Compliant Mechanisms: Principles and Design
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Lecture – 69
Micro-newton force sensor

Hello we are into the last week that is 12th week of this course. We actually summarized in the last lecture, the entire course content what we are left with now are 6 case studies that illustrate how compliant mechanisms can be used in real applications and all this case studies are chosen from our own work and if you look at people who have worked on compliant mechanisms, all of them will have lot of this case studies that they had worked on to apply the principles and design techniques of compliant mechanisms and put them to good practical use.

The first case study we considered in his lecture is a micro machined accelerometer actually I should say accelerometers, because there are different variants of that which we will consider now. So, let us look at our first case study, which are micro machined accelerometers with compliant amplifiers. So, we are using compliant mechanisms here to amplify the displacement and work on accelerometers that have some advantage over without the compliant amplifiers.

So, this work was largely done by my form of PhD student Dr. Sambuddha Khan who is now with metal power analytics and it was supported by NPOL that is national physical oceanographic laboratories in Kochi, Dr. V Natarajan was closely involved with us in this work.

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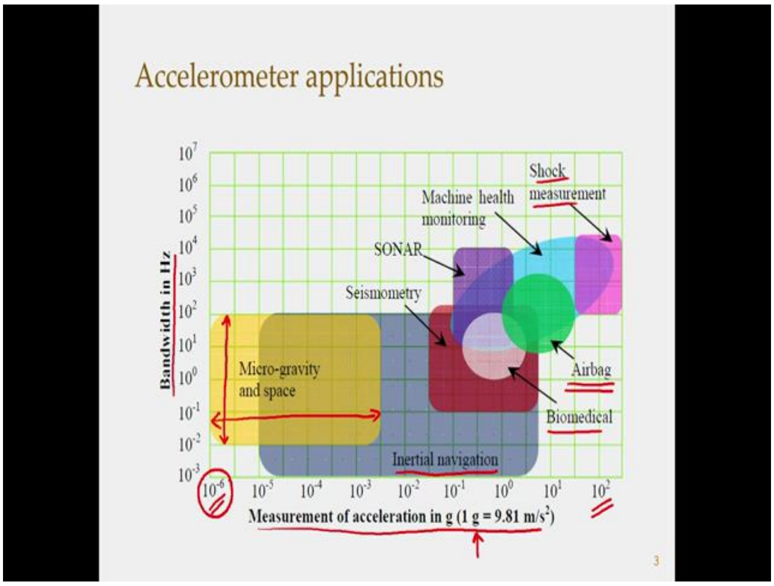

So, if you look at just accelerometers and their applications we are portraying n number of applications here, Bandwidth on the y axis and the range of acceleration that is needed on the x axis, this range meaning that for what range of acceleration where normally people use acceleration to gravity as a unit. So, we say we have 100 g accelerometer one g or micro g or whatever; the scale goes from micro g 10 power minus 6 g all divided to 100 g. So, where do different applications lie and what is bandwidth? Band width is the frequency over which the sensor works satisfactorily, that is the bandwidth. So, every sensor will have limited bandwidth as you can see also very application also has a bandwidth, in the case of micro gravity it may go from 0.01 hertz to about 100 hertz, it could be more, but this is one source where we had taken that what we have the bandwidth range and the range of acceleration if you look at this that is goes from micro g to about couple of milli g that is the kind of acceleration that they want to measure in a particular applications.

So, they also have in a rocket takes off I guess there again there will be a need for a accelerometers that is going to be able to measure very large acceleration, but we are talk about micro gravity and space once it is there, what kind of accelerations too they see and they want to sense, but most importantly it is this lower end micro g that is of interest.

So, different applications are there biomedical air bag, which is a more successful commercial application and SONAR Seismometry shock measurement. So, inertial navigation which is there everywhere now so for all of those things you need accelerometers, their range and bandwidth differ applications, accordingly you have to make accelerometers.

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So, here is an application in consumer products, many consumer products such as the mobile phones, laptops and wearable sensors and toys have this. So, is one of the things that one of the students here had worked on Dhruv Saxena and Hitesh Rao and if you others who had done this, but this particular design of what we call Cognitive Jewellary was done using that I have one of this here of course, a big one so if I were to wear this like a ring of course is a big one, does not look like platinum or gold, but it has accelerometers and gyroscopes in this that we can make gestures and make things happen. So, is like a mouse to a mobile phone, it will talk at the mobile phone or computer whatever you want and can be done actually I can give this presentation where I can change the slides with a stroke of my hand. So, it has bluetooth microprocessor and everything and important thing is accelerometer that is there in this.

So, that lot of applications where accelerometers are used in consumer products and its going to be more and more as the technology improves.

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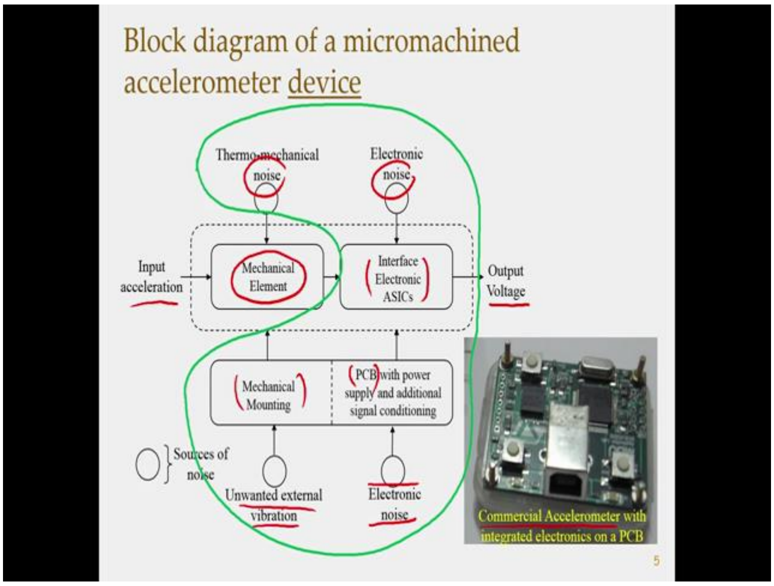

So, what does accelerometers have let us look at that. So, our interest is this mechanical element that is the accelerometer, but that is not enough is a system the whole thing as you see a commercial accelerometer with integrated electronics put on a printed circuit board PCB it is a device. So, we have mechanical element, there should be electronic things and then you need to have a proper mounting and then there should be this printed circuit board with all of these things if there is acceleration that comes to it on which this is mounted we will get some voltage and that voltage indicates to us what the acceleration is.

But then we also have noise, various noise sources - there is thermo mechanical noise electronic noise and then there is unwanted external vibration, that you may not want to measure, but that is there similarly there will be lot of electronic noise at the PCB level as well. So, whatever we design has to keep in mind the things that are other than our mechanical elements. So, we have all of these things that we should worry about where we worry about this mechanical elements, which is the accelerometer that is the key thing here it is work with everything that has to be kept in mind.

This presentation is quite long there are more than 100 slides clearly it is not possible to cover all of them in detail in 30 minutes that is allocated to this lecture, so I am going to point you to important things in the presentation, the presentation slides will be available to you to know more detail. So, that is what I would do with the case study there will be more information in the slides than what we will actually discussed in the lecture. So, it is important to have the information accessible to you while guiding you in this lecture what to look at.

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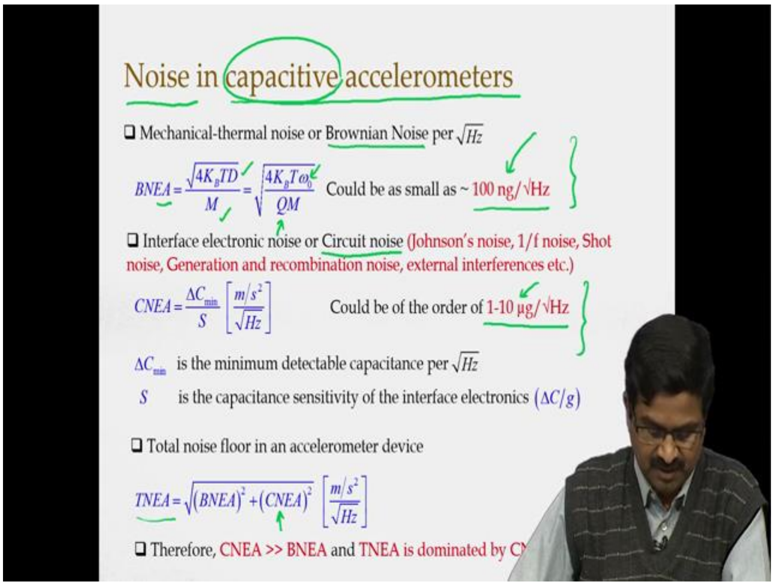

So, some of this may not be relevant to compliant mechanisms directly, but it is definitely relevant indirectly one of that is the noise. Any sensor, noise is a very very important aspect in this particular case we are looking at capacity accelerometers meaning that looking at accelerometers, which measures the acceleration by measuring capacitance whose capacitance changes with the acceleration that you want to measure. So, acceleration is the signal we want to measure, but that is going to change the capacitance of a capacitor using some electronic circuitry and that capacitance is correlated with the accelerations. So, that is the capacitive accelerometer here.

So, there is a noise. So, the noise is given as an equivalent acceleration so that EA stands for equivalent acceleration, and BN stands for Brownian Noise and that is a strange unit per root hertz with acceleration g per root hertz, and that is because it comes from. So, when you look at the BNEA that is Brownian Noise Equivalent Acceleration; so acceleration is some force per unit mass. So, you see mass here and there is a force, so what is the numerator here is 4 K B times T times D under square root sign, that should be equivalent to your force and that is the mechanical force or random mechanical force is thermal noise as we call it.

When a something is there it is actually when it that temperature above the absolute zero, it is going to be in constant vibration inside or even outside. So, that A has (Refer Time: 09:28) do with our mechanics in a way that is actually some to do with a statistical mechanics not the Newtonian mechanics. So, that is why we have Boltzmann constant K B is Boltzmann constant and T is a temperature, and D is the dissipation coefficient that we have in the dissipation. So, when there is thermal because all the dissipate energy goes there. So, at that is there. So, all this is not relevant to compliant mechanism per say, but when you are designing accelerometers you need to know somehow these as well. That we can transform into quality factor and then natural frequency. Usually this Brownian noise equivalent acceleration in micro machined accelerometers will we have the order of 100 nano g per root hertz, it varies with frequency that is why its per root hertz, it is a power and then you take square root and that is why root hertz comes again that detail we are setting aside for now.

And then when you have interface electronics, there will be lot of other noise sources 1 over f noise, Johnson's noise, Shot noise and all these noise sources exist electronic circuitry. So, you can write that also, when you are measuring capacitance that also will have its own noise and that is CNEA that is capacitance noise or circuit noise I should say C here is not capacitance circuit noise circuit noise equivalent acceleration, that is change in capacitance whatever that you are looking at divide by S where is the capacitance sensitivity of the interface electronics.

It turns out that this would be of the order of micro g per root hertz, notice that this is nano g 100 nano g, this is there are about 2 orders of magnitude difference here. So, what this tells us is that when you are designing in accelerometer you have to pay attention to noise because that decides the resolution capability of the accelerometer, when you have accelerometer you want to know what is the minimum acceleration that it can sense reliably; that means, that when there is let say it is a micro g accelerometer; when there is change of 1 micro g can the accelerometer show that reliably.

So, for that what we worry about is the noise, because even when there is no acceleration the output voltage of the micro accelerometer circuit will be constantly showing some voltage that is all noise. In fact, if you take a multi meter and try to measure resistance, the last decimal place will always be flickering. It is not that resistance of the thing is changing it is that the measurement circuit has a problem that is the noise. So, here if you look at that noise from electronics a lot more noise comes than a mechanical element.

So, when you try to look at the total noise equivalent acceleration, you take basically norm like thing a square of these 2 sum and then take square root. So, clearly if this is larger that is going to nominate the total noise in the accelerometer not the mechanical noise here, but the electronic circuit noise.

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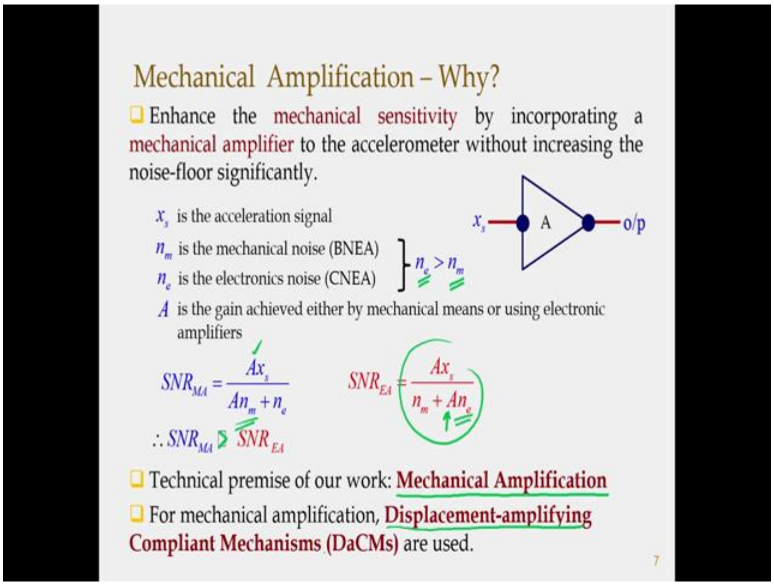

So, when you amplify, so we are trying to design an accelerometer that is more sensitive than what it is right now then you try to amplify the signal. So, that you know if micro g acceleration changes let us say a millivolt change in the output, if you do some amplification that millivolt become 10 millivolt; that means, that you can measure point 1 micro g let us say millivolt is a resolution capability for the voltage.

So, if 1 micro g cause millivolt you can only measure 1 micro g; if you are able to amplify the signal, then 0.1 micro g also may lead to 1 millivolts that is your resolution in measuring the output voltage. So, we go for amplification, but why mechanical amplification, why not electronic amplification because there are lot of methods to do electronic amplification? So, we see that when you have signal to noise ratio, we know that there are 2 noise sources that is electronic noise, there is mechanical noise; electronic noise is larger as we discuss in the last slide.

So, when you amplify let us say mechanical signal as oppose to electronic signal if you do; then if you look at signal to noise ratio, you multiply the mechanical amplification factor n m rather than ne here you are doing ne right, which one will be better because when you amplify a signal both the signal and the noise get amplified. So, if you were to amplify electronically electronic noise also get amplified by so much, that is why we have a here. So, signal to noise ratio if you take over all this is not going to be very good; here this is much lower than ne even if you amplify it is not going to change a whole lot, but this amplification factor A is there, so we have signal to noise ratio of mechanical one, greater than that of the electronic one.

So, it makes sense to use mechanical amplification rather than electronic amplification. So, that is the basis for this work; where we are going to use displacement amplifying compliant mechanisms to amplify mechanical signal so that you get better signal to noise ratio that we have to understand.

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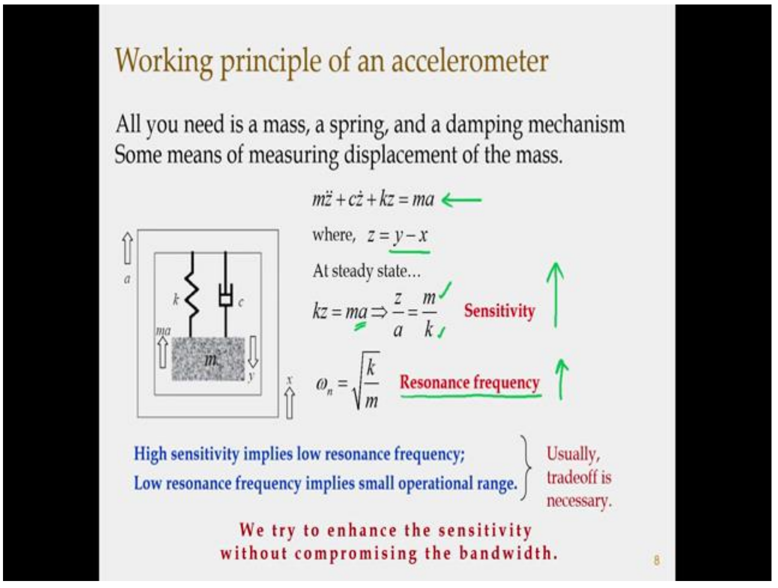

Beyond that if you just look at accelerometer, it is everybody knows this from vibrations those of you taking vibrations course: there is a mass, and there is a spring, there is damper when the frame accelerates that translates to the motion of mass, by measuring this motion we can see what the acceleration is right. So, when you these are the equation of motion forward degree of freedom and this ma where you measure the z that is related to displacement of the frame versus this mass, which is y minus x - y is the motion of the proof mass, x is the motion of the frame difference of those 2 will be z that z by a is equal to m by k.

So, if you want to have high sensitivity then you want to make m large proof mass large and k small, but then if you look at the bandwidth that is related to resonance frequency, that is exactly opposite of that k over m. So, here m over k for high sensitivity that reduce the band that is why I showed you the beginning bandwidth versus the range of acceleration you want to measure. So, this a trade of require between these 2; high sensitivity implies low resonance frequency and hence low bandwidth, low resonance frequency implies small operational voltage that operational range that you can go.

So, there is a trade of require between the sensitivity and the resonance frequency that is another point to note. It turns over that when you use DaCM displacement amplifying compliant mechanisms, you will not only increase sensitivity sometimes you can even increase the resonance frequency, you can design it so that bandwidth is increased and sensitivity is increased at the same time; there was no other method before this that could do this. If you take electronic any kind of amplification you do, you have to go for either high sensitivity and low bandwidth or other way around, but not simultaneously that is what compliant mechanisms made possible here. So, we can enhance both sensitivity and bandwidth or at least without compromising the band width.

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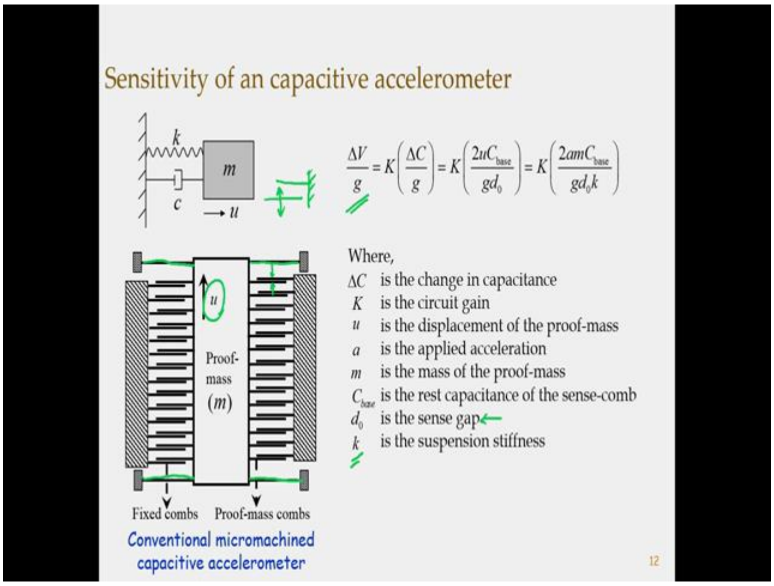

If you look at an accelerometer, the sensitivity is changing voltage that I showed the device flow chart in the beginning per acceleration applied in this case we take g as the unit of acceleration, 9.81 meter per second square, delta V per g will depend on all these quantities. There is of course, acceleration is applied a and there is proof mass and the base capacitance and of course, the acceleration applied there per g we have we are writing, and then d not which is the sense gap, how is the capacitance measured? It is measured by modeling each of this comb fingers as a capacitance.

So, there is one static finger there is a moving finger, the static one is fixed moving one is going to move up and down between 2 of these electrodes there is capacitor, when the mass moves these are u is the (Refer Time: 18:41) mass when that moves, this gap is changing that changes the capacitance that gap is the sense gap and k here is the suspension stiffness; we talked a lot about suspensions and in fact, said that in MEMs compliant mechanisms basically come in the way they suspend the mass here it is suspended with these 4 beams, that is the stiffness of suspension.

So, if I want to increase the sensitivity here I have to go for large mass, large base capacitance that is why many more fingers here many more capacitors and then small sensing gap between the fingers d naught, and small k that is very low spring constant of the suspension they are (Refer Time: 19:30) you can do.

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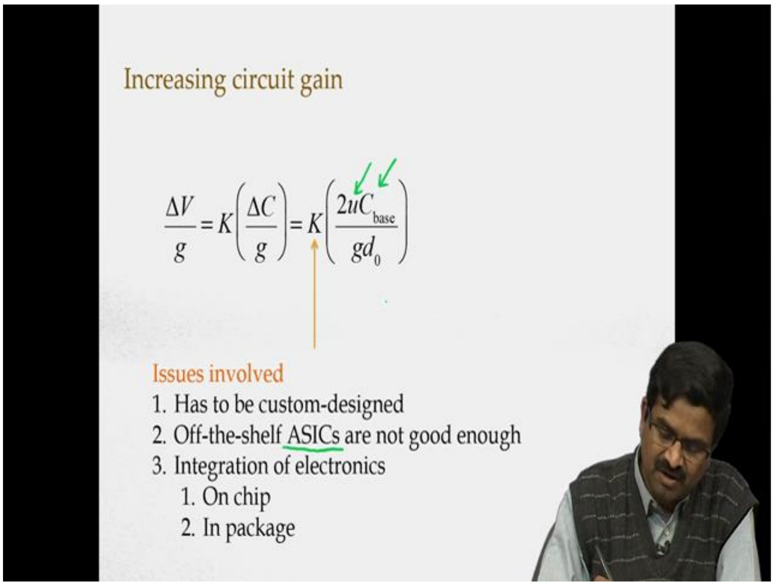

And it turns out that anything that you take and issues involved. So, there is this K some the gain you can just put that. So, we have to first of all this gain, it becomes a factor of the application specific integrated chips, now that is not in our hand like a amplification that is there electronic designers will take care of that. Beyond that what is in our hand is a displacement, how much displacement you can get after amplifying and how much base capacitance you will have and what is a sense gap, if you increase any of these.

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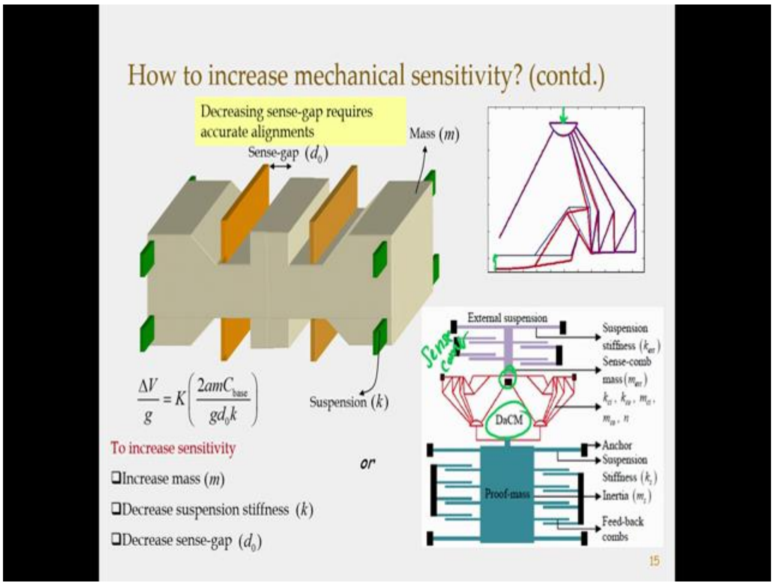

So, let us say increase sensitivity increase the mass out of plane sensitivity will be affected, because when you are trying to make in plane accelerometer out of plane sensitivity will be affected if you have a large mass and large mass also increases stresses on the beams.

And if you decrease the spring constant that also increase sensitivity, then your resonance frequency as we said has the problem and if you decrease the gap that is what is needed to make sensitivity higher and the fabrication becomes difficult. So, anything that you try to manipulate here something you know will be heard. So, there is a not much you can do and people have tried their best in terms of getting the high sensitivity and high resolution capability. So, with existing process, what can we do (Refer Time: 21:05) the DaCM comes.

So, rest of the presentation has the lot of details, but I will just point out things. So, what we have doing instead of measure the displacement of the proof, we attached to a displacement amplification compliant mechanism and measure the displacement over there at the output. So, these becomes the sense comb fingers these are there only for feedback if you want to may close to an accelerometer are for testing purpose. So, if you add this then we can make it better as we see here this is the input, output is a lot more so; that means, your capacity changes that much more.

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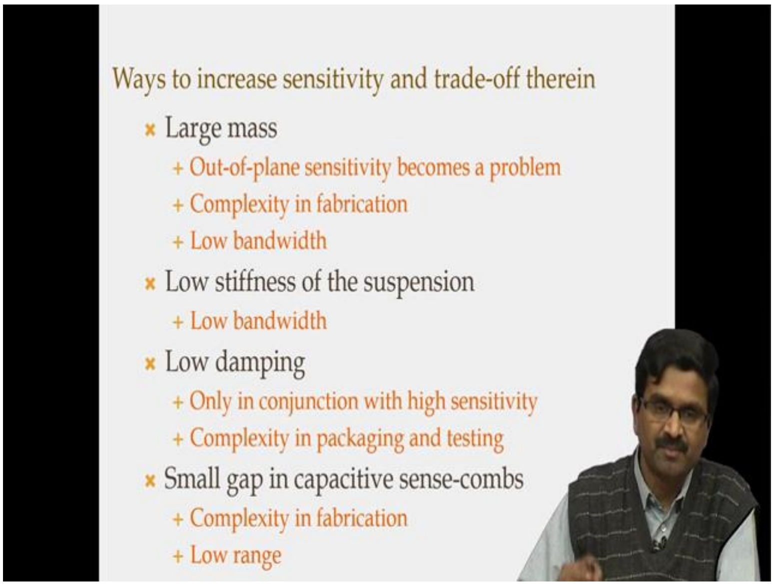

So, we already said large mass has problems, low stiffness has problems, low damping has problem there is a quality factor there small gap has problems, all of them one problem or the other so we go for mechanical amplification.

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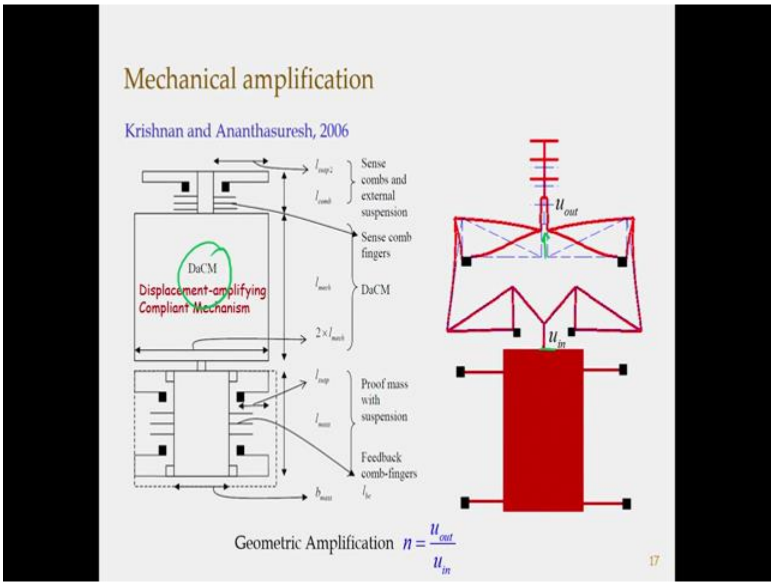

So, we cut down the mass here put a DaCM which has the one shown here, this is hardly moving whereas, this is moving a lot. So, capacitance changes so much and capacitance runs out to the inversely proportion to the gap. So, as gap decreases capacitance is going to increase and that is what we want. So, making output displacement large makes a lot of sense.

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We have seen this mechanism before, so I will not play this movie.

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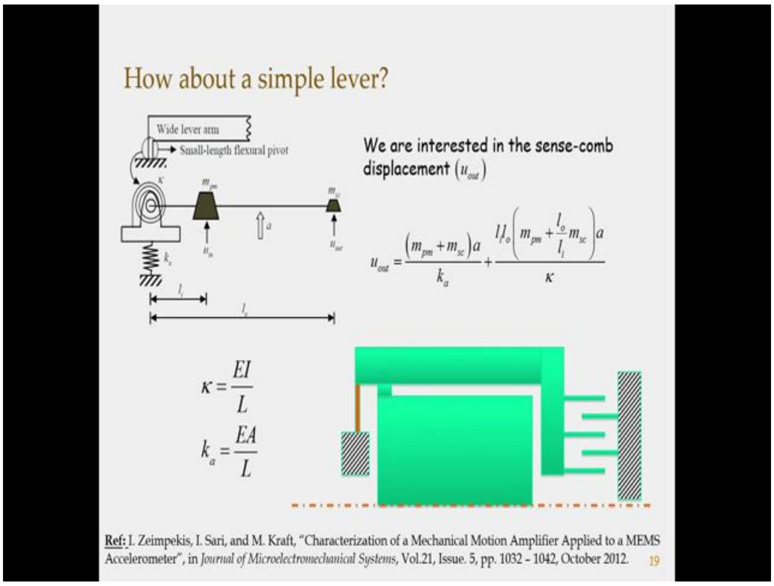

So, one can say why not a simple lever. So, there is an explanation here I encouraged to vied in the slide, why a simple lever will not do why we need a complicated DaCM? Because normal lever also it would, but it is not enough as you will see there and understand.

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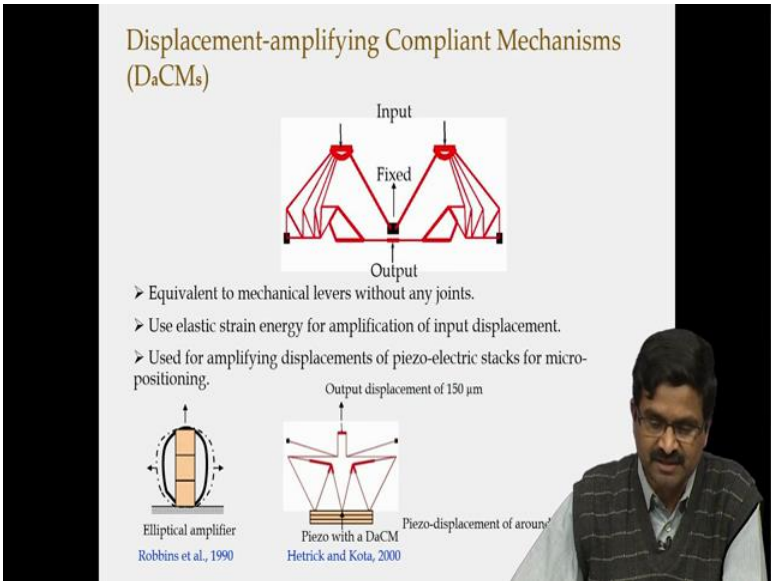

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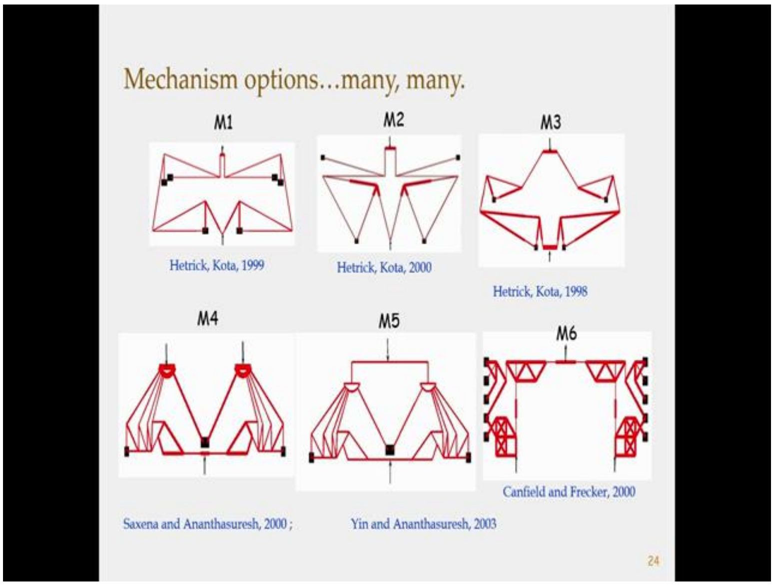

So, there is enough information there has to what would not work and then there are some things about DaCMs of various kinds and a number of them we had seen a data base, we can look at all of them we have here we have taken 6 and then see how they would meet the specifications in this problem.

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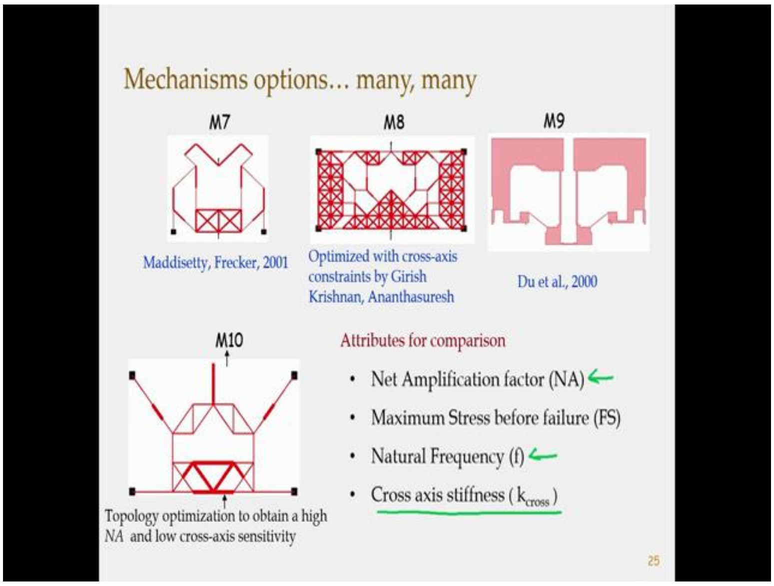

So, there are 4 more here and all them we have to keep in mind the natural frequency and net amplification factor as well as cross axis stiffness that is also important we have measuring (Refer Time: 23:31) in one direction the other direction motion should not affect your capacitance. So, cross axis stiffness is also important number of factors if you go through this thing.

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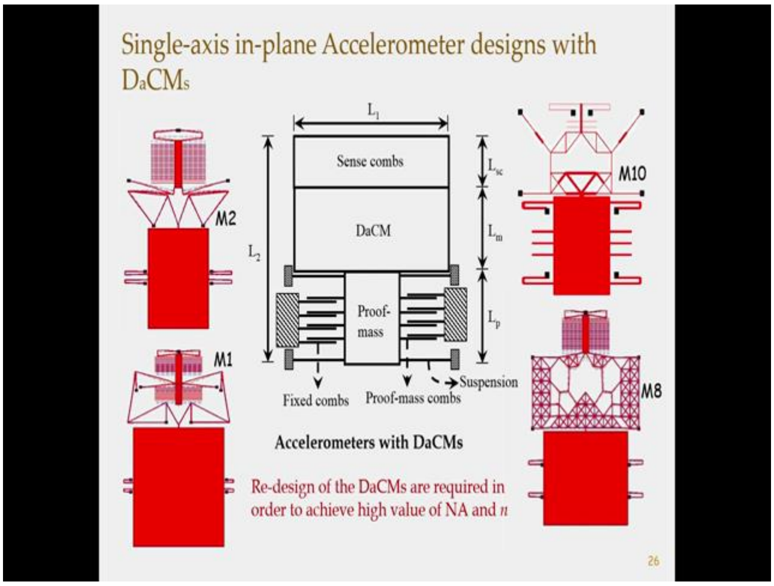

So, we considered a number of them and try to design each one of them, and see which is the best one.

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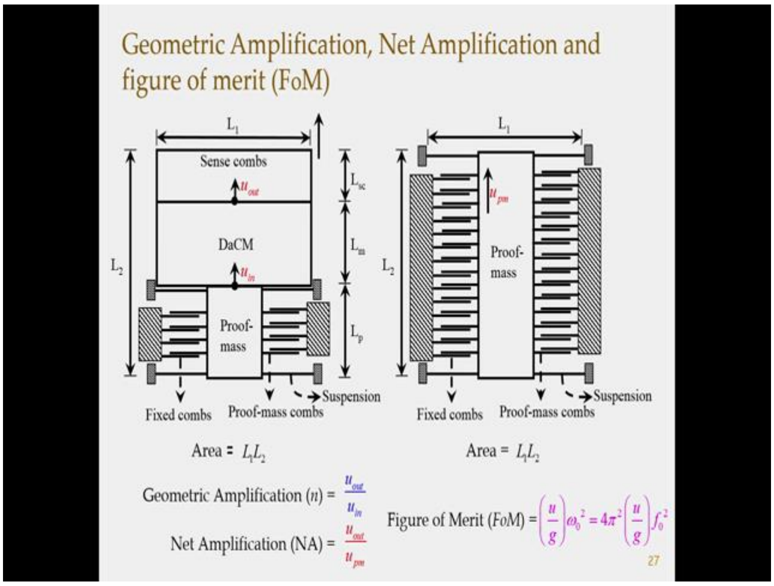

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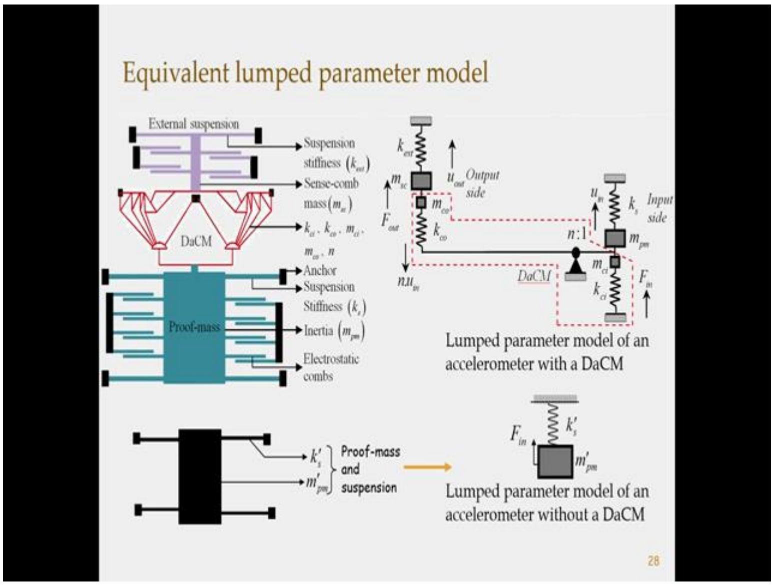

So, there are details I will keep all of these you can always read it in here we designed it, using this spring mass lever modeling.

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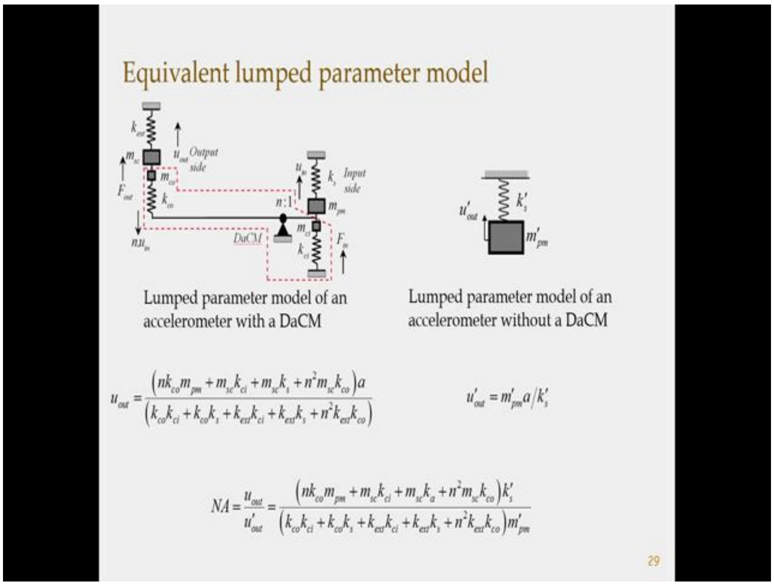

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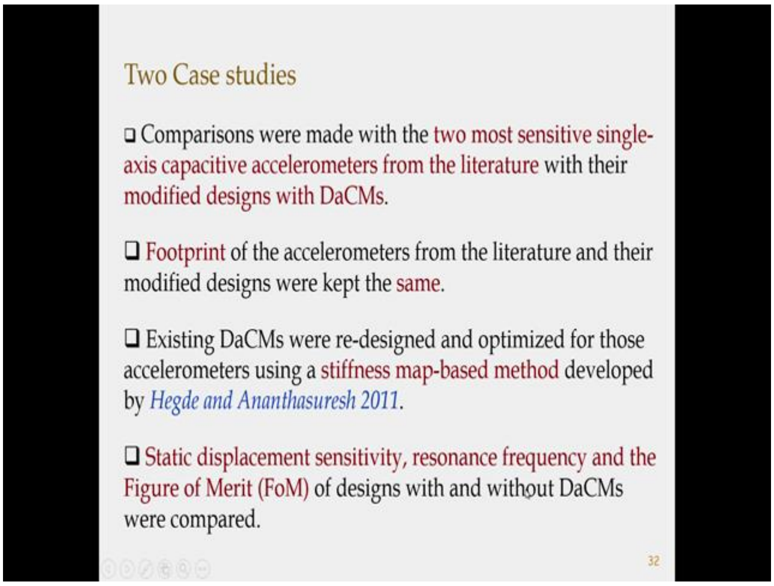

Where we do this feasibility map that we had discussed in other lectures and considered different this is case studies within a case study.

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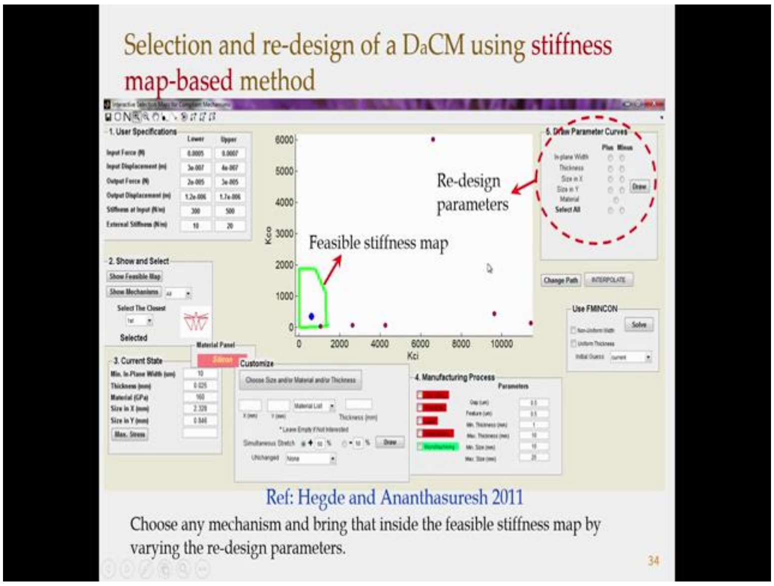

So, there are lot of them so I will skip all this, we had actually use this feasibility map do design the accelerometer.

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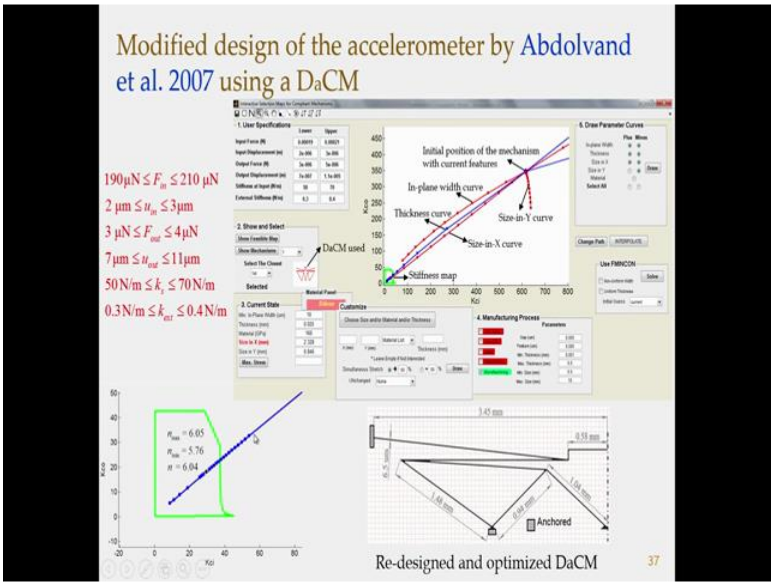

So, I encourage you to go through this slides and then read the specification numbers that (Refer Time: 24:25) what we got as the feasibility space.

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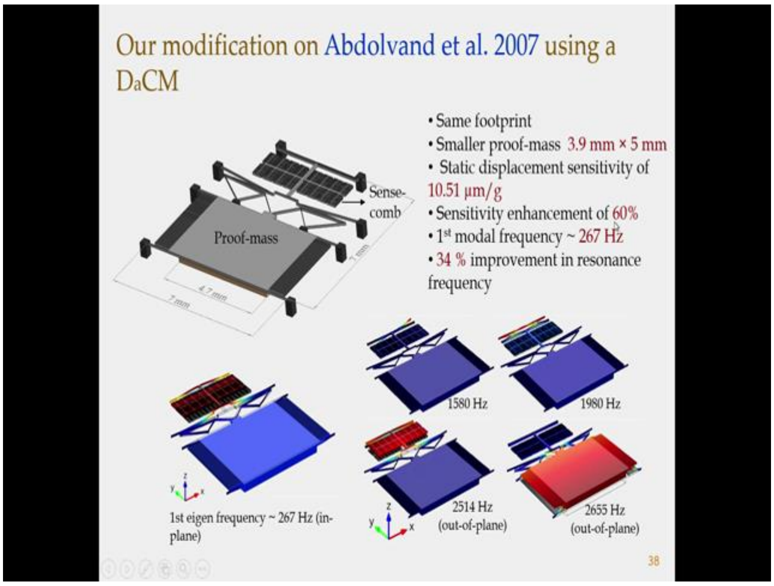

And how we got a design that was not inside got it outside for outside to inside and designed these beams that look like, this there is proof mass, these a DaCM, this is a sense combs and actually what we did was we took one of the very good accelerometers from the literature by Abdolvand 2007 added DaCM without increasing the area we are able to improve both the resonance frequency as well as sensitivity; sensitivity was 60 percent, was improvement 34 percent improvement resonance frequency.

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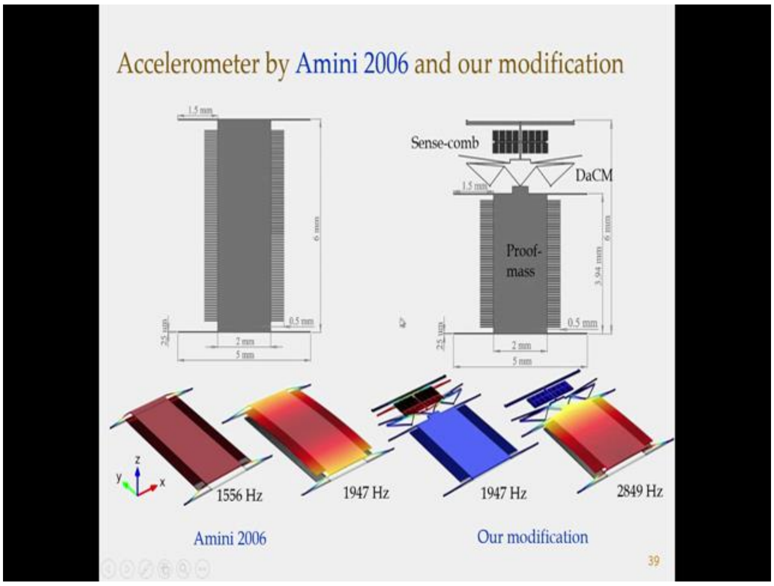

So, we are confident that anything we take from the literature by adding DaCM we can enhance the performance.

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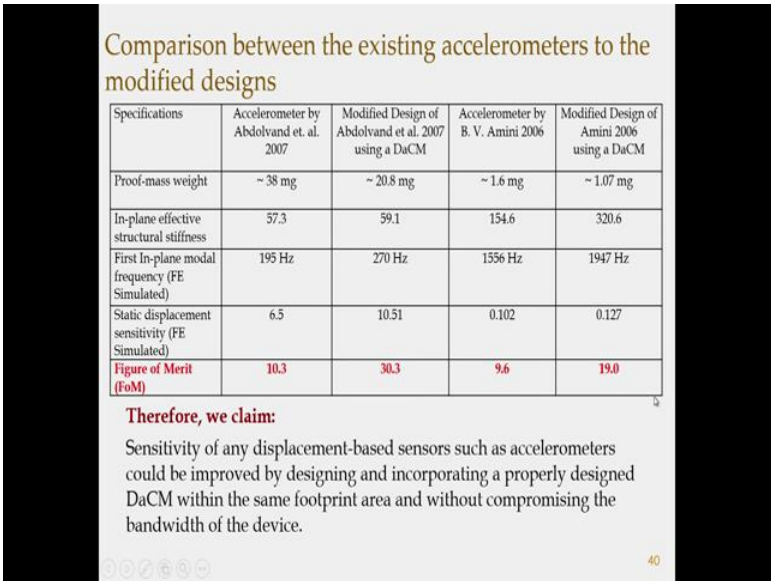

So, that is what is actually given here, whatever we took and with some we define as a figure of a merit that takes into account sensitivity as well as the bandwidth. So, it is much higher than what we started out with when you modify we get that modify we get this factor of 2 factor of 3.

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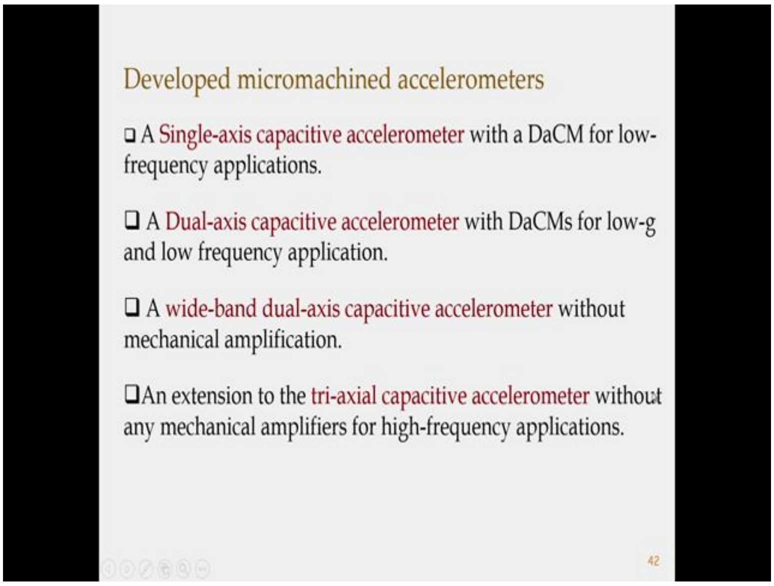

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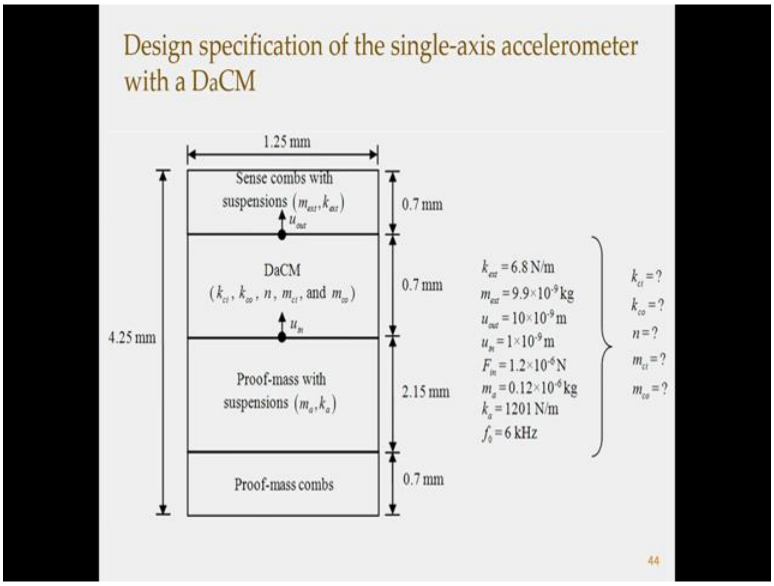

So, those are the things that are there, there lot of details about single axis accelerometer and this papers also have details about this and essentially we should understand that we want to come up with the DaCM to meet certain spex on that to work on this compound mechanical element of the overall device of the accelerometer.

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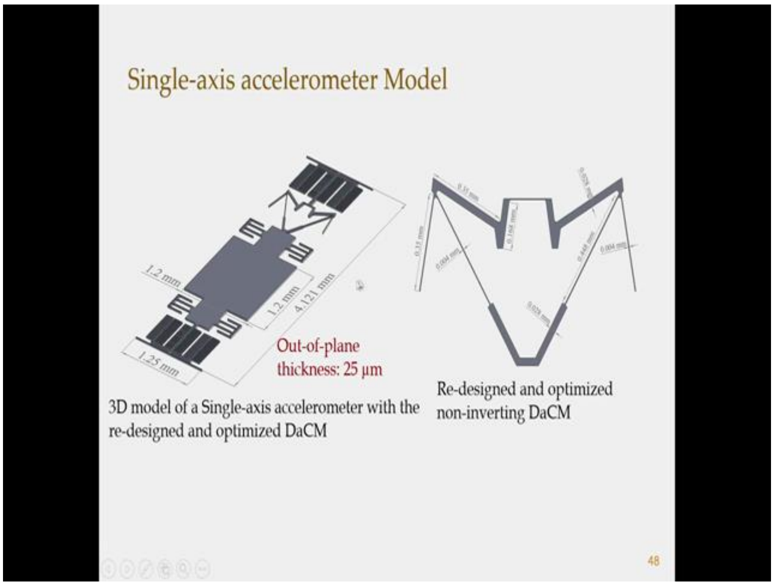

So, there are these details, and you can look at again the how we design the accelerometer and got it the right dimensions. So, I am just skipping through all of these things.

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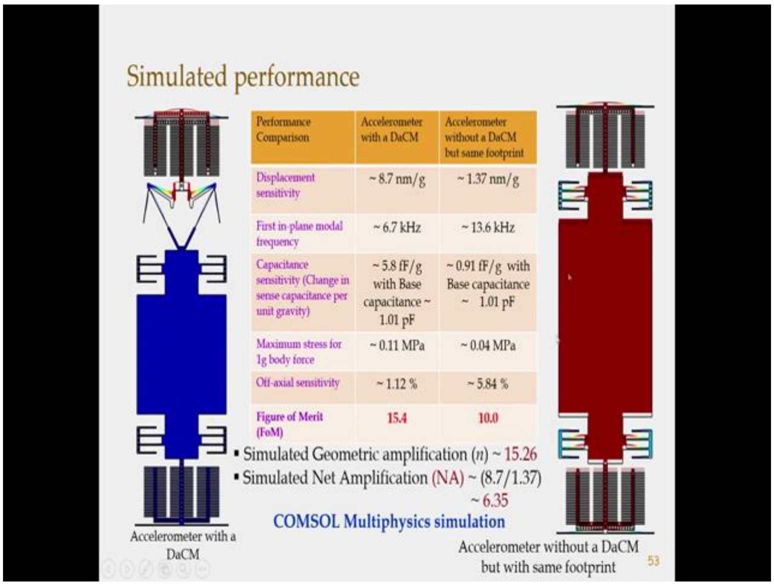

So, what needs to be noticed is that if I take an accelerometer without DaCM here, in the same area if I put another one with a DaCM this should be better than this that was our thing; we have to compare things when they occupy the same real estate on the chip. Relation on the chip is also expensive so we are not increasing the area by putting a

DaCM. And here we could see that we could get 6 times sensitivity improvement as compared to the case without the accelerometer without the DaCM that is something to note and there are frequencies and mode shapes and all the details here, some details about fabrication and these the device I think I will skip all of these.

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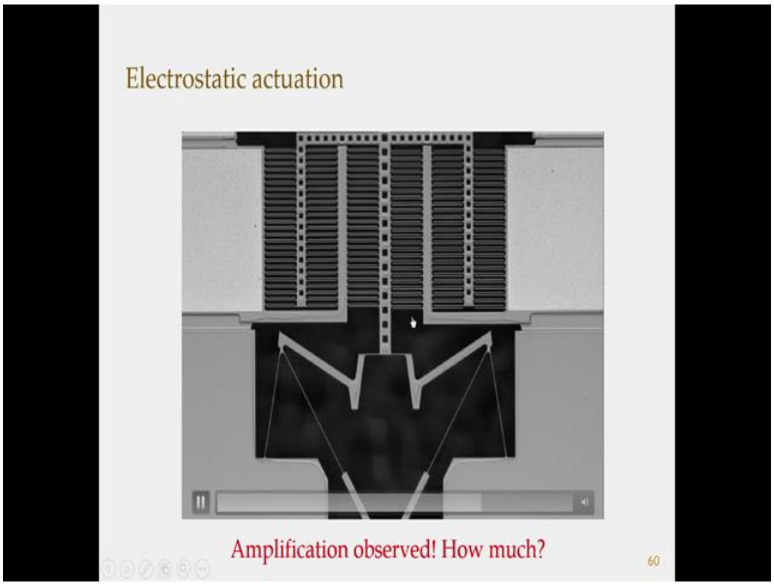

This actually shows this movie shows the entire accelerometer, so we will watch this. So, it actually moving, these combs are moving now the whole accelerometer is moving because you want to show the entire device. So, you can see the proof mass these folded beam suspension these beams are only 5 microns wide. These are proof mass and the black one is the gap, so proof mass can move now we just moving the whole thing to view in this video and when it passes that is when accelerometer acceleration is applied on it, you do not see much movement here now it is its not moving in the sense frame is not moving this thing is moving a little bit, now you hardly see the beams that are there. So, these are the beams now you do not see the movement here, but you see the movement there it will become very clear when we bring the comb fingers into view you see these are actually moving significant that we can notice so there is display amplification here.

These are all tested and verified and all the details are there. So, just coming back to compliant mechanisms, I will point out to what happens when you have a dual axis that you want to measure both in and out that is.

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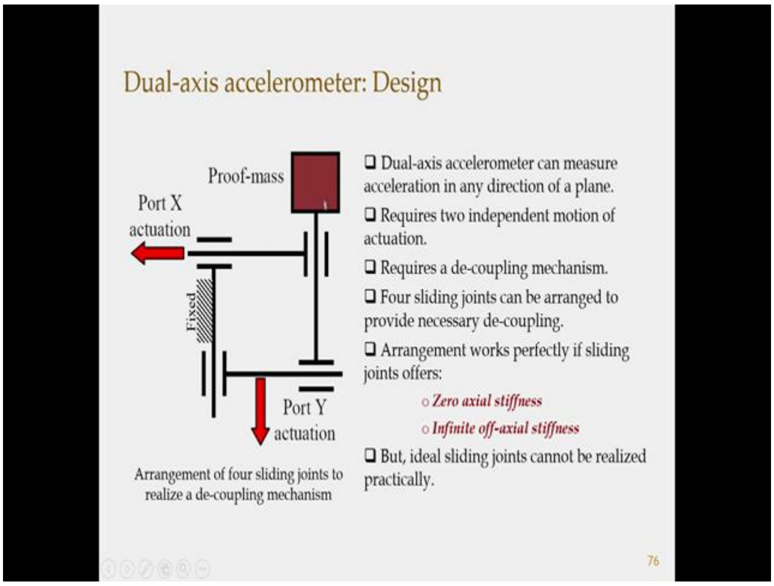

Where again our mechanism principle comes that this particular 4 bar linkage with all 4 sliding pairs, when I move it in the x direction nothing will happen to the y, when I move it in the y direction nothing will happen to x meaning.

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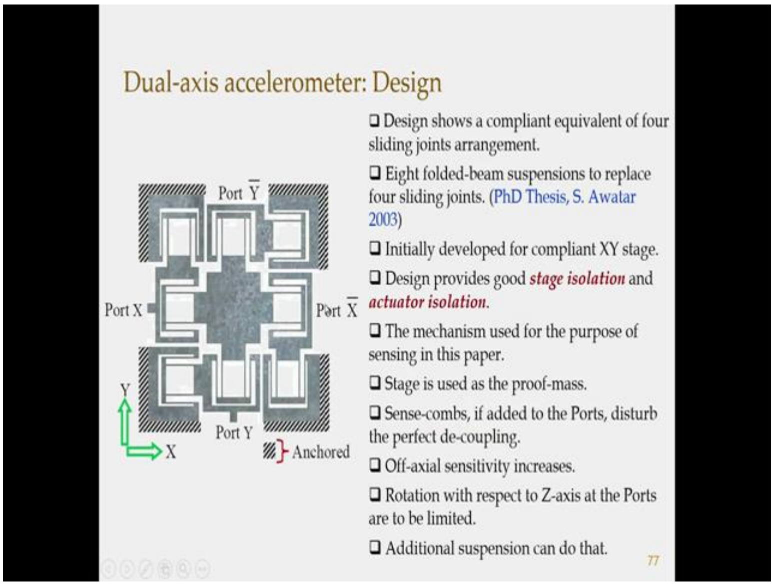

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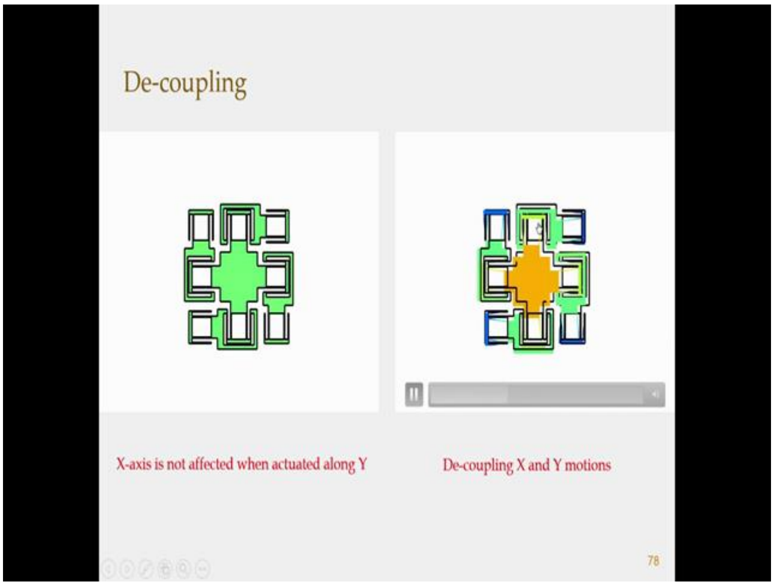

It will be something like this, there will be a platform where if you move in the y direction whatever is connect with x 1 so do not move at all and likewise when you move in x and y directions, this moves purely in x that moves purely in y. So, there is a decoupling.

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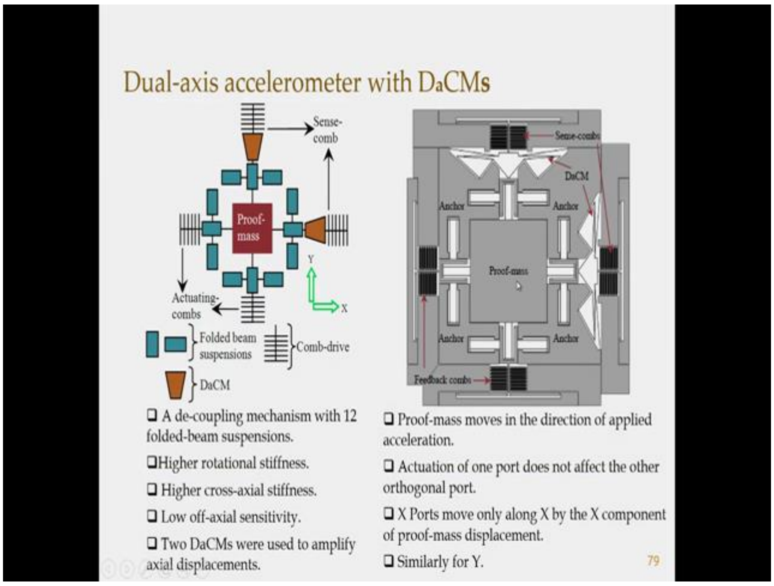

So, we can use this and make the accelerometer with DaCMs added with this decoupling that was the 2 axis one, otherwise all other things are similar. That is something again details can be look that and how we improved the designs that we had on hand using DaCMs.

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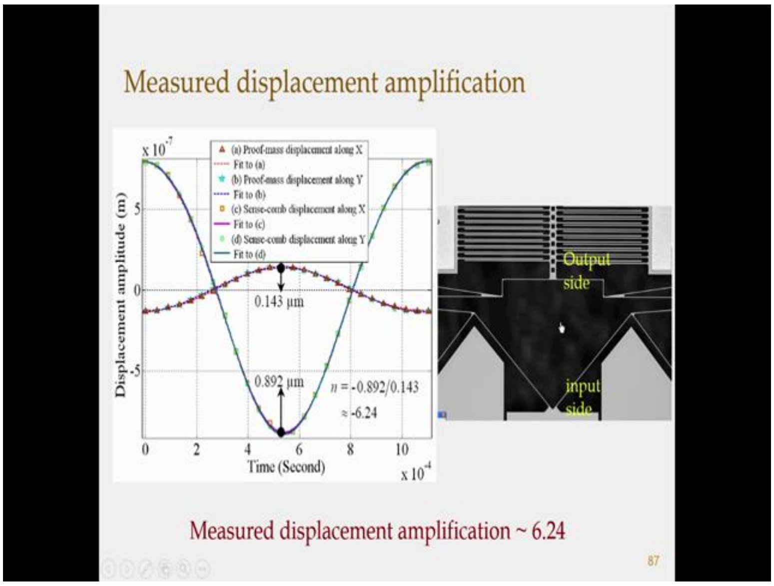

For all of this work DaCMs are the really the key. So, you can see there is little motion here there is a lot more motion over there these are dual axis accelerometer.

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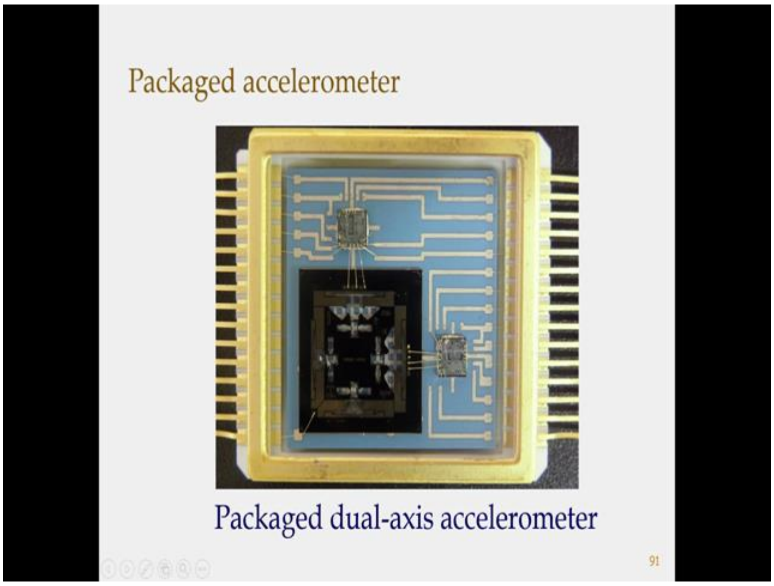

And this was packaged, this is the mechanical element I showed the flow chart at the beginning like system diagram these are the axis for capacitance measurement in the x and y directions, there is a PCB and this lot of electronics in this and then there is some outside the PCB also when we connect to battery and other things were calibration everything was done, alright.

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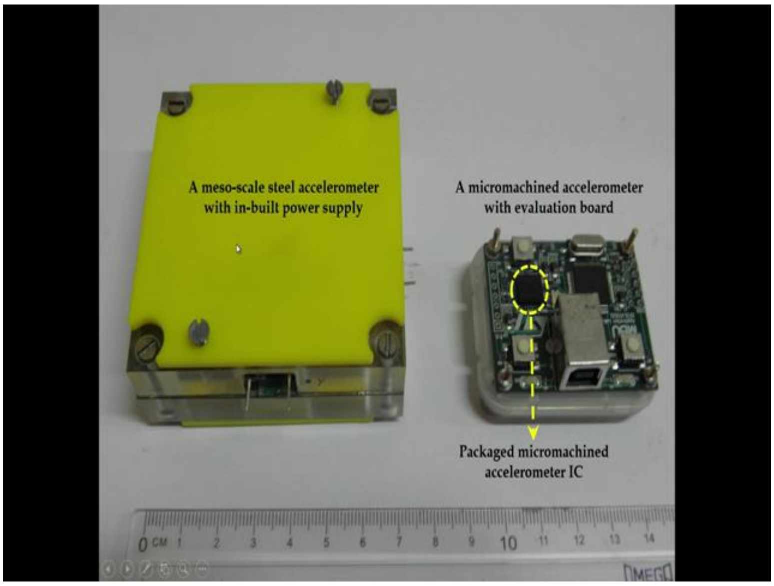

One can do with springs steal at meso-scale. So, I just want to say there are couple of papers that described that also. So, when you are making an accelerometer you see packaged one looks accelerometer element is IC is small integrated chip and rest of it is quite big. So, if you make a little bigger, you can also make accelerometer not using silicon, but you can use spring steel you can see the size on the ruler here.

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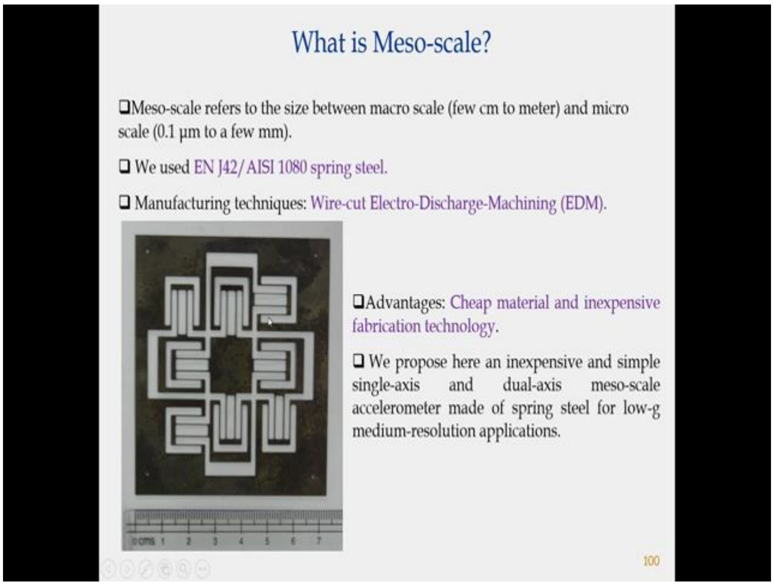

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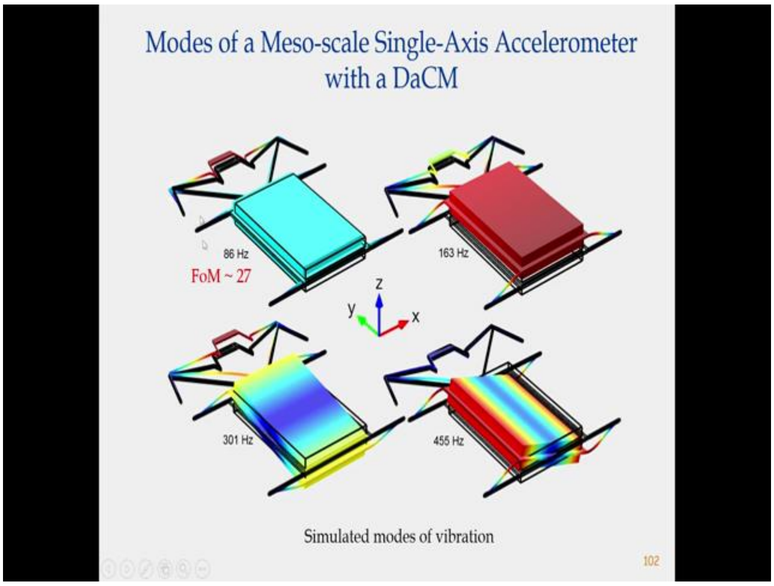

So, what we did here was to use chemically etched springs steel strip, you can see this is 7 centimeter and here we have again modeling and you know all of this.

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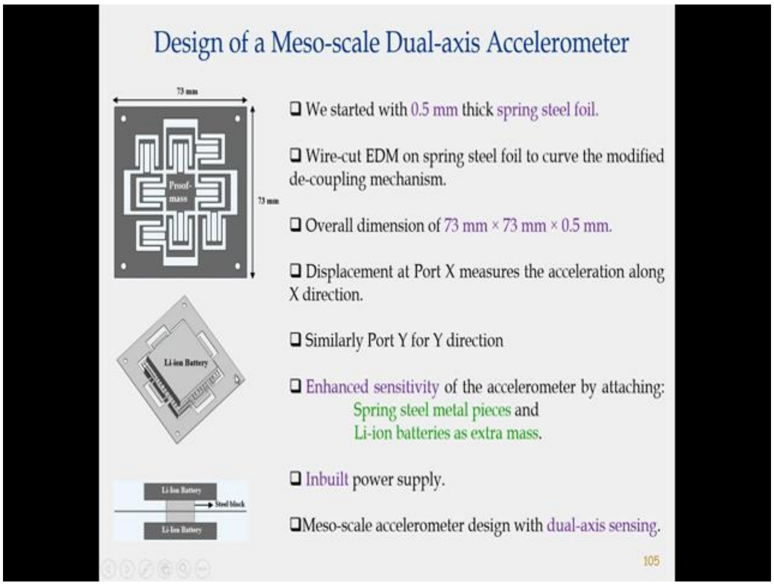

The nice thing about this was that we use actually battery as proof mass. So, there is battery here which is the proof mass and that enhances as we saw already, when there is a mass is more you are accelerometer going to be more sensitive. So, that could be done here, this also worked. And these something that anybody anywhere can built you do not need micro fabrication.

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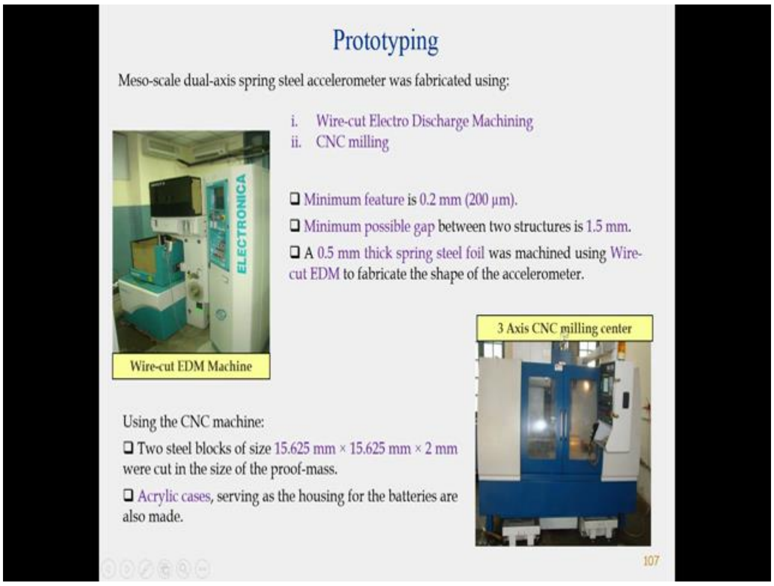

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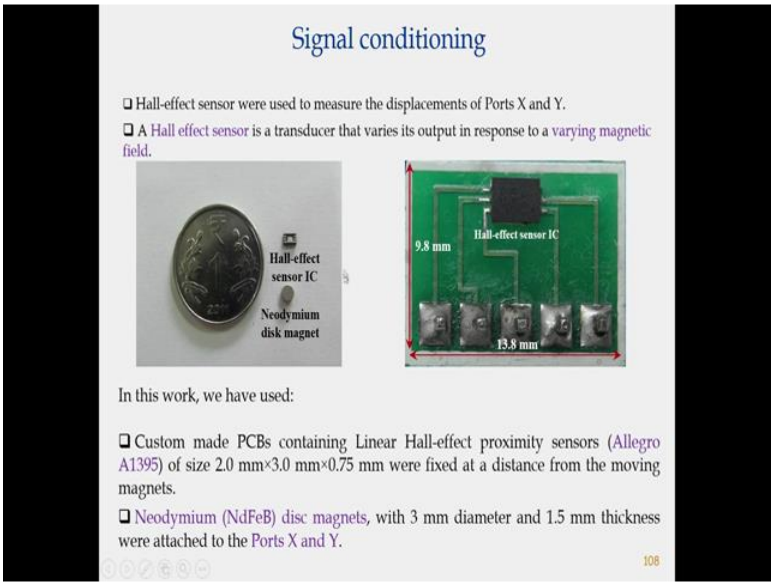

You just need some wire EDM CNC milling, that I think every collage everywhere will have access to and even collage does not have it you can go and get it made somewhere outside you can actually make in this particular case we used hall effect sensor not capacitor, whereas neodymium disk magnet which are very small and then hall effect sensor you can buy them for few rupees and put it all together this becomes an accelerometer.

And this has milli g resolution and if you are little bit more careful you can even make it 0.1 milli g also. So, what we have done now is look at the over view of the accelerometers to see what compliant mechanisms can do, they can do 2 things: one is they can amplify the sensitivity without compromising the band width; and when you are making dual axis accelerometers they can also decouple the x and y signals, which more like splicing of the signal; signal comes with both x and y accelerations, mechanically you are decoupling x and y and that I do not know you noticed or not, but that was meant by proof mass when it moves like this the x part moves only in this direction y part does not sense it.

When the proof mass both moves both moves in x and y the x and y sensors are going to pick up only x and y motion accelerations. So, that is the nice thing about this. Otherwise now only people what they do is they put one accelerometer to measure let us say this is y like that another one like this to measure x 2 different ones not the same here its integrated and here you can also be made it to a tri axial accelerometer x and y z, x y z are actually decoupled and amplified and bandwidth being bigger. So, that is what compliant mechanisms are able to in this application.

Thank you.