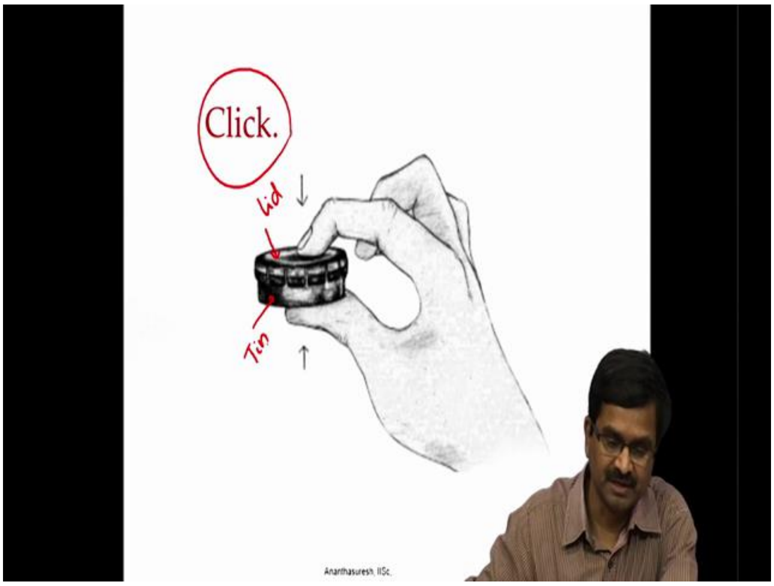

So, here is a sketch of this device it is a Click Clack tin lid. When you press on it, it makes that Click sound and you can take out the lid. Lid is very tight where it is on the bottom thing here this is the lid this is the tin when you press on it, it becomes loose and you can take out the lid.

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And then when you want to close it you have to press on the sides you have to press on this sides or the tin and it makes the Clack sound. Let us hear it to see what this Click Clack sound is what I have shown you is this tin lid here. So, there is a tin and there is a lid here and it is very tight.

So, you cannot open it you can turn it like this, but you cannot open. You have to use a lot of force if you want to open it this way, but it will open if we just press that way that is a Click sound you hard it now it easily comes out it just comes out.

Now if you want to put it back before that let us see the Bistability here this is the tin lid circular and there are Flaps on these sides here and it is another side and if you look from this side there is a little curvature down here like this. So, you can do this Click than Clack, Click, Clack. So, you can do that, but then when you put it on the tin then you cannot go underneath to push it like that. So, what do you do that is why there is a nice design feature here with these Flaps on the side which are slit you can see the Flaps on the side.

So, if I put it and then press it on the Flaps from the side it makes the Clack sound now it is tight, it does not come. So, I have to really apply lot of force to take it out, but I cannot put it back also that easily because these Flaps are there. So, this Click Clack is the thing here. Such a thing we call it Bistable Bimodal or Bimodal Bistable device because it can be switch back and forth like this and it can also switch back and forth like this.

So, this way and then return in another way, so this Click Clack Tin-Lid is what we are going to analyze or also use it in an applications. First let us look at the Energy and Force Curves in this Bimodal Stability. So, what is shown here is an energy curve again energy here is Potential Energy. So, we have Potential Energy.

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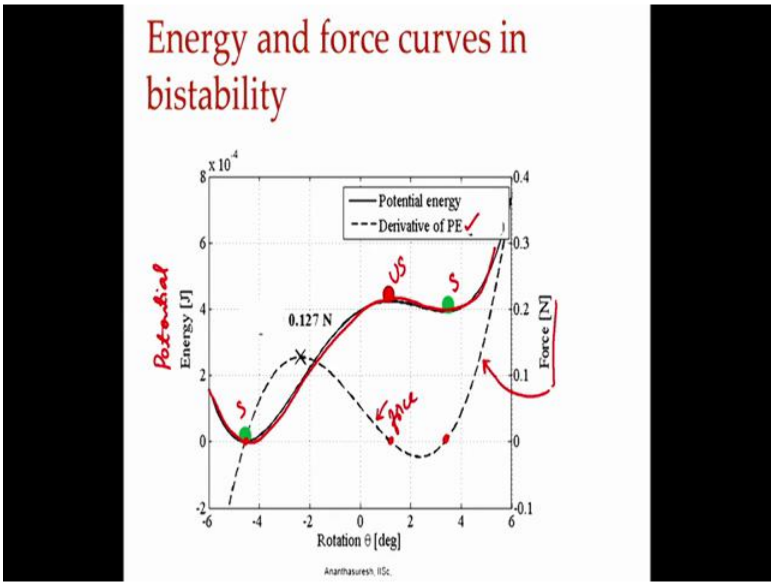

And there is a Rotation Angle given that is the angle if you where to look at a 1 Dimensional model which we will discuss, but idea is that it has Potential Energy which is like this. So, there is once stable position here, another stable position there, there is a unstable position this is stable, stable and unstable and the dashed curve is the Force Curve that is derivative Potential Energy that is the Force Curve. It is 0 here and 0 here again. It is also 0 in between, but that is the unstable point.

So, the force is showed on the right hand side with is dashed curve. It is the Bistable device is also Bimodal because when we have the actuation what we can call Port 1 Actuation where we press it like showed here and the Port 2 Actuation, but press it on the sides.

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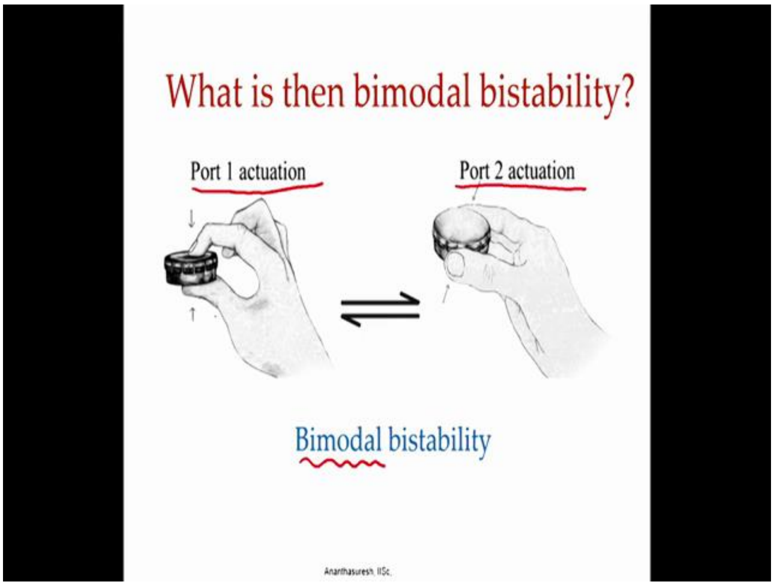

So, it has two ways that we can actuate that is why we call it Bimodal. There are two modes of actuating this tin lid, one this way and the other second way we can go back and forth between state 1 and state 2.

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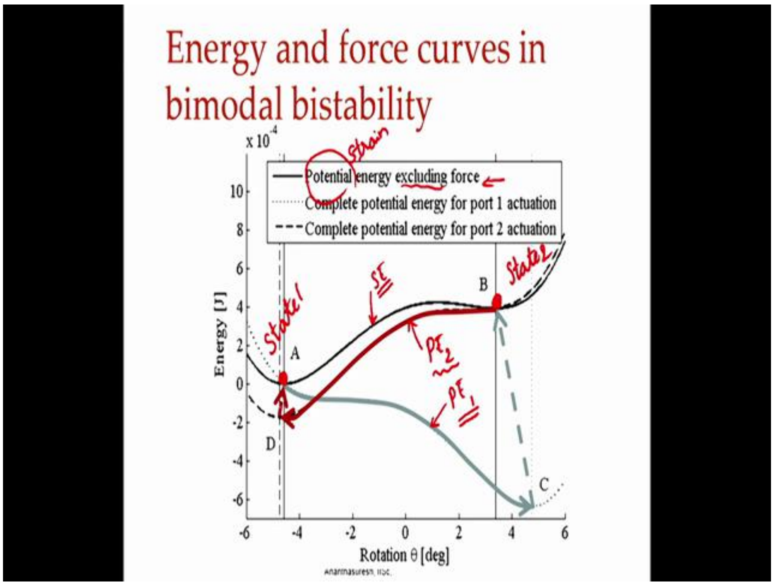

See if you look at the Energy Graph this we are showing the Potential Energy Curve in this line solid line and then dotted line is the Potential Energy when there is Port 1 Actuation. The first one in fact, we need not call it Potential Energy this is simply the Strain Energy of the elastic body of the tin lid. Strain Energy plus work potential becomes the Potential Energy. So, when there is no force that is excluding the force that is Strain Energy itself that we have. Then we have Port 1 Actuation Potential Energy and then Port 2 Actuation the other Potential Energy. This is Strain Energy, this is Potential Energy with Port 1 Clicking sound and then P 2 Clacking sound.

So, how does it operate when Strain Energy is the way it is imagine that there is a ball here and the moment the energy landscape this is the all the energy that we are plotting energy landscape which is from Strain Energy to P 1, the ball starts rolling until the curve remains is black one the ball will be where it is the moment we apply Potential Energy one landscape that is apply Port 1 force it becomes like this and the ball from there would roll and reach that point.

Then remove the force it comes back to where it should be that is the second stable state. This is Stable State 1, this is State 2. It comes there. Now you have to switch it back of course, you can come back this way and go there that is energy landscape moves again from S E to P E 1, then it will retrace it is path, but what we do here is change it to P E 2, then from there it would take that path because that is the minimum now comes back here and then it will move second port actuation and will come back there. So, going and coming back or different here that is the Bimodal Bistability that we seen this unique tin lid.

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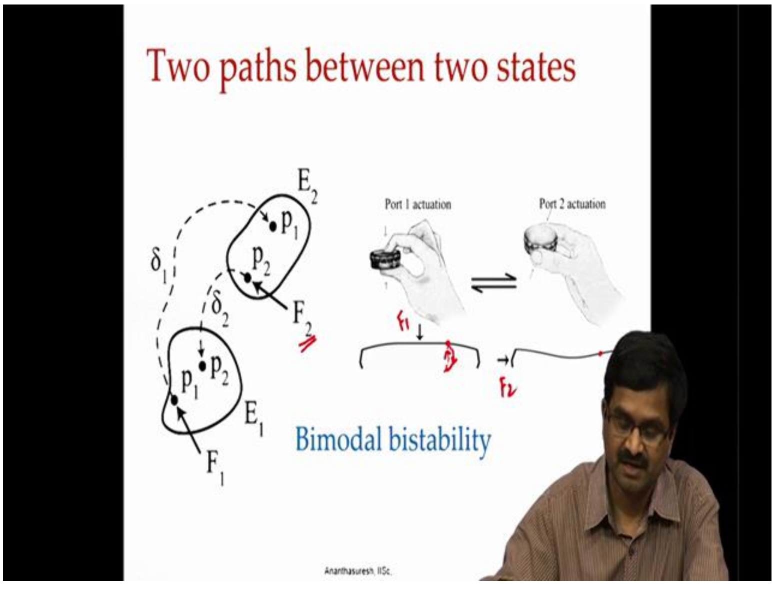

So, depicting in a using a figure you have a point P 1 in energy state 1 goes to P 1 energy state to a point and when it comes back it will take a different path because you applying force elsewhere at different point and that P 2 in that energy state 2 will come back at P 2 energy state 1. So, going back forth if this is our Port 1 Actuations, then these are our Port 2 Actuations, we take point it will take one path going that way and then when it is here let us say that point when it goes there let us say that is here then will take at different path to go back to this. So, from here will take a slightly different path to go back it will come like this go like that. So, that is what we have.

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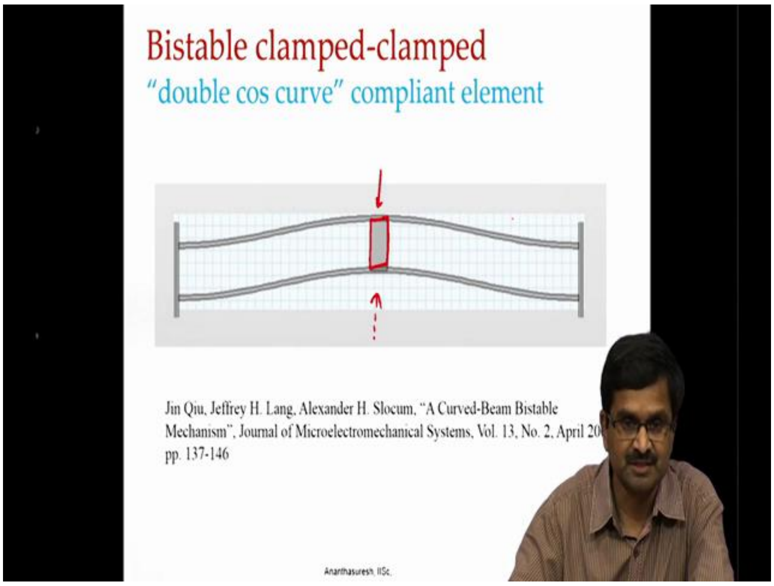

So, that is what is being shown here, the paths between the two states or different. When it goes from state 1 and state 2 it goes along one path and then coming back takes another paths because the actuation force itself is different and this Double Cosine Curve that we have discuss in last lecture the reason that it is there is to prevent the Asymmetric Mode that exists this one.

So, Double Cosine Curve is only you apply the force here and then you put it back here where it goes to other side that is only a single port by stable mechanism, you can apply force elsewhere pretty much there all will be similar, but not like this Bimodal one, if you want Bimodal one we can use pin joints here.

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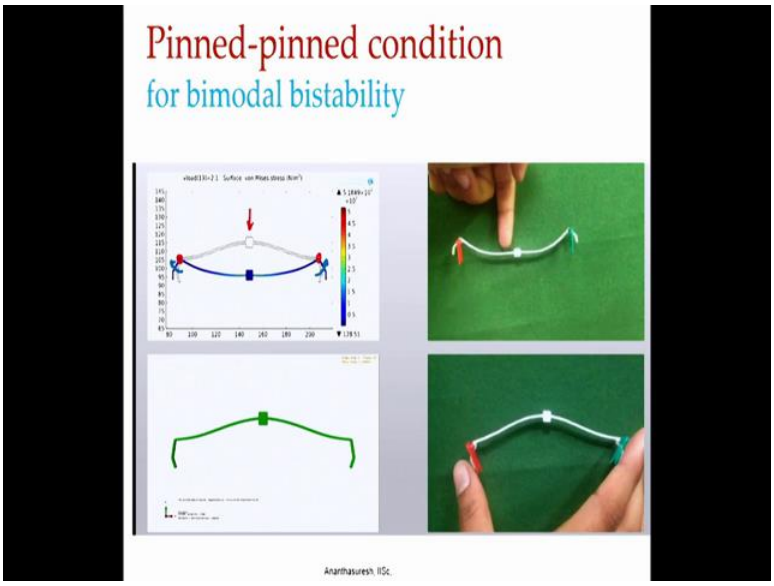

So, we have pin joints there and then we can apply force that way that is Port 1 Actuation or we can also apply force on here on a torque. In this case if you move it up like this it will just switch back to other position that will be Port 2 Actuation as we will see the movie here.

So, if I run this you will see that both simulation in this figure, let us put that there simulation in the figure over here and you can see as the force is applied how it is going to switch to each other position we can see it here also. So, we have it there when we switch it, it goes to the other state pretty a much these are the thing, another simulation where we are applying force and it will switch to the other position.

So, let us play that again to see this simulation over here Finite Element Simulation it comes so you have the force applied it is goes to other state we can also apply the torque if you want both ways it would work. This is the 2 Dimensional versions the tin lid I showed.

Now, you see when you press on the sides it goes back again. So, let us play it from here. So, it is in this state when you press there it will switch to the other state. So, I have these things here so you can actually see it in the real work. So, let us put one of these over here what we saw in the simulations there.

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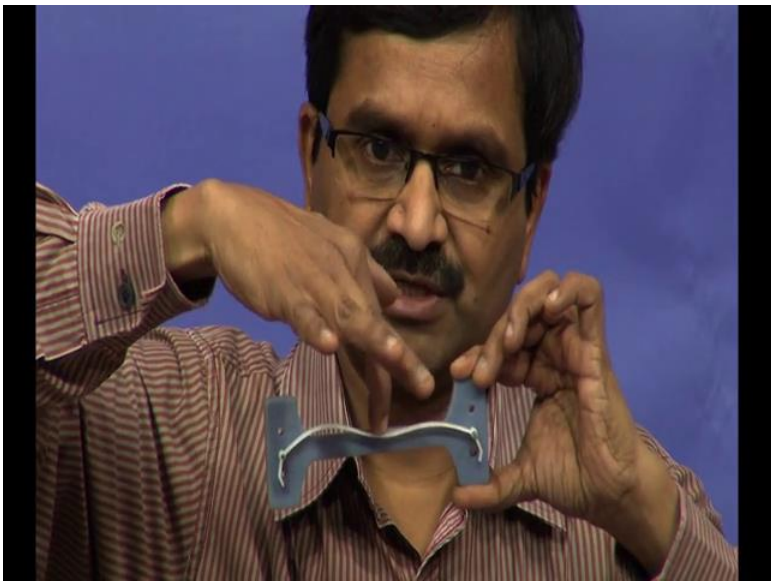

This is an Arch which as the pin joint and there also Flaps, just like tin has on the sides the Flaps you take one section of it 2 D version of that, if I got it a shell this is this now apply a force in middle this is one stable state where we are now, when apply a force it will go to the other state that is the second state it is stable no external force that is the definition of Bistability that is it has two stable states without external force acting on it.

Now, when I apply force back of course, it comes back you can see how it actually snaps where is this is as fabricated load free or Stress Free state now when I do this now it is under stress that is why when you apply force it just snaps back when something under stress it want to relief stress. So, I can do this I can also do this by applying torque on this flap that is can rotate this flap like this, this flap like this. So, I can push like this and also do that. I can either do this or I can do the other way there is a pin joint here that I will just put it here there is no preload here I can just do this apply the force it stays in other state stable state move it back.

There are different curves that different Arches we talked about if we take the buckling mode shape with straight beam so here is actually they combination of the first and third thing looks more like a bow. So, this particular one, this one stable state apply a force it is goes to other stable state. Apply a force back again it comes back now if it is here I can also apply the torque here and it switches.

So, the force required for going like this. So, there is some force I need to apply the force required in the sides is very little that is something we will exploit when we consider an application. So, there are a number of shapes that we can take, here is another shape which looks slightly asymmetric that also is asymmetric shape and that also goes by stable again Flaps there to switch it.

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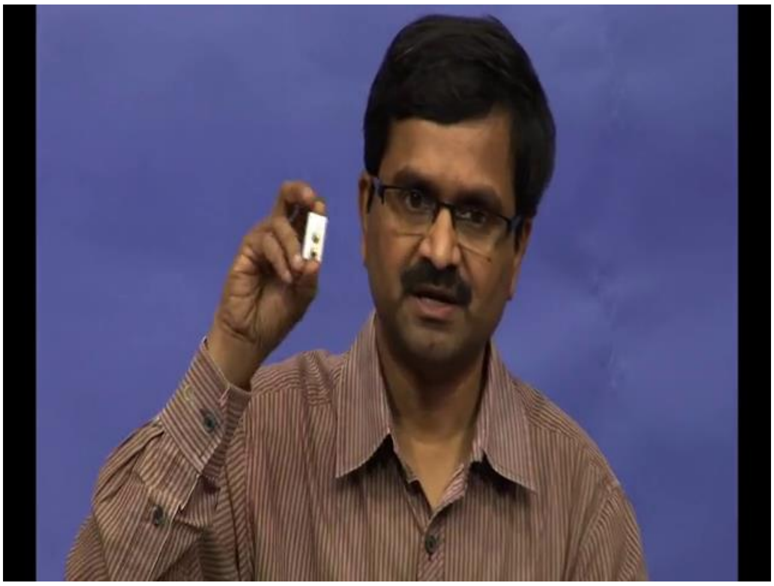

So, we have two modes of actuation over here as oppose to what we considered this the switch the electrical switch that we have tuck, tuck we have all the switch boards that has a nice little mechanism interesting, simple but not that much in terms of analyzing. It is very simple lever that it has the noise you can hear. So, that is Single Mode Bistable Mechanism where the once we are thinking on the Bistable mode.

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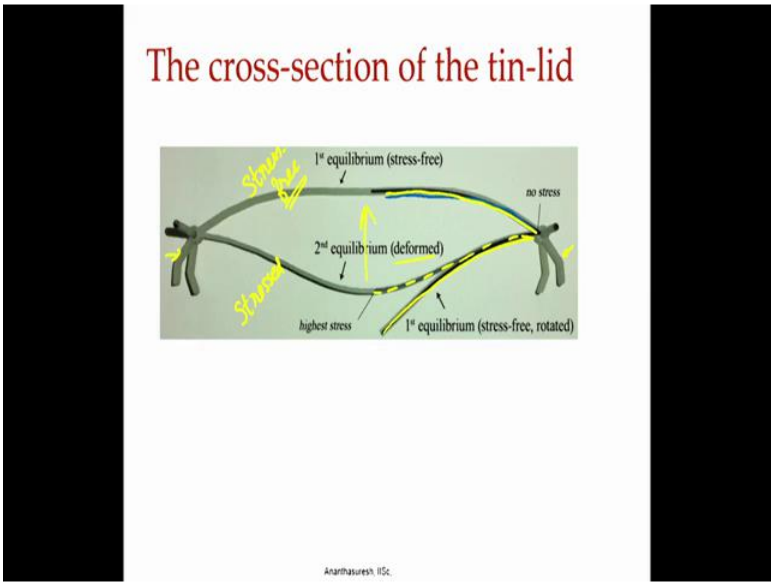

So, if you look at the two stable states in this particular case you would see that it is the actually deformed because, if I take this curve here from here to there let me use a different color that is more visible, if I take curve from there to here if I simple rotate I get this, but what is happening in the other stable state is it is deformed; that means, that in the second state this deformed one this is Stressed. So, there is stress in it where as the original one as fabricated is Stress Free state that how this Bistable thing works. So, when you apply when it is other state when I just apply forces like that which is going to switch back to the other state from here it will go back there.

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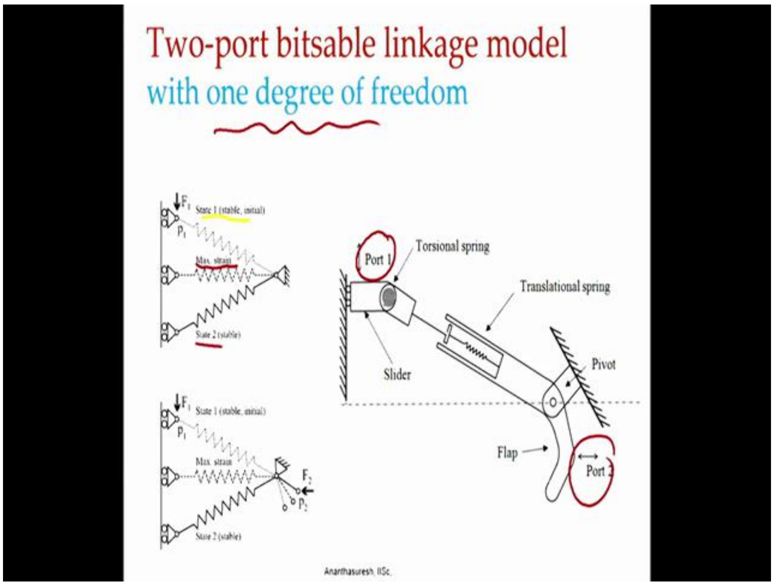

How do you model that? We had considered a Single Degree of Freedom model earlier we can also consider Two degree of Model. So, it basically says that if you have a spring like it is shown in state 1, when it goes to this state 2 in between it goes through a maximum stress or maximum strain state and that gives the Bistability. We can capture that over here where the torsion spring there and a translational spring here and we can have Port 1 Actuation and Port 2 Actuation a Single Degree of Freedom model that we are considering once again now.

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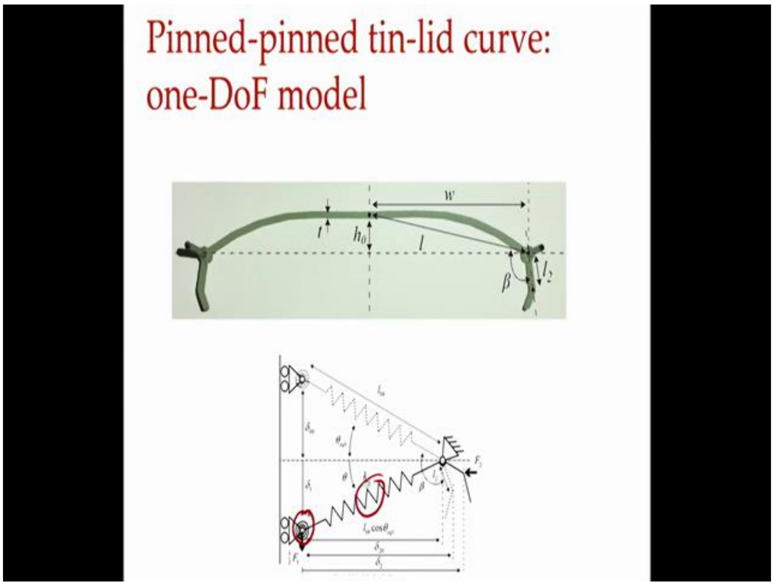

So, we can write the Strain Energy for this once we write what the torsion spring, what is translational spring constant are.

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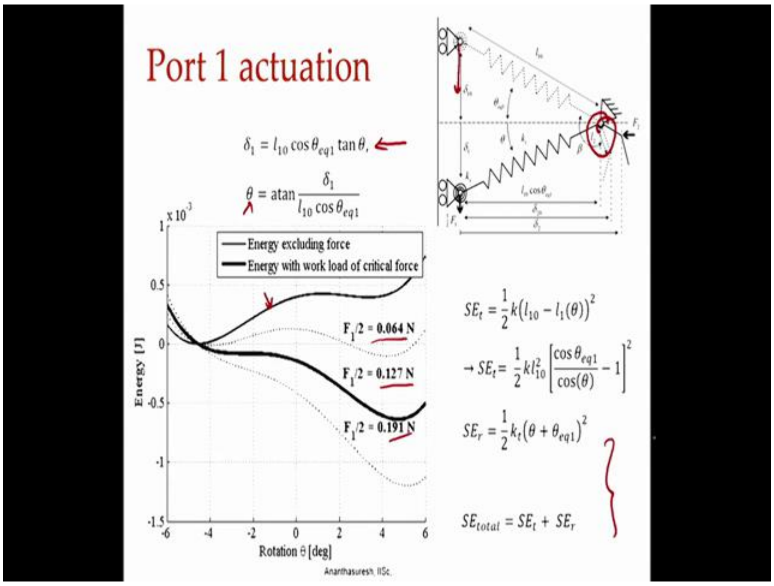

And sketch this energy landscape we can actually do everything to trigonometry the delta that is how much this is moving under theta how much it is rotating over here then we write this for various forces we can see how energy landscape changes. So, original one that we have this one over there and then how different values the energy landscape changes and where the other minimum would lie we can make all of these things.

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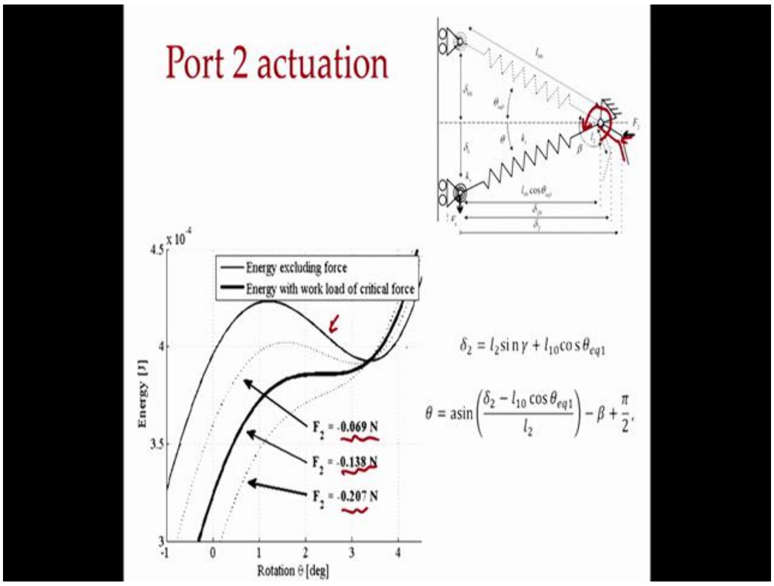

Likewise when apply Port 2 which is the torque over at this joint that also original one looks in particular way and depending on the force for the Port 2, we are applying torque by applying little force of the flap this the flap here we apply some steps that creates a torque at that thing or various values again.

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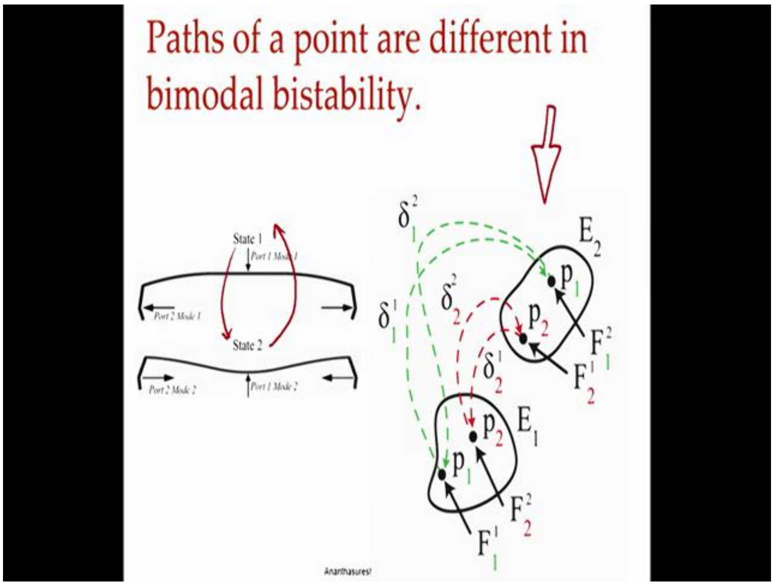

We see how the thing changes and between the then both of them are there we said that the go from here to there comes along one path going back it takes another path as it is emphasized over here.

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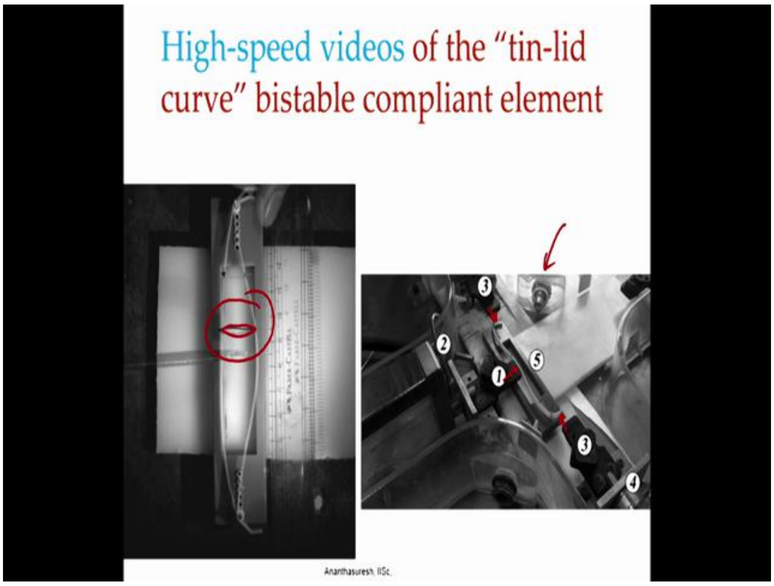

With it High- speed video of this things which is demonstrated, if you notice here it takes one path and then takes another path to go back and that is the Bimodal features of this one we used the by axial system so that we can hold it, we can apply force this way on the Arch as well as this way on the of flaps.

So, with that when you record it will give these that take a different path when I play it on the thing you would see that it goes very fast. So, you cannot be sure that it is taking simulation shows that it takes a different path in experiment also with High-speed video we can say that it takes a different path.

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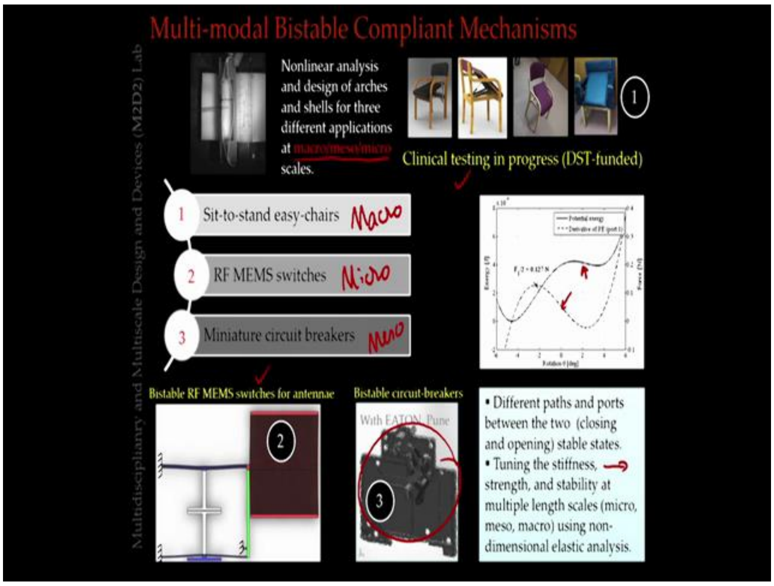

So, with this Bimodal Bistable Compliant Mechanism since our lab we work on macro, meso and micro we have one application for both, this Sit-to-stand easy-chair is a macro application and then this is a micro application RF MEMS switch and then we have Miniature circuit breaker that is the meso scale mark.

So, we have three applications that are been perceived with one concept we discuss the chair now and in a case study later and also RF MEMS switch we will discuss now and then the Bistable circuit breaker that is being done with a company. So, I have intentionally blurred it all so that we do not reveal all the details, but essentially it uses is Bimodal Bistability of having this force deflection behavior and this two energy two minimum energy states.

Show in the stiffness and stability at different length scales is what being done here for the chair, for the micro switch as well as the miniature circuit breaker or the meso scale one. In the all cases the paths are different that makes it an interesting problem.

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So, let us look at this Easy-Chair Based on this Bistable device, we said that the Click Clack tin lid force in one direction is much more than the force in the other direction. So, for the easy chair like this if somebody sits in the chair, the weight of the person is the force that is Port 1 Actuation when they want to they go to the other stable state and comfortable while sitting.

And they want to get up they will press on the handles that is the Port 2 Actuation much like pressing on the Flaps of the tin lid little force with enough tin lid, that will gently push them it will not make them fly like a projectile, it will gently push them that is this Bimodal Bistable Easy Chair.

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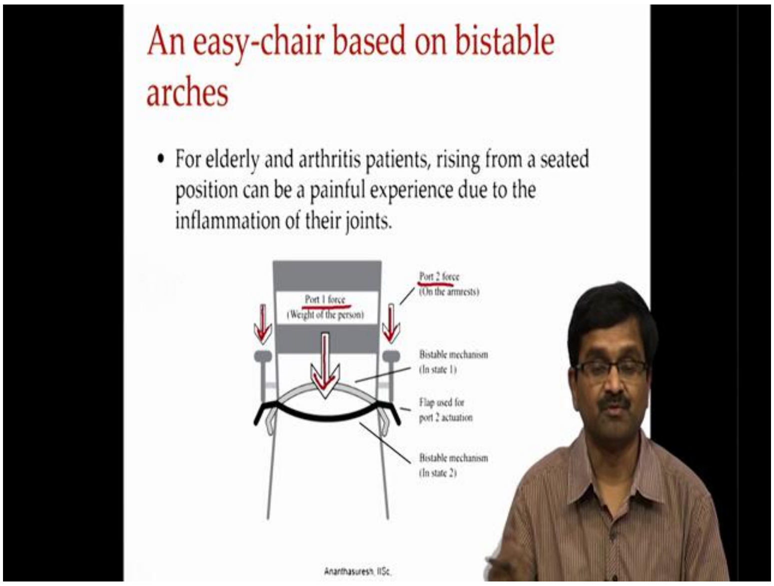

So, the idea this is the Port 1 Actuation and this is the Port 2 Actuation as it is mentioned that is what you want to do here.

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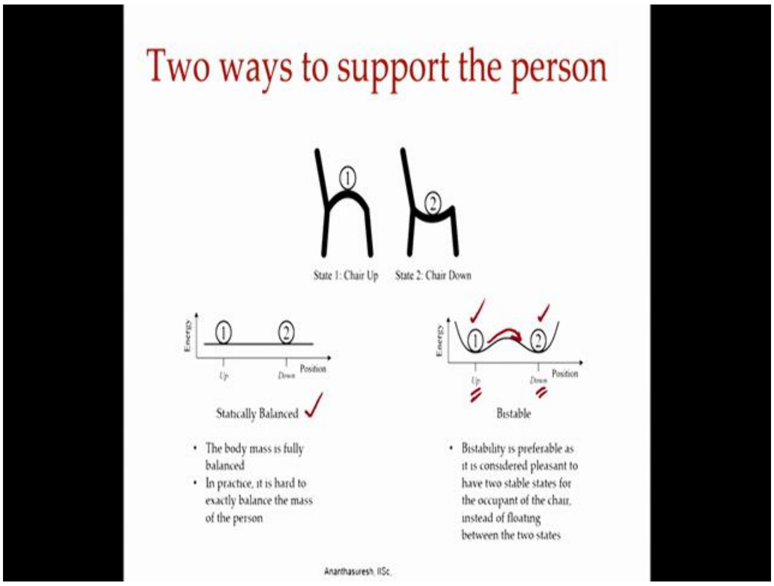

So, Chair Up and Down there are two states and Static Balancing so that energy state if you do if it is circumference difference that is a good thing we will be talking about Static Balancing in the next set of lectures and Bistable is like this, we have up position down position in between we have to go over the hill to settle down in a minimum like in state 1 and state 2.

So, here is a model of that of the device. So, it is actually several bistable things all over here other side and they can go from that state to this state you apply if somebody sits there they come back and here and they are stable over there.

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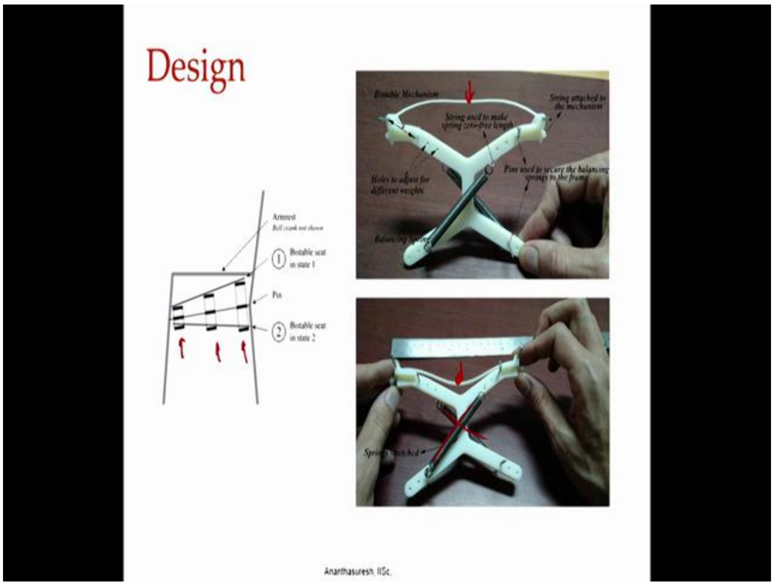

And of course, no force actuate is not there stable it is done with this springs and will discuss static balancing in the next set of lectures.

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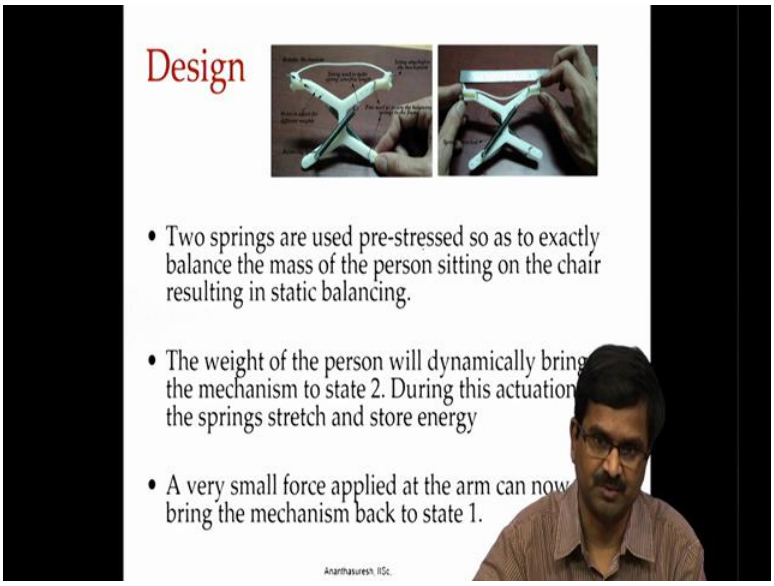

And here these springs are used in a pre-stressed manner that we will discuss later, how to pre-stress them so that there will be energy stored in them to begin with and that energy gets realized where you want to switch back to the other state, that the weight of the person that energy will be stored in the springs which will itself help the person to raise from the chair.

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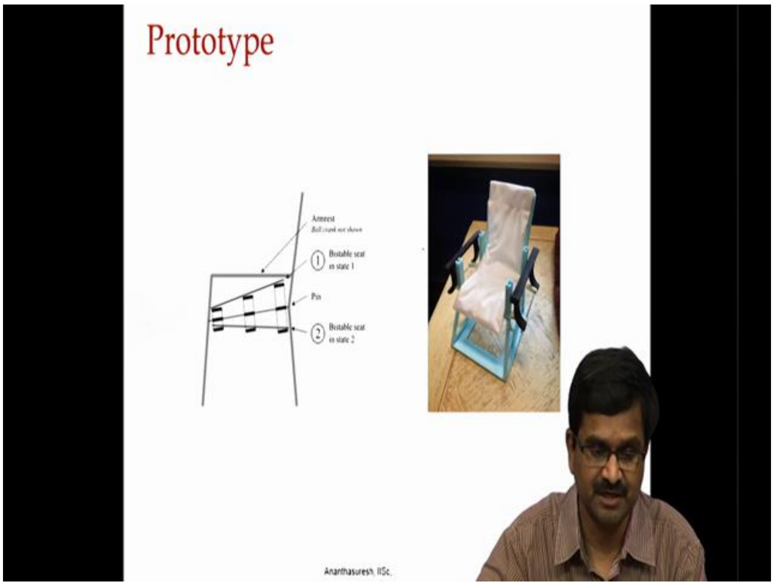

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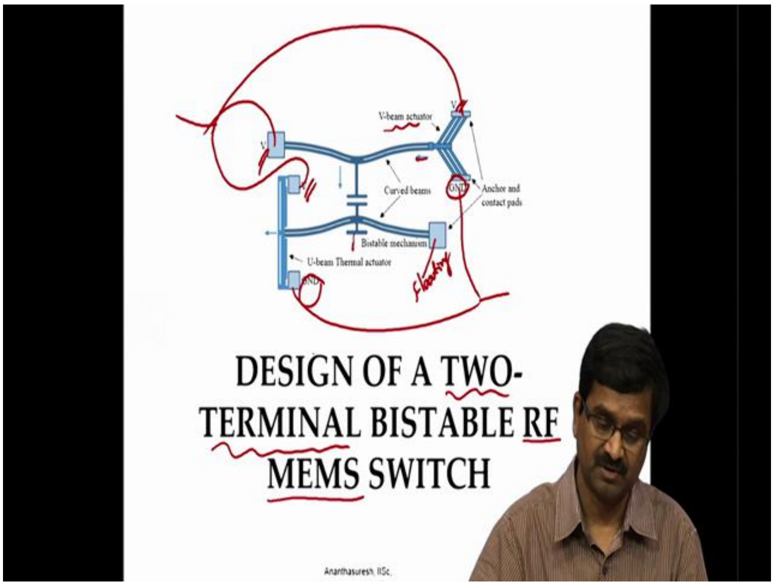

And very small force needs to be applied on the handles much like our tin lead, first required for Port 2 Actuation is smaller than the force required in the Port 1 Actuation and that is how this chair was designed. Now we will be discussing that chair in a case study in great detail in a later lecture. Right now let us look at this Two-Terminal

Bistable RF MEMS Switch MEMS stands for Micro Electro Mechanical Systems, RF stands of Radio Frequencies switching, switching antenna arrays and so forth, Two-Terminal meaning there will be only two electrical terminal which is appreciate power electronic designers they needs to power supply, then if this two terminal it is much better in the device that they have, it is actually two terminal there is a ground another part ground there is a voltage applied in three different places, but there is only one wire that goes with all of these thing between this and this we have common ground and there is another one which is like a floating thing here or to will be ground.

So what will happen is when you supply force it is a V-beam electro thermal actuator it applies the force, it switches to from one position to another position and then it touches and it contact to the r f line and makes or breaks the switch and you apply again it will try to switch back it is also kind of a Bimodal Bistable device.

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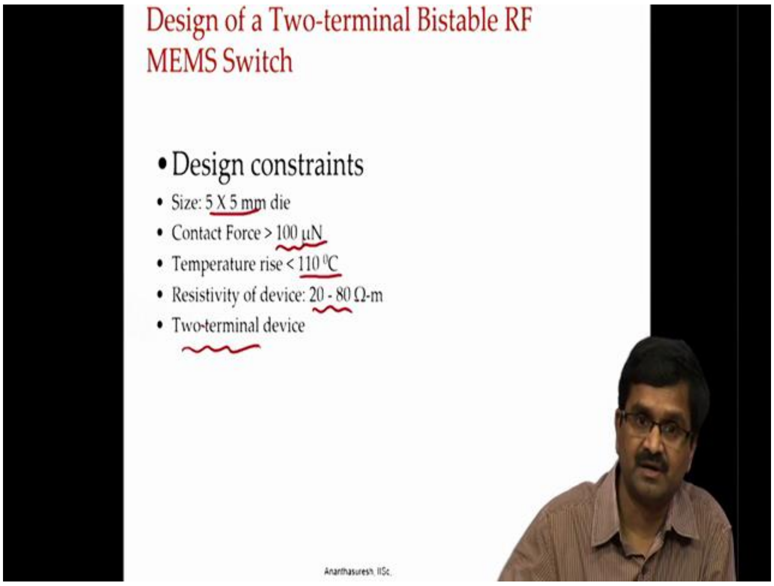

Design constraints for this problem it has to fit in a 5 by 5 mm die, Contact Force should be at least 100 micro Newtons, it has to withstand 110 degree centigrade, Resistivity some value is given, IT should be a Two-terminal device.

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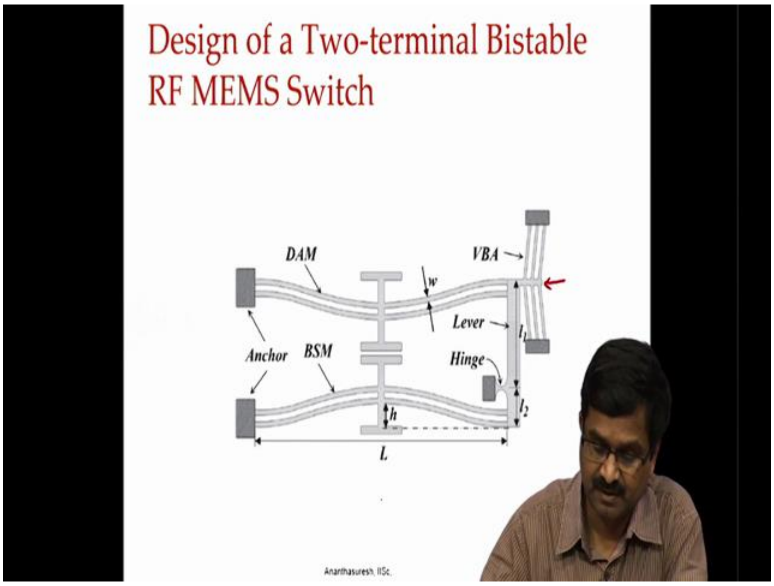

And this is the design here. So, you apply force like this by applying between ground and the voltage activation point. So, that will move from there to here to switch and then it will push this here.

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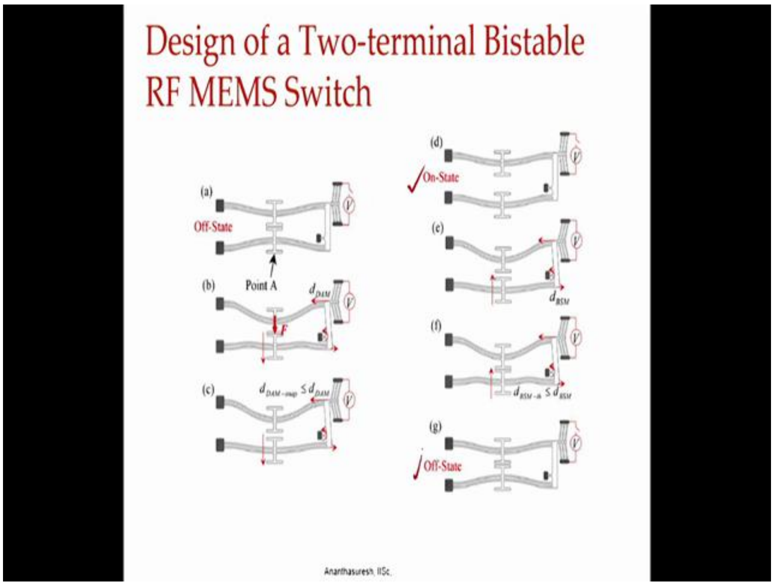

And then it will push back to the other state, I think it is best explained with these two diagrams, when you do this it will switch back and then when you do it again it will switch back to the original state from there and here and similarly this is shown what happens with various actuations given, how it suggest from one to the other state On-State over here to Off-State over here.

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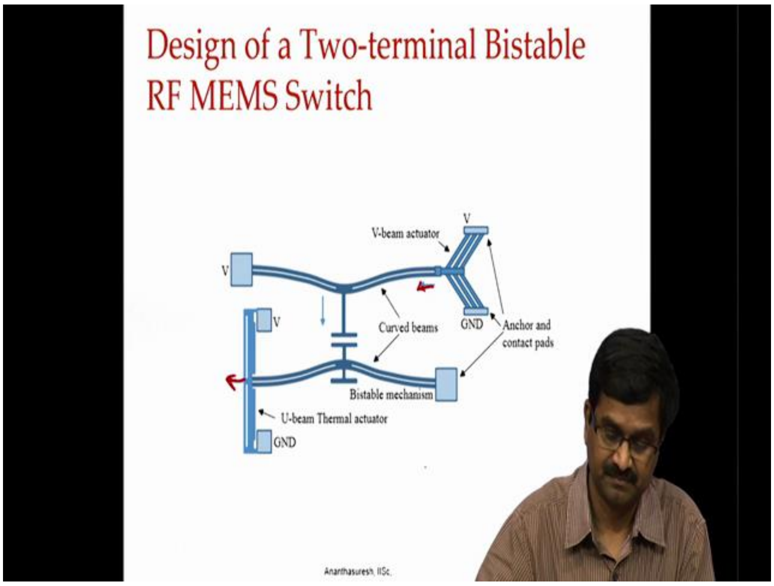

There is a small variant were the force is applied here for Port 2 and this is the Port 1, if we do that between voltage and ground if we do this and this both will be there in one case, when it is here it switches to the other state and the case switches to the back to the first state. So, we can watch this moving.

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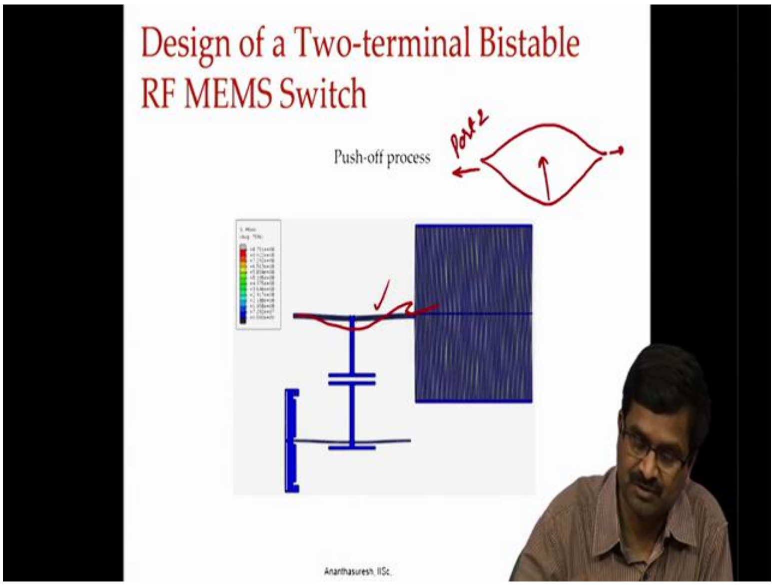

So, now this actuation is applied and it is moving down and down and go to the other state now when you pull it back it comes back to the same sate, let us play this again.

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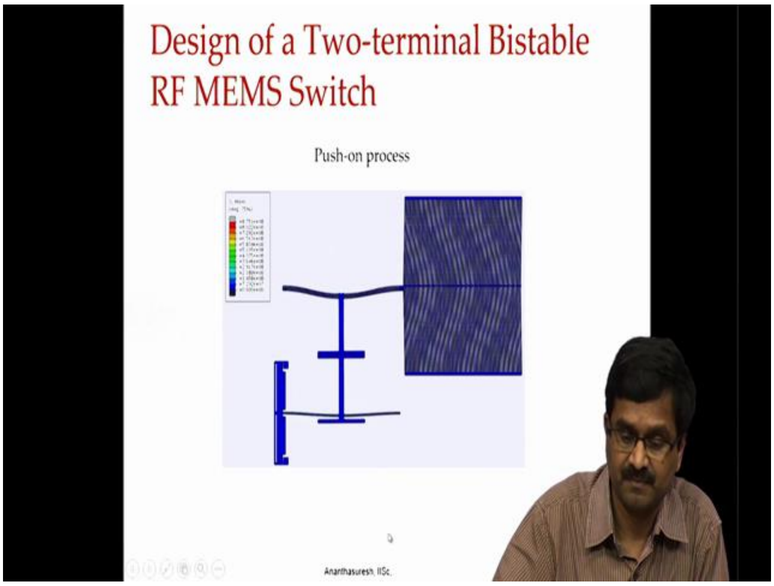

Let us play this, actuation electro thermal actuation when it is pulled that way switches from there to here and there when you pull this way it switches back to the original state, let me play it again it is very small micro switch. So, and they were on this displacement is very small with two actuators, but with two terminal electrical connection it can switch back from one state to another state.

This is the Push-on process this is the Push-off process. So, we have let us go back to Push-on from that state it will go to the other state and we will do the other one Push-off that is the next one, when you do this again goes back to that state, this is also Bimodal Bistable where we are looking at the arch so that we have the arch here.

So, let me go back and get at the pen. So, when we have this second actuation is let us say you apply the force here it is going to switch to the other state. Now second port if you pull it like this also, it will switch back from there. So, this is the Port 1 Actuation, this is the Port 2 Actuation. The Port 1 Actuation also it is like other you apply the force there that is not what we have here so what we have is to switch back this one for like this switches and then goes back to the other one.

So, here it is downwards to begin with, it is like this when you apply a force like this way it will go there and then push it this way and that way there is Push-off is already here we have to Push-on one this has a slight slope when you apply the force it is going to switch here push on and push off with the two terminal. So, we have macro and micro there is a meso one and first cannot talk about this, but there is this circuit breakers which can benefit a lot from these Bistable switches.

So, they have plenty of applications which we had discussed and we will be discussing the easy-chair design in much more detail in a later lecture. So, Bistable phenomenon again to summarize it needs to have an elastic element that stores energy and stores energy to the maximum during the travel and then it decreases, so the chair energy should increase and then decrease if that is the feature it will have Bistability and decreasing chair energy for a Compliant Mechanism advantages from the view point of mechanical advantage also as we had discussed earlier.

So, Bistable devices inherently have this nonlinearity which we exploit and get this feature of having states with stable and another stable in between there will be unstable. All these things that we have this feature, it is a very nice feature to have in a Compliant Mechanism when you want switch between two states and they have applications from an aircraft wings all the way to simple hair clips as we had discussed.

Thank you.