MEMS & Microsystems
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Lecture No. #22
MEMS Accelerometer for Avionics-A Case Study

We were discussing on inertial sensors. In my last lecture I discussed different kinds of inertial sensors and their basic principle. Mainly piezoresistive capacitive and tunneling current accelerometers were discussed. Today I will discuss in depth, a specific accelerometer how one can develop starting from the design specifications, its analysis, its layout generation and fabrication and at the end testing, that we call it a case study. I have chosen a particular topic on which IIT Kharagpur has got strength and we are working on that particular device last 2-3 years and that is MEMS accelerometer for avionics. That means for space application avionics application we need some kind of accelerometers which has got certain specifications, not the same as accelerometers used for the interterm electronics or say household appliance there. And those specifications are highlighted in this slide here you can see.

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And it has been recorded from the data required for guiding an aero plane that is flight control system normal mode. So for them a specific requirement is resolution of axis, sensitivity, temperature, stability, linearity, and etcetera. So those points how one can achieve those I will discuss today and the accelerometer we which we are going to develop, that is based on piezoresistor mechanism, piezoresistor sensing mechanism and it is used in aircraft. The range of that particular accelerometer is of the order of plus minus 13 g. Its resolution is 2 milli g; natural frequency is greater than 100 hertz, full scale output is plus minus 6.5 volt DC that has been taken from the accelerometer which are normally used in aircraft motion sensing. Those are bulk conventional accelerometer that is why they need that much power supply.

Obviously if you go for MEMS accelerometer and if the whole control system is made with the modern electronics, obviously the 6.5 volt full scale output is not required. Because now days most of the ASICs either CMOS or bipolar that is low voltage low power ICs are there. If you go for CMOS application, so that people are working 1.2 volt power supply. Obviously the output of the supply, output of the signal of the accelerometer in case of MEMS accelerometer may not be exactly 6.5 volt may be different. But since people are using 6.5 volt supply for control electronics and other things in case of conventional accelerometers. We will try to design that 6.5 volt DC output. But MEMS device output will not be that much, you have to amplify it to get that value. Linearity is 1 percent full scale, damping ratio is 0.7 plus minus 0.2. These are the specifications and how to achieve that specification, how one will proceed to get those objectives, that is the topic of discussion today.

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Now we are going to design a silicon micromachine piezoresistive accelerometer with low off axis sensitivity. What is off axis sensitivity, I will discuss in earlier classes. And low off axis means how much low? Particularly in case of aircraft motion sensing or avionics if it is a 1 axis accelerometer, so off axis sensitivity should be extremely low and that order should be at least third order low. So sensitivity if your desired direction is for example if say 1 percent, then you have to go for a 0 0 1 percent sensitivity in other 2 axis. So that is the normally third order is desired if you get more than that is also highly accepted. But it should not be say 1 order difference. In that case the along with the desired axis other 2 axis sensitivity also will come into the picture.

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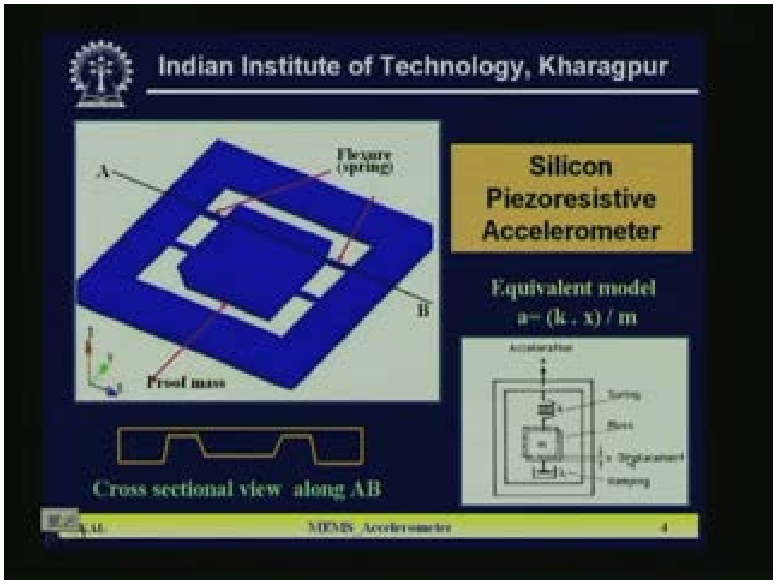

So those are the points and those points we have kept in mind when you are going to design these accelerometers. Now you can see here the basic silicon piezoresistive accelerometer for this application is not as simple as possible which I showed you a structure in last class. That is only 2 flexure 1 proof mass is held by 2 flexures and because of the acceleration the proof mass will go up and down and accordingly the piezoresistor resistance will change at the flexures. Now that particular design has got certain drawback and the drawback is that is not highly stable. Because the accelerometer which you are going to design, that has to survive with shock. One parameter is shock survivability. So for example certain shock or certain jerk the proof mass should not break away from these flexures. For that reason in this particular case we have used 4 flexures; not the 2 you can see in the figure.

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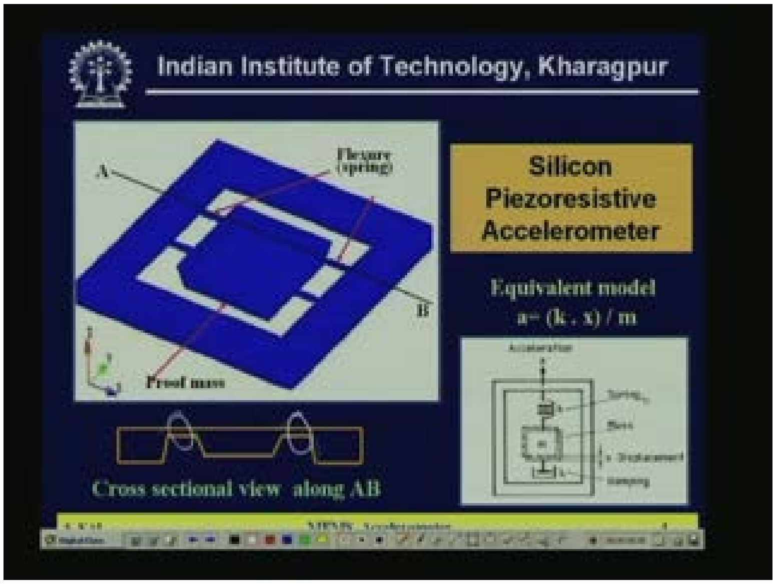

So there are 4 flexures, not the 2 and so here you can see that the 1, 2, 3, 4 and this is the proof mass and this is the beam so that even with jerk or power acceleration, the proof mass will not break, it will be stable. And if you say a cross section diagram along AB it looks like this. So this is the proof mass here, in the bottom diagram you can see here and this is the flexure dimension, here is the flexure and now if you, this is the flexure size and here is the flexure size where you are going to measure going to fabricate the resistances. Now the equivalent model of the accelerometers is shown in this picture where you can see is spring and this is the mass, spring mass model and if you give acceleration a, mass is the m is the proof mass weight though acceleration is a force is equal to mass into acceleration m into a which is equal to k dot x, k is the spring constant and x is the displacement, k dot x is equal a into m. So obviously acceleration k dot x by m, that is equivalent model of the particular accelerometer.

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Now if I go for the next slide then you can see here. The first job after finalizing this structure, so we have to have mesh sheet for stress analysis because you are going for numerical techniques. So obviously final techniques means you have to define small element which is known as a meshing. So meshing of the total structure is shown in this diagram where you can see here the mesh sizes are not same throughout the structure. Why it will not be the same that I also mentioned earlier. And the bottom figure shows the resistance part and here the basically the diffuse resistance we are using. So the total resistance will be decided by the number of square. If you know the width of this resistance and total length of the resistance. So we know how many squares are there, that is multiplied by sheet resistance will give you the total resistance. Now the two end of the resistance is having 2 bonding pad, contacts.

So these two color is the two contact region and obviously if you metallized it, so or the contact must be at the middle of the resistance. So for alignment tolerance 10 micron each side we have allowed. So if the dimension of the width of the resistance is 20 micron. So the areas will be 40 by 40 micrometer. Now this resistance value is one parameter which you have to decide and it will be limited by different requirements. So if you use very long resistance, long length, width is large and length is long. So in that case the problem is you know this stress region is not very large. Maximum stress region, if you place the resistance, so obviously its sensitivity will be more and pickup signal will be more. So that maximum stress region is not very large. So over a limited region the maximum stress occurs.

So obviously the length or the size of the resistance should not go much beyond the maximum stress region. That is one limitation and second limitation is that if you want to have very small resistance over the only centralize maximum stress region. In that case there is a fabrication tolerance is also there. In if you go for say 2 micron or say 4 micron or say 5 micron width resistance that is not possible. That means that is coming from technology limitation. So keeping in mind of the technology limitation and the maximum stress region, limitation you have to decide the value of the resistances. At the same time if you want to have change, large change over small stress, so the value of the R should not be very small. So it depends on the value of R, so you are not going to fabricate 50 ohm, 100 ohm resistance. At the same time you are not going to fabricate 10 mega ohm or 20 mega ohm resistance.

It should be somewhere within few kilo ohms so that the delta R is also large. It can be fabricated over a small region and another thing is you know, sheet resistance also depends on the doping concentration. The doping concentration side, the third limitation, it cannot choose any value of the doping concentration of the resistance. This kind of resistance is normally fabricated using boron doping. Because we have seen that P type silicon as got the piezoresistive coefficients larger value compare to the N type. So in that angle we will choose the P type silicon in getting the piezoresistances and not only that, in order to have to comfortable technology with the VSLI fabrication. So it is better to choose a resistance by P type diffusion. Because in VLSI most of the resistances are made not by N diffusion, but by P diffusion. So that is why along with the normal resistances in IC, if you want to fabricate the piezoresistance also in silicon, so we have to go for P type silicon diffusion for getting the resistance.

So these are the various limitations and with all the limitations keeping in mind you have selected the geometry as well as doping concentration. Doping concentration limitation is because of various reasons. Some of the reasons I will highlight in today's lecture itself. Those are the variation of the piezoresistive coefficients and variation of the TCR with doping concentration. That point we have to consider when you are selecting a particular resistance. And another is, if that doping concentration is much different from the doping concentrations used for making resistances of integrated circuits which are coming side by side, if you go for smart sensor that is also not desirable. So these are the different limitations based on which you have to select the doping concentration, resistance geometries and values of the resistances.

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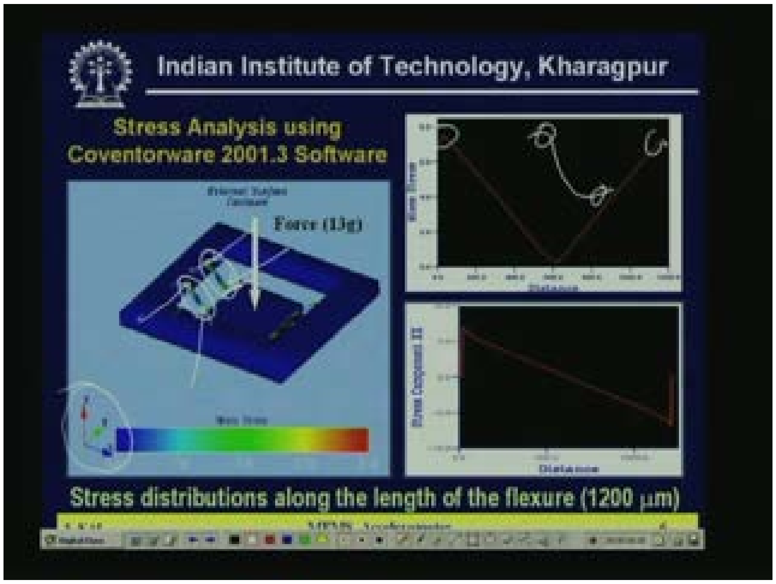

Now this slide show how accelerometer, that means the structure what I have shown in the earlier diagram looks like if it is facing an accelerations in z direction and there you can see that this is the x, y and z directions. Now z direction is the vertical upward and downward. So it can go in this direction. Now for 13g force, the proof mass will go downwards because of its inertia. So as a result of which you have seen here the flexures, this is one flexure and this is another flexure, how the flexure will take the shape and if you go for stress analysis, then the color notation here shows the variation of the stress along the length of the flexure and obviously the colored indication shows that maximum stress is this point. We are having maximum stress here also. This point is a maximum stress, here this point is a maximum, and here also this point is maximum. In the middle the color is same as the frame color is a blue, so that is a zero stress.

That means at the middle point there is no stress at all. The same thing is reflected in the right hand side diagram where missus stress is plotted across the distance. So this analysis has been done using coventorware 2001.3 after meshing. So now here you can see one thing is accurately you can locate the maximum stress region. This is important to choose the location where the sensitivity is maximum and you are going to place the piezoresistance in that particular location. So now you see here missus stress means it is a magnitude why it is plotted over distance and here is the stress component is shown in the bottom diagram where it is shown positive and negative. Because you can see here in this flexure near the frame end it is basically this stress are two kind of compressive strain and tensile strain. So is near the frame end is a tensile stress and near the mass end is a compressive stress. So since elongation is something like that. So obviously it is like this.

So here the elongation will take place and here the compression will take place. So now because of that you have seen here where elongation takes place, this stress is positive and compressive stress is negative is opposite in sign. Tensile stress and the compressive stress, so one is positive one negative. But if you plot the magnitude wise then is a missus space it is known as width distance, distance flexure dimension is here 0 and this point is 1200 micrometer. So this scale is 0 to 1200 micron. Now you found this maximum point is very not at 0. But very close to that is nearly the 70 or 75 micron it is there in the next view graph. Similarly here is a very close to the frame end the maximum peak points are there. This is maximum peak region, this is the maximum stress, peak is here, means maximum stress is here and here is a minimum same thing shows in the colored diagram also is a blue color here.

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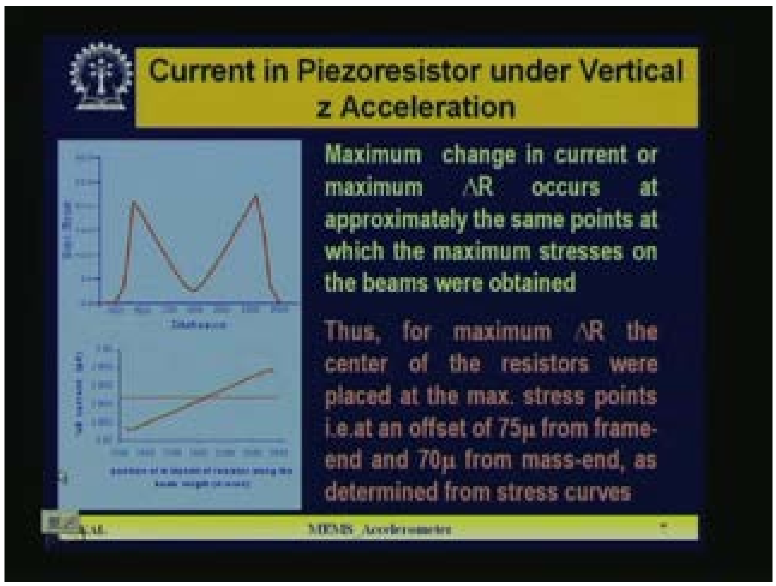

So now if the next view graph is the current, also you can see because depending on the change of resistances, the current components also is going to change. That is an ampere into 10 to the power minus 9, so that you can see the current variation direction is also going to change. If you localize the current simulation if you do using coventorware using a constant supply voltage, so delta R will change. If change is in positive direction, then current will change some direction and if it is a delta R is negative direction, the current may be in opposite direction. That is why you can see the current variation. Now we found the maximum change in current or maximum delta R occurs at approximately the same points at which the maximum stresses on the beams were obtained.

This is this point here and another is a peak is here. So these two peaks is almost the same magnitude. Thus the maximum deltas R, the center of the resistors were placed at the maximum stress points. That is at an offset of 75 micron from the frame end and 70 micron from the mass end as determined from the stress curve. So this is 75 microns here from the frame end and another is a 70 micron from the mass end, is a proof mass end 70 micron. So I am telling you can see at this point may be the 75, here this point is 75 and this point is 70 micron from the frame end. So that is the maximum stress location.

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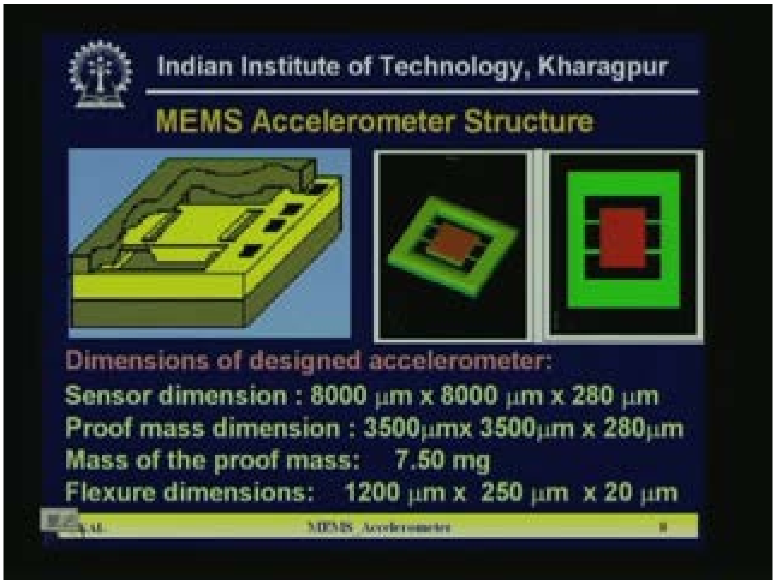

So now after finding that point, now you can place the resistances. The one job is over. Where to keep the resistance? Now the complete structure because as is mentioned in the requirement of the sensor specification, there is damping will be 0.7 plus minus 2 and at the same time you have the resonance frequency or the frequency is great than 100 hertz. So those points are there. So obviously this kind of accelerometer will not be there. You have to have a top cap layer and bottom cap layer, so the total structure is shown here. So top cap layer is here, bottom is there, in between middle is a sensing element. So there the dimensions were chosen now and the sensors dimensions again how do you select that? In this particular case obviously the sensitivity also depends on the weight of proof mass, mass of the proof mass. So the mass has to be more so that you will get higher sensitivity.

At the same time over the flexure there will be wiring. Wiring means if u make resistance and then it has to be connected with some wire so that the collections will come at the frame from where you can apply the signal and you can take the pick up the signal also. So that the metal lines will flow over the flexure width, so if the flexure width is very small, so then again you cannot take out. So all these limitations keeping in mind you have to design the flexure dimension. Means length and width and we have found in our application depending of the technology limitation of our laboratory. So the flexure dimension was chosen 1200 micrometer, 250 micrometer and 20 micrometer. 20 micrometer is the thickness of the flexure, 250 micrometer is the width of flexure and 1200 micrometer is the length. If you go for 2 inch wafer then its thickness is near in 280 micron.

So if for 280 micron if we take the proof mass size, 3500 micrometer by 3500 micrometer thickness is same 280 micrometer, then its weight is coming to be 7.5 milligram. Now this weight if you want to make more and more, so sensitive will be higher and high. So this total sensitivity depends on prime 2 factors. One factor is mass of the proof mass; other is thickness of the flexure. So thickness of the flexure here we assume 20 micron. But if you go below that, the problem is the handling of the piece wafer. Because after making the center, the sensing element top and bottom glass wafers or silicon wafers has to be substrate bonded. So that means some mechanically movement mechanical the pressure has to be applied there. So because of that if you go for very thin flexure then the proof mass may break.

So for that reason you cannot go the 10 micron or 5 micron although your laboratory you can make the flexures very thin. But keeping in view of the handling of the wafers bonding of the wafer you cannot go very thin the flexures and it depends on the technology available in your in your foundry. So for 20 micron that is one parameter another is proof mass. So proof mass weight you can go on increasing and here we have use same as the substrate thickness. But you can increase more how by depositing some gold films on the proof mass. So if that is normally done by electroplating, if you electroplate gold on the particular, the proof mass, the square proof mass which is used, so then it although you are going to use 2 inch diameter wafer. So the thickness of the proof mass may increase by addition of gold layer over the proof mass. So these are the dimension we have chosen.

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Now the resistors specifications we have used here 120 micron; 120 micron by 20 micron is the resistor dimension, Contact pad dimensions are taken 40 micron by 40 micron because 20 micron is the width; 20 by 20 is the contact and the pad should be 40 by 40 because it has to be align in to the resistor. That is why 10 micron both side more it comes to be 40 by 40. Resistor materials we have chosen boron sheet resistance we have chosen 250 ohm per square. Junction depth is 2.5 ohm 2.5 micron junction depth is 2.5 micron. Now this junction depth one point is if you go for stress analysis, so stress is case of silicon we told you that it will be confined over the surface of the silicon.

It will not go vertically deep in to the silicon since it is confined to the surface the stress region. So and again we want to fabricate the resistor in to the maximum stress region. So in that case junction depth limitation is also coming in to the picture and we will see in the next few slides. So junction depth because you are see temperature efficient or variation of the resistance also depends on the junction depth. So junction depth should be such that within that depth the stress variations is confined, if we make resistance will below that area where the stress variations is there, so it sensitivity would be will be low. So that is another point and at the same thing we have to keep in mind. I told it was many of the factors depends on the technology limitation of your foundry but if I cannot if I find in my simulation that the maximum stress region extend just below say 1.5 micron from the surface.

But the 1.5 micron or 1 micron junction depth if I cannot make in the laboratory with confident with repeatability so then I cannot make. So if that normally if you go for un-implantation, so junction depth accuracy is much more compare to the diffusion techniques. So if you go for un-implantation technique for making the resistances then obviously you can choose the junction depth as required by your stress analysis. Otherwise if you go for diffusion if you cannot control junction depth within 1 micron, then you have to go for higher junction depth. So you at the cost of little bit low sensitivity. So any way keeping all this factors in mind we have chosen the resistors properties like this.

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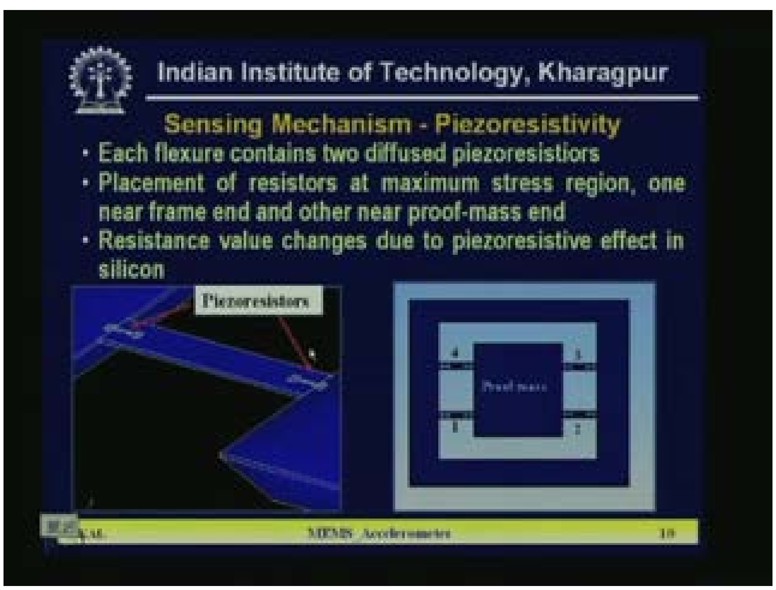

Now the sensing mechanism and next point we are going to address is the low off axis sensitivity. How can we achieve it? So now for that we have made 2 resistances on each flexure. So simple piezoresistive accelerometer diagram which I showed in my last lecture, they contain 1 proof mass in 2 flexures and each flexure is having 1 resistance at the maximum stress region. But here in order to meet this specifications required by the avionics people. So here we have change the structure little bit and here we have made 4 flexures instead of 1 and each flexure is having 2 resistances. So total resistances will be 8. So 1, 2, 3, 4, 5, 6, 7, 8. So the resistances are shown here. You can see here is the 1 resistance; here is 1 resistance at the maximum, the stress region and now the basic principle is known the resistance value will change due to the piezoresistance effects.

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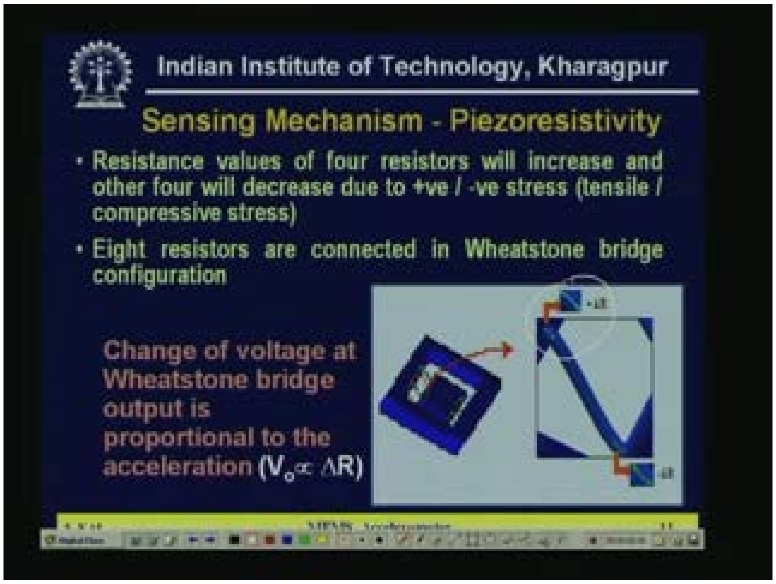

Now the resistance values of the 4 resistances will increase and other 4 resistors will decrease due to positive and negative stress. Positive stress we call it as a tensile stress and which is here you can see the positive stress. This is the region where you can see, this is the positive stress region where plus delta R. So you can see the 1 flexure has been shown here with much amplification the diagram. So here the bending on the resistances like that it is shown here. So automatically here it is a plus delta is which is tensile stress, obviously in opposite sides is a minus delta R because of the compressive stress. So that means each flexure the 2 resistances, one resistance is facing the tensile stress other is facing the compressive stress. So if I make like this, the total 8 resistances, so out of the 8, 4 resistances will increase other 4 resistances will decrease. So now the change of the output change of voltage at the Wheatstone which output proportional to the acceleration and that is the V_0 is proportional delta R because delta R is proportional to acceleration.

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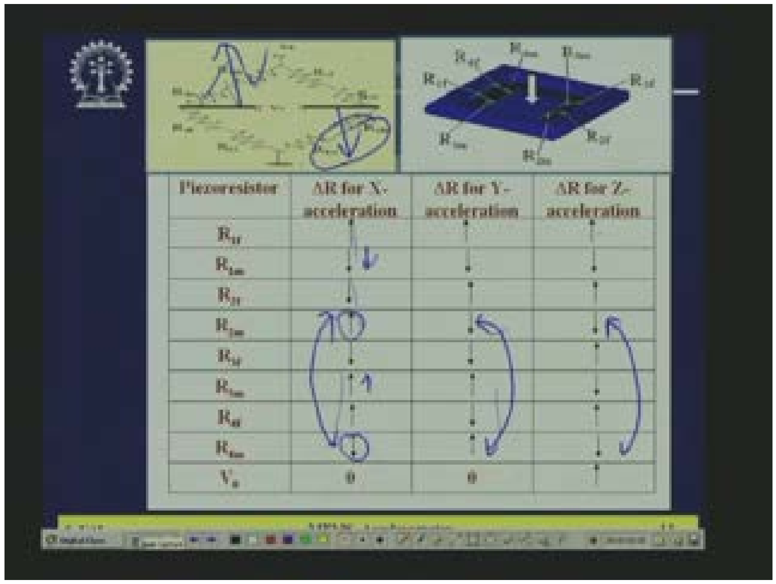

Now if I see this diagram how we you can get the off axis acceleration? Now you see this the again I have shown the sensing element where the 4 flexures are there and I have named to the 8 resistances by R_{1f}, R_{2f}, R_{3f}, R_{3n}, R_{4f}, R_{4m}. So now here you can see here, so now R_{1m} and 3mR connected m stands for mass end and f stands for flexure end. So you can see the opposite arms. So 1 and 3 the m are connected in opposite to that 2 and 4 the m as connected mass and resistances. Similar other two side of the Wheatstone bridge the 1 and 3, here 2 and 4. So 1 and 3 is here; 2 and 4 here. So one is the frame end-frame end, mass end-mass end like that. Now if you look into the individual resistances when delta R for X acceleration, delta R for Y acceleration, delta R for Z acceleration. Now under the no stress condition if I make all the resistances are of same value which is nearly 1.5 kilo ohm. In calculation or in fabrication it may very little bit may be say 1.3 to 1.5 kilo ohm.

All the resistances are the same, then under no stress condition the total resistances value of each R will be 3 kilo ohm, if it is 1.45 kilo ohm per resistance. Here 3, 3, 3, 3 so bridge is perfectly balance. Now if you go for acceleration for example Z axis acceleration the proof mass will take this safe. Now let us see how the resistances are going to change. Here for Z axis acceleration you can see R_{1f} which is here and R_{1m} which is the mass end is here. So 1f plus delta R, so 1f is increasing 1m is minus delta R it is reducing for Z axis. Similarly for second flexure or 2f all the frame end resistances are increasing all the mass end resistances are decreasing. Because all the frame is are getting the tensile stress and mass end as getting the compressive stress. So in this way so normally you can see if 1f and 1m are connected together then there is no change. Similarly 2f and 2m R connected together no change, it will remain same. So in that case will not get any output. That means 1f and 1m in any R of the bridge is not connected together.

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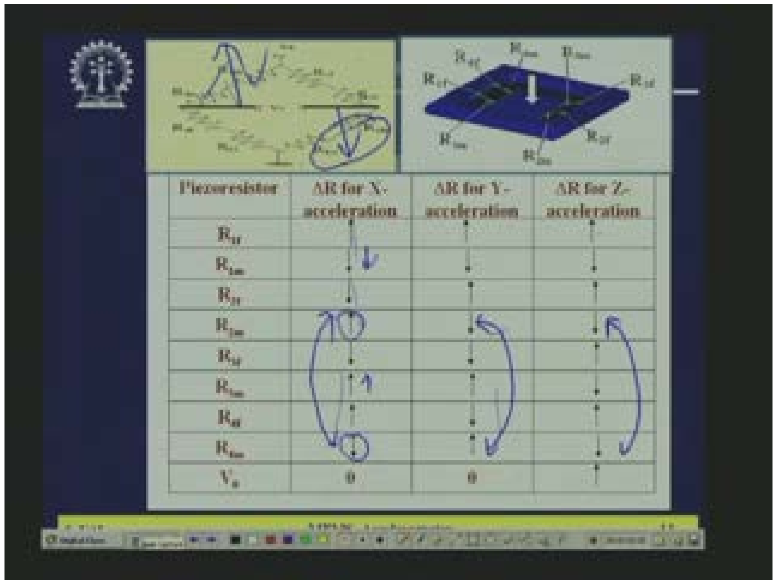

You can see 1m is connected to 3m; similarly 2m is connected to the 4m. So 1m and 1f for not connected in that case the total output will be 0; that we do not want. We have to get under Z axis acceleration V_0 should be some should have some value but R, X and Y axis it should be 0. Now if I connect this in this fashion then you can see for X axis, so where the first we have 1m and 3m are connected. Let us look 1m has a reducing and 3m, 3m is here is increasing. So 3m is increasing, so 1m is reducing for this f. So that mean you can see if you add these two, this and this; one increases, one reduces. So automatically total value will be same, total change will be 0.

Similarly you can see here 2m and 4m. 2m is increasing this part you can see and 4m is here is reducing. So now if you add this 2, so then you can see the total remain same. There is no change. Isn't it? Similarly for Y axis is you can see here this is reducing and here this is increasing. Now if you add this and this together, so what is happening, it is also 0. One increases is another reduces. So in this fashion will you fine that all the 4 arms if you add like that, so total change delta R will be 0 here and 0 here. On the other hand if you add this and this together so you can here this is also going down, this is also going down. So total in this is arm 2m and 4m, 2m and 4m connected here, 2m in connected is here so this also reducing, this also reducing.

So there will be total delta R will be much more in this case in Z axis acceleration which not same in X and Y axis acceleration. Similarly here if this total reduces at this total will increase in case of Z axis. So in this way if you connect judiciously this 8 resistances, we found that in particular direction of acceleration the maximum output will be obtained for other X and Y direction acceleration, the resistance increase or decrease cancels each other. So that in those two direction will not get any voltage or may be very negligibly amount voltage you can, so that you can get very high off axis sensitivity.

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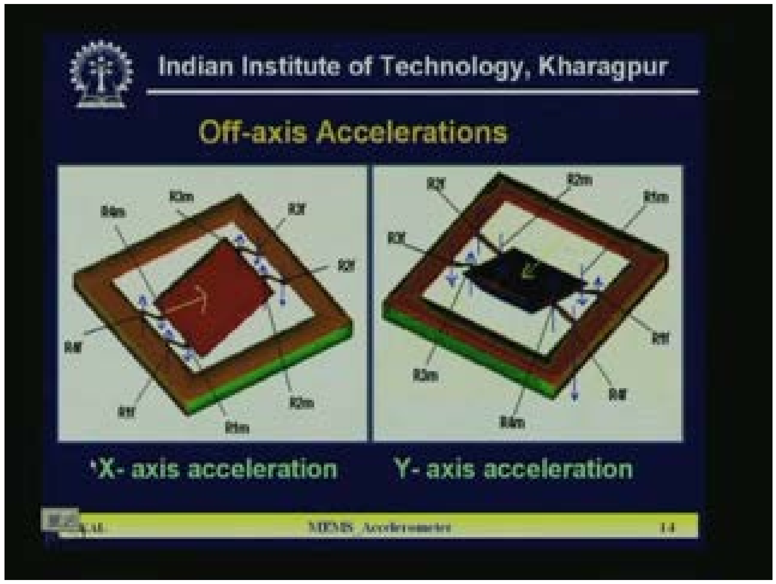

Now if you look in the next diagram so what I just told you it is shown here for this for X and Y axis acceleration. So in X and Y axis acceleration you can find here, you can see this each arm. I have shown by arrow increasing and decreasing. So here you can see this is under X axis acceleration, these along the X axis, this is along Y axis acceleration, they are perpendicular each other. So along X axis the proof mass will take this step. So this is along X axis is shown here. So if proof mass will take this step, so now here in each arm from that table I have drawn the diagram here. So one increases another decreases. Here this increases, this is going to decrease, here this increases, and this is the reducing increases reducing like that. So that means the total delta R change will be 0 in this case. Similarly here also, here also you can see this increases opposite the reducing and this is also increasing. So total change is 0, here is also is 0, here is also, here is also 0. So X and Y axis acceleration you will should not get any output.

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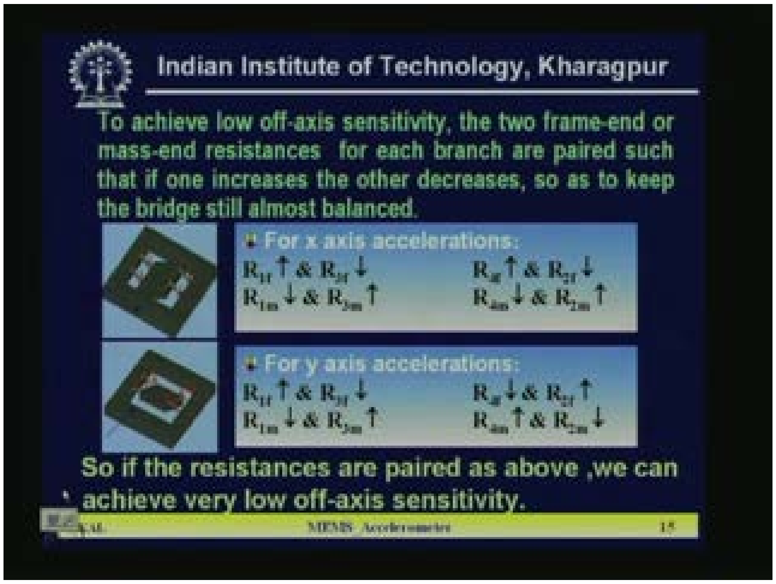

Now so now if you summarize that we can say to achieve low off axis sensitivity that 2 frame end or mass end resistances for each branch are paired such that if one increases the other decreases. So as to keep the bridge still almost balanced and here is shown how the 1f and 3f going in up and going down 1m and 3m 4f and 2f and 4m and 2m. Those are connected in pair and that is fixed in each arm. So if the resistances are paired like this, you can achieve very low off axis sensitivity. Now this is okay. Next point is I had to go for designing that the frequency should be greater than 100 hertz, the natural frequency. So for that we have to do some modal analysis because any structure if you do the modal analysis it will go for the first mode, second mode, third mode like that.

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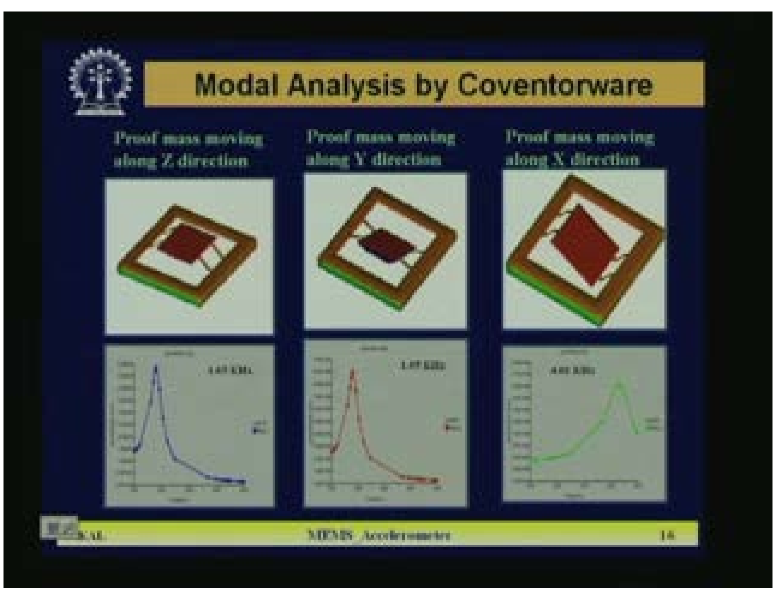

So that model frequency the frequency verses response if you plot, so there will be act the resonance frequency the maximum output will get. But we do not want to resonate the complete structure. So that may create problem to the total device. So we should because we know our devices are all DC and very low frequency signals are there in those sensor. So that the resonant frequency of the complete structure mechanical analysis if we do so that for different mode we have to see whether it is below 100 hertz, that we have done using that is normally obtain from modal analysis using coventorware. So Z direction, Y direction, X direction the frequency the frequency versus the signal output or the magnitude of the displacement all things is plotted here and we found there in all cases the frequency of is well above the 100 hertz.

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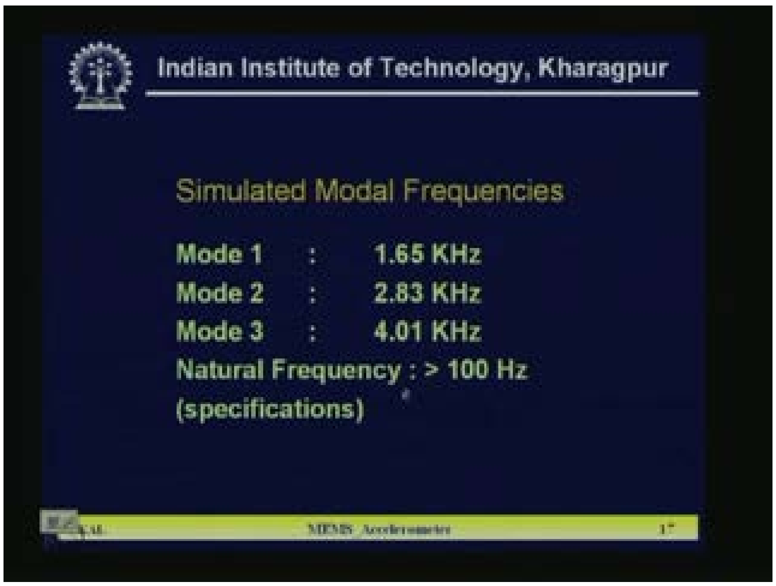

So now if I see mode 1, the modal frequency is 1.65 kilo hertz. For mode 2 it is 2.83 kilo hertz. For mode 3 it is 4.01 kilo hertz. That means our specification should be greater than the natural frequency is near 100 hertz and our design should be greater than hertz. So in all cases is well above 100 hertz so that specification is meeting. So that mean in that so for the natural frequency is concerned, this structure satisfy this specification.

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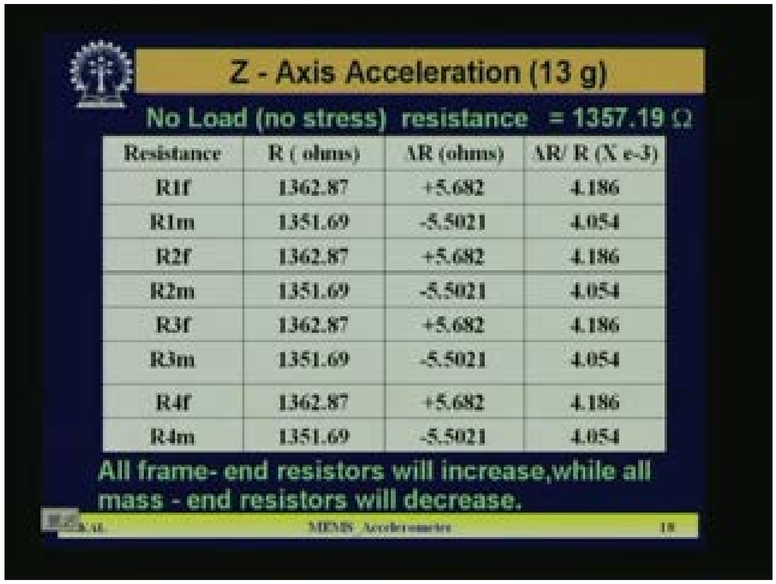

Now the next point is the simulation where you can see how much the value of the resistances are going to change. So now for here you can see the R1, f1, m2, f2, m3, f m 4 f and 4m. So each resistance, so it is a no stress value is 1357.19 ohm after the doping and other things is utilizes junction depth is decided. So it was like that 1.357. So this resistances are shown here and delta R, delta R the change of a resistance for 13g acceleration. That is also calculated and those values are shown. Delta R is you see one is plus another is negative. Plus minus plus minus plus minus it stands for one for tensile another compressive. So tensile is the positive and ten the other one is negative is for compressive.

So is another parameter is basically delta R by R. So delta R by R here you can see so this delta R 5.682 divided by 1357.2 ohm. So it is coming nearly 4.186 into 10 to the power minus 3. So now if you critically analyze the result you will find that 1f, 2f, 3f and 4f, all are 4.186, 4.186, 4.186, and 4.186 in to 10 to the minus 3. On the other hand the 1m, 2m the 4.054, 4.054, 4.054, 4.054. So that means all the resistances are change are in the compressive and this tensile, one is increases and decreases are in the same magnitude. That means it is total structure shows a uniform variation. That means we found here all the frame end resistance will increase while all mass end resistance will decrease.

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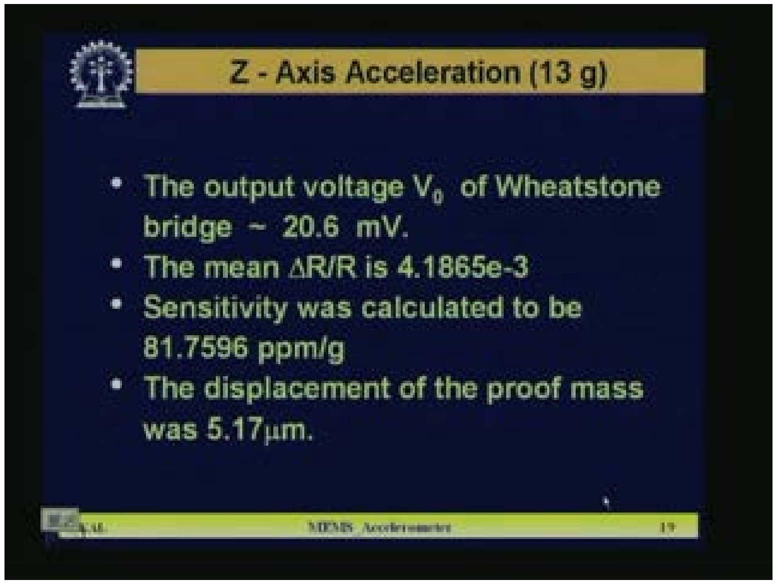

Now the next table. So the next slide shows the output of the simulation. The output voltage V_0 for that delta R by R change. So total output voltage is how much delta R by R in to Vs; Vs is the supply voltage. So if you apply Vs 5 volts, so then the bridge voltage is found is nearly it is coming 20.6 millivolt and the mean delta R by R is 4.186 into 10 to per minus 3. Sensitivity was calculated to be 81 points 75 ppm per g. This is a Z axis sensitivity the displacement of the proof mass was found 5.17 micrometer; displacement means from no stress to 13g stress. So that means the proof mass will go down from the rest position 5.17 micrometer only for 13g and you will get 20.6 millivolt output if you supply the bridge voltage 5 volt.

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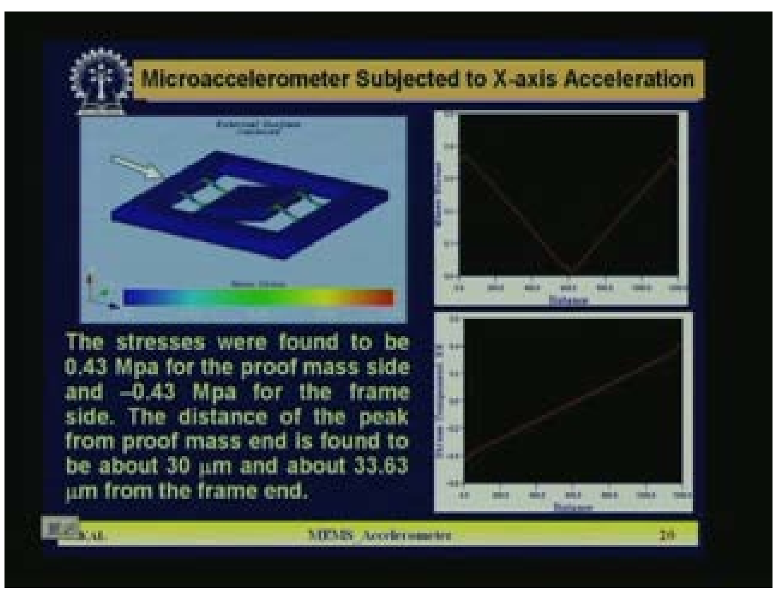

So now this is X axis, the earlier table is for Z axis. For X axis the simulated result shows that the stresses were found to be 0.43 megapascal for the proof mass side and minus 0.43 megapascal for the frame end side. The distance of the peak from proof mass end is found to be 30 micrometer and 33.63 micrometer from the frame end. So these 2 points here and here an earlier case was 70 and 75 when Z axis. But for X axis it is nearly 30 micron and this is 33 micron. The maximum peak points a peak stress regions.

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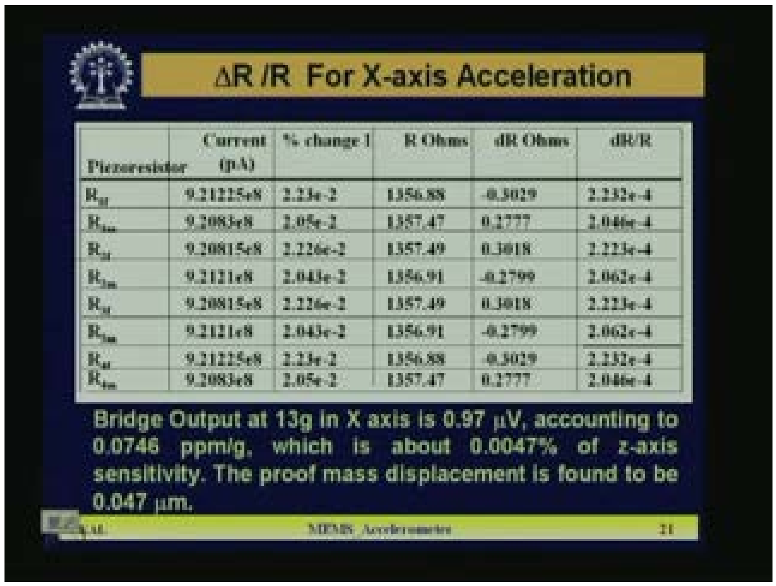

Piezoresistor	Current (pA)	% change I	R Ohms	dR Ohms	dR/R
R_{1f}	9.21225e8	2.23e-2	1356.88	-0.3029	2.232e-4
R_{1m}	9.2083e8	2.05e-2	1357.47	0.2777	2.046e-4
R_{2f}	9.20815e8	2.226e-2	1357.49	0.3018	2.223e-4
R_{2m}	9.2121e8	2.043e-2	1356.91	-0.2799	2.062e-4
R_{3f}	9.20815e8	2.226e-2	1357.49	0.3018	2.223e-4
R_{3m}	9.2121e8	2.043e-2	1356.91	-0.2799	2.062e-4
R_{4f}	9.21225e8	2.23e-2	1356.88	-0.3029	2.232e-4
R_{4m}	9.2083e8	2.05e-2	1357.47	0.2777	2.046e-4

And the resistance values here also calculated for X axis acceleration. There will found you can see the 1f is minus 3029 and the 1m is plus 2.777. So delta R by R value you can see 2.232 for 1f, 2f, 3f, 2.223 and the 4f, 2.323. You can see here slight be all the R not same; here is 2.046, here you are getting 2.062, here you are getting 2.062, here 2046. So slight variation is there even which is increasing and which is reducing same value is not there in all R. So because of that the sensitivity of X axis sensitivity will not be exactly 0. But some value will get because of the in a third decimal place some variation. So now if you found the bridge output at 13g in X axis is 0.97 micro volts which you got in Z axis a 20 millivolt.

But here in that you will get only 0.97 micro volts accounting to 0.0746 ppm per g which in earlier case how much is sensitivity is 81 ppm per g you can see here. 81 ppm per g which is coming down here the 0.0746 ppm per g that is the sensitivity, which is above 0.004 percent of the Z axis sensitivity. Here proof mass displacement is found to be 0.047 micrometer. In earlier case nearly 5 micrometer in Z axis, but in X axis the displacement is very small and the Z the sensitivity is 0.0047 percentage of Z axis. So that means as I told you for this if the avionics application the off X axis sensitivity if you need for one X axis design off X axis should be low and is a third ordered. So it is really you are getting the variation is a third order variation compared to the Z axis acceleration.

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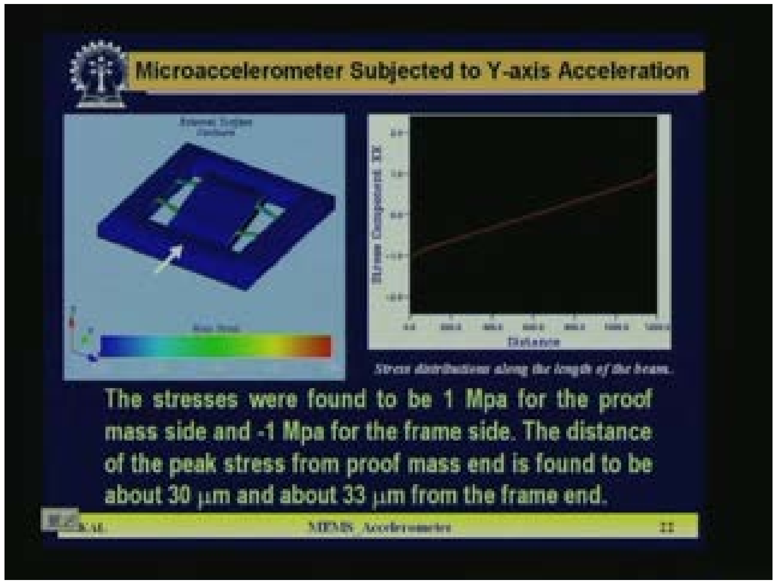

Now let us see in now in Y axis. If you if acceleration is subjected in Y axis acceleration. In that case again the similar analysis will carried out just like Z axis and there we found this stress is found to be 1 megapascal for the proof mass side and minus 1 megapascal for the frame side. The distance of the peak stress from the proof mass end and from the frame end are respectively 30 micrometer and 33 micrometer that you show in this point here. This the peak and here is the peak point that is the nearly that and along the Y axis the safe of the structure looks like this. If you push in this direction is Y, Y axis is here and in this direction if you push it the proof mass will take this shape and as a result of which the resistance change will be like this.

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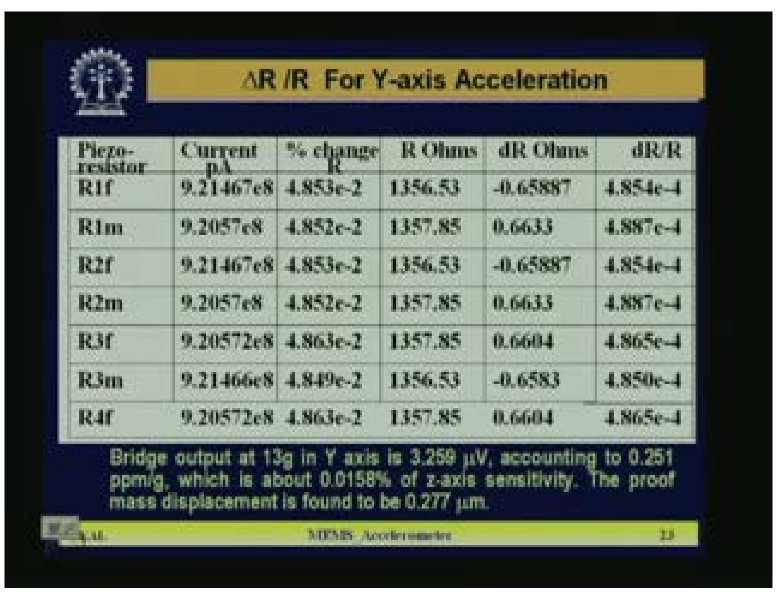

Piezo-resistor	Current pA	% change R	R Ohms	dR Ohms	dR/R
R1f	9.21467e8	4.853e-2	1356.53	-0.65887	4.854e-4
R1m	9.2057e8	4.852e-2	1357.85	0.6633	4.887e-4
R2f	9.21467e8	4.853e-2	1356.53	-0.65887	4.854e-4
R2m	9.2057e8	4.852e-2	1357.85	0.6633	4.887e-4
R3f	9.20572e8	4.863e-2	1357.85	0.6604	4.865e-4
R3m	9.21466e8	4.849e-2	1356.53	-0.6583	4.850e-4
R4f	9.20572e8	4.863e-2	1357.85	0.6604	4.865e-4

Here you can see some important points. So that the change of resistances or delta R by R value is not exactly same in all cases and you find in a third ordered and second decimal is point is varying. So 8 point you can see here the 8 point, this 1f is 4.854, 4.854, here is a 4.865 and here is a 4.865, similarly in a other is 4.850 is a m mass end here is a 4.887 and another mass end is 4.887. So because of that little bit variation you will get some sensitivity in the Y axis and bridge output is 13g, in Y axis is 3.257microvolt. In earlier case you got how much is a 0.97 microvolt along the X axis and here you are getting three little bit more than that. That is 0.973, 0.2 here amounting to 2.0, 0.251 ppm per g is a sensitivity which is above 0.0158 percent of Z axis sensitivity. That means the X axis the off X axis sensitivity is much low compared to the Y axis here you are getting second ordered 0.01and in earlier X axis you got 0.00 something. Isn't it? Now here the Y axis sensitivity is not that much what we expected. Although it is very low compared to Z axis sensitivity but still it is not the like X axis.

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So for that you can have some design modification and that modification if you do then you can get both X and Y axis, the sensitivity is again third order less compare to Z and what you did there the flexure what you shown here, you can see the flexures here is not at the edges. This is the proof mass, you can see the proof mass and if you make the flexure at the edge here this point and this point then it will be improve and you see this diagram in the right side diagram the flexures is not in between the edges but at edges. So you can see is at edges you are made the flexure this is edge have made the flexure. So if you do like that again you go for the complete analysis that will not change your Z axis acceleration value. But X axis and Y axis output voltage will again drastically low and sensitivity will further improve if you put the flexure at just edge of the proof mass and that we have done. Again the same simulation and then we found the results are also increasing.

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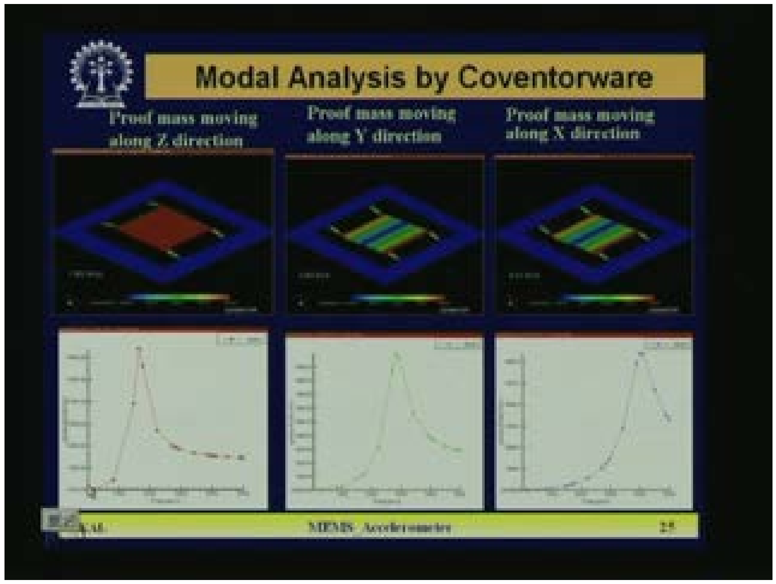

And here the similar way we did the modal analysis. In the modal analysis I have found that receive the 1.65 kilo hertz is the frequency here, resonance and the second is a 2.83 and here is the 4.01. So not much change of that modal analysis because of the movement of the flexure.

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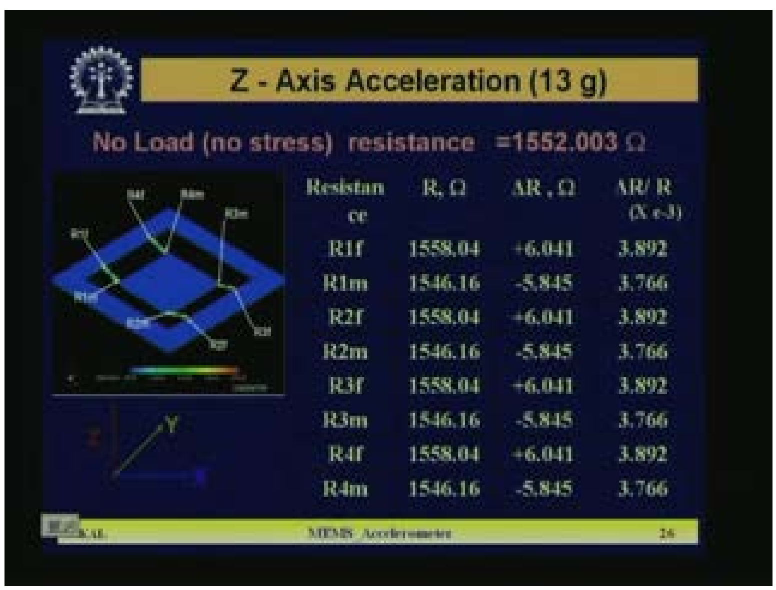

But here the change of resistance valued values for Z acceleration, no load stress. Here is a 51.5 kilo ohm and here the resistances are R1f 1m all the same kind of location we have used and there you can see the values delta R by R you can see 3.892. Here in 3.892, 3.892, 3.892 for frame end. An all the mass end is 3.766, 3.766 here 2m; 3m is 3.766, here is 3.766. So this all uniform change.

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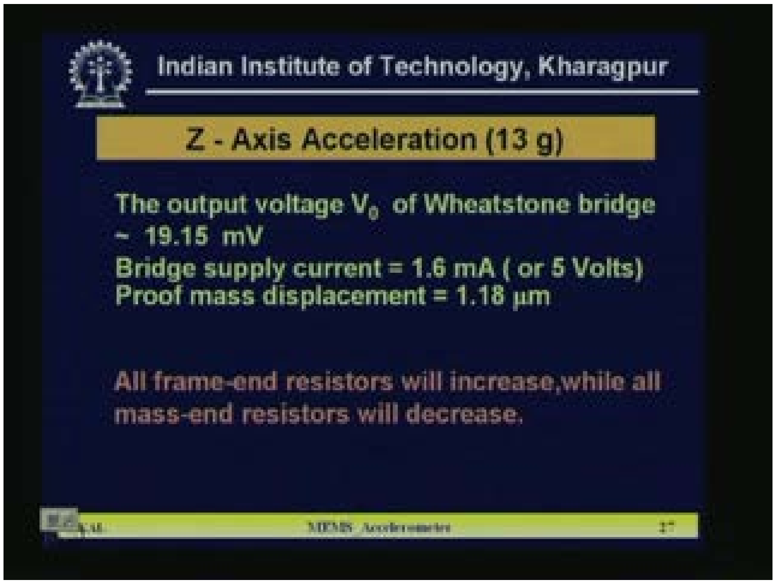

And if you go for the output simulation, we got here this output voltage V_0 of Wheatstone bridge is a 19.15 millivolt. In earlier you got nearly 20 millivolt. So for this Z axis acceleration is concerned. The output voltage is not going to change at all; modal frequency is not going to change at all. Bridge supply current here is again 1.6 milliampere or 5 volt and proof mass displacement here is different 1.18 micron wherein earlier case nearly 3 to 5 micron. Although the proof mass displacement is the different, but the output voltage is coming almost very close to that. That means the so for output is concerned, it will not change at all.

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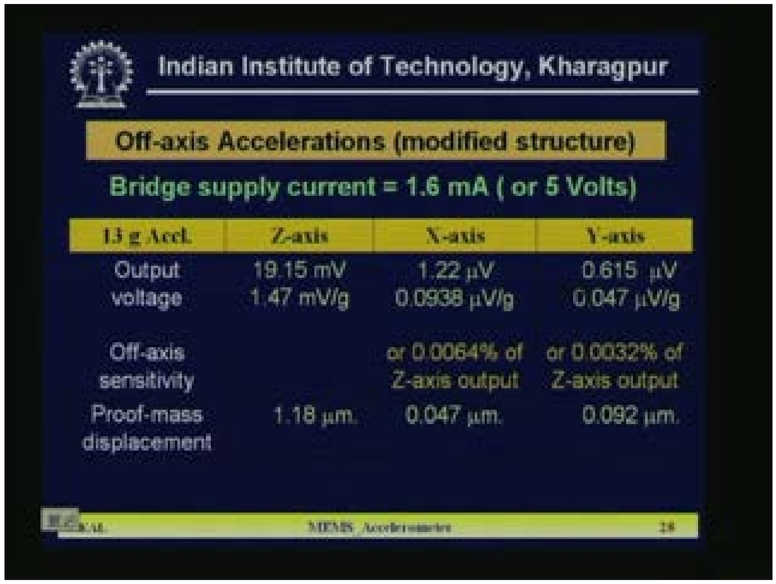

But if you look in to this result, what is result? That is off axis acceleration result, so lot of improvement has taken place. So here the output in this particular case is 19.15 millivolt and per g this is for all 13g. So per g it is coming 1.47 millivolt per g. X axis is 1.22 micro volt total output, so per g you are getting 0.0938 and in Y axis 0.075. So if you calculate the off axis sensitivity you can see here for X axis you get is 0.0064 percent of this Z axis output. Here 0.0032 percent of the Z axis output. So all are third order change you are getting. So that means so for off axis sensitivity is concerned, so if you shift the flexure at the edges, so improvement has taken place. So only for off axis sensitivity is concerned. But there is no change Z axis and here proof mass displacement here is 1.18, 0.047 and 0.092 micrometer. So this kind of design may improve the off axis.

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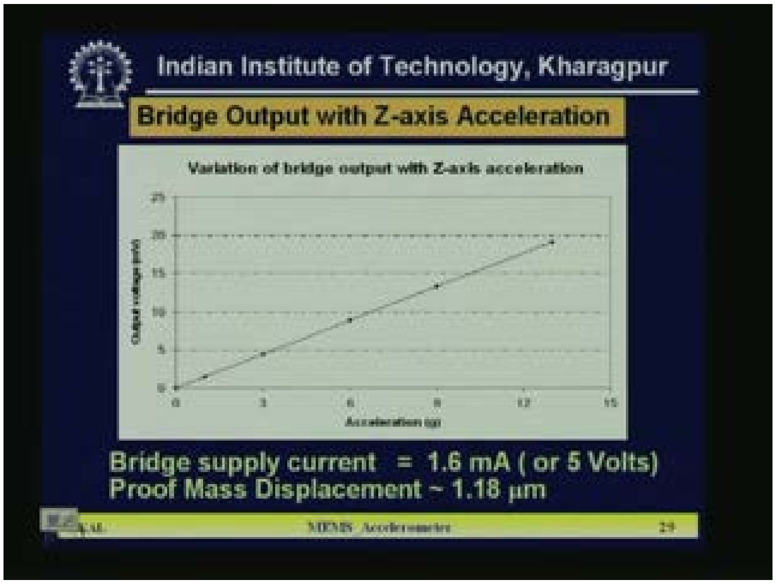

And the complete calculation of the output voltage with g has been done. And that plot is shown here for bridge supply voltage of 5volt and here you can see from 0 to 13 volt, we have calculated the output voltage at 13volt I told you. In earlier diagram also shown is a 19.6 or 7, some volt millivolt you will get it and for different g value the output voltage has been calculated from the change of delta R by R and the plot is shown here is exactly linear. That is all of the requirement of any kind of this a sensor, the performance is highly linear. So for along Z axis acceleration is highly linear and the value is in the order of millivolt and that you have connects are amplified to get it in volt ordered.

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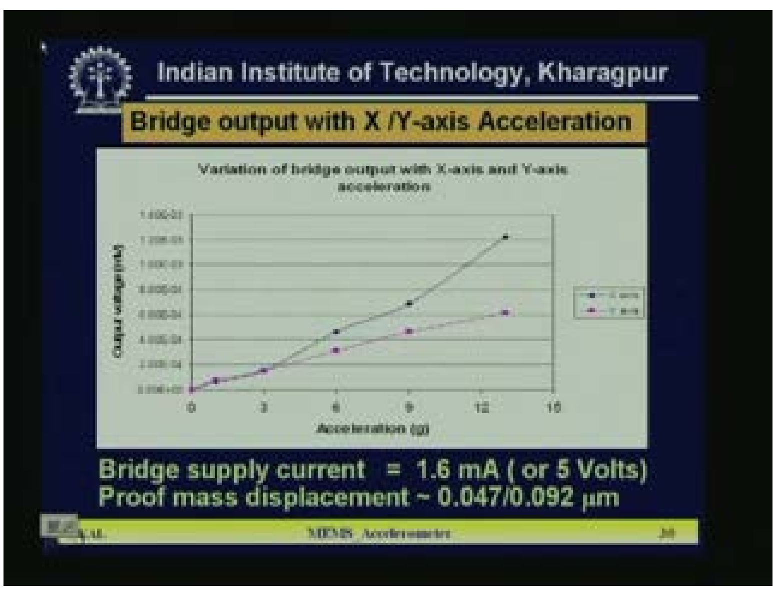

Now so for end X and Y axis is concern, acceleration is concern you can see here, the scale you can see it is a millivolt 10 to the by minus 3. Now it is in a micro volt ordered and again this X and Y is not as linear as obtain in Z axis that we do not we want this values will be as minimum is you see compared to Z it is a third ordered less output voltage and that variation of from 0 to 13g is plotted in this curve.

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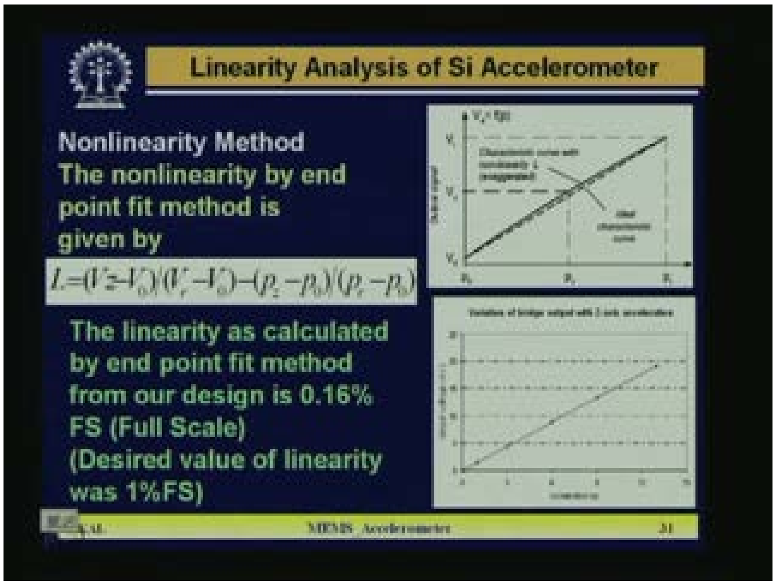

Now that means at the end of this design another parameter we discussed here, that is linearity. So linearity is another point which we want. This should be linear should be 1 percent linearity. So there the linearity can be calculated from end point fit method. So here is the how we can go for calculating the linearity value. So this say a plot versus input is a p is a input variation and is output is always you want the voltage variation. So P_0 to P_r is the change here V_0 to V_r is this arbitrary some curve. V_0 to V_r is the output P_0 to P_r is saying input change. So your ideal characteristic is linear which is shown by the dotted line. But your real curve which is obtained from the experiment or simulation may be like this solid curve. So solid curve and curve card has certain deviation, so that deviation. How much deviation? So that is basically the linearity and it is calculated by the relation the linearity L is given by so any point at the middle where the maximum separation is there. That is the maximum deviation. So that point to select as Z point here so that voltage V_z here, for in input P_z. so for input P_z if you get output V_z. So now this if you calculate like that V_z minus V_0, V_0 is here. There are V_r, V_r is the end point.

One end point V_r that is why end point fit method, this called to end point values are taken in V_0 and V_r. So then V_r minus V_0 minus P_z by minus P_0 divided by P_r minus P_0. If you calculate this value, this is called the linearity and the linearity as calculate by the end point fit method from our design, our curve is this curve, Z axis acceleration which I am I just the earlier plot has been repeated here. So acceleration versus the output voltage, so this curve linearity was found to be 0.16 percent of the full scale. Our design is 1 percent of the full scale. So we are getting for less than our design our expected value. So in that way, so for the linearity is concerned, we are satisfying our specification off axis is we are satisfying our specification and the linearity off axis the modal frequency analysis we are satisfying natural frequency. So those 3 thinks has been done in our simulation and let me stop now. So in the next lecture I will do other two parameters which are also very important damping and the temperature drift or temperature variation from the piezoresistive sensor. Thank you very much.