Micro and Smart Systems
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Lecture - 40
Capacitive Micro Accelerometer Part 2

Okay, we had done some basic discussion about the micro machine silicon accelerometer and we continue the case study with this lecture.

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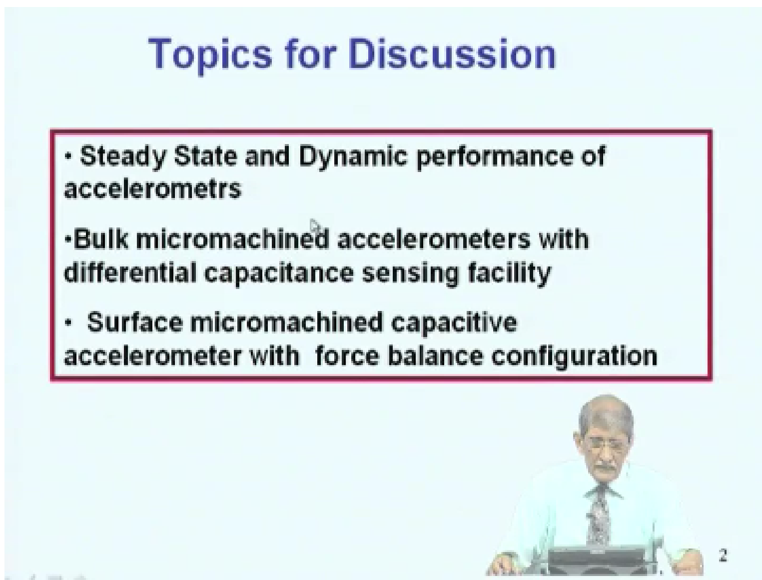

And what we plan to do will be, the topic for discussion are that we are discussing are steady state and dynamic performance of accelerometers, then we will discuss bulk micro machined accelerometer with differential capacitance sensing facility, we finally take up surface micro machined capacitive accelerometer with force balance configuration, these are the main topics today.

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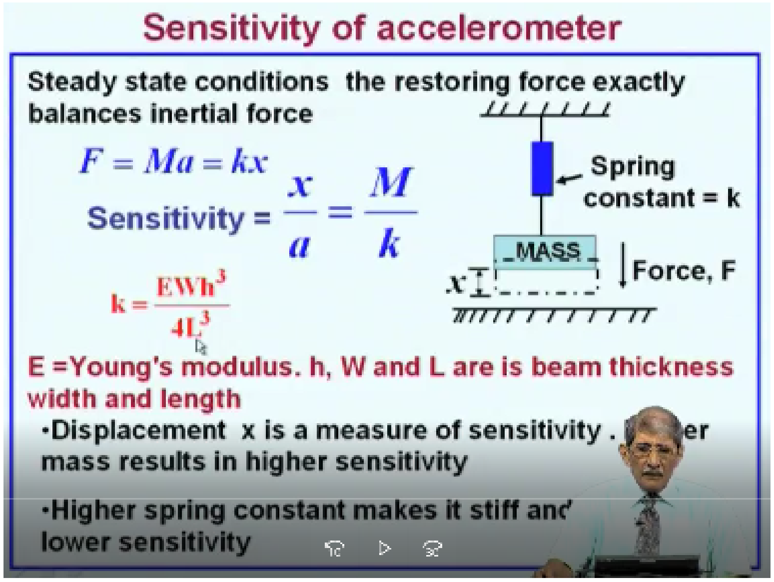

Now we have already defined sensitivity and to reiterate what I said earlier the accelerometer consists of spring, mass combination and the mass experience as a force in this direction it moves via distance X when it moves by distance X, the force, restoring force exerted by the spring is K*X and force experienced by the mass is mass* acceleration, So K is the spring constant which depends upon the dimensions of that spring that arising in beam, Beam E is young modulus, W is width of B.

H is the thickness of the beam, L is the length of the beam, so longer beam for more flexible and shorter beam for you know less flexible, similarly thicker beams are less flexible, okay under certain state conditions, the forcing is mass*acceleration that is force experienced by the mass equivalent K*X that is the restoring force, so the sensitivity is the displacement X/acceleration, so X/A is M/K.

You can see that X can used as a major of acceleration because both M and K are both known quantities, in facet you can calibrate X or X acceleration usually all these accelerometer calibrated by initially before this is made available commercially, so displacement x is measure of sensitivity hour mass results in hour sensitivity, because X/A, for given acceleration X will be more if mass is more.

If the spring constant is fixed, see early if the spring constant is higher and M is fixed, M/K is smaller which means displacement is smaller, so hour spring constant less sensitive, higher mass more sensitive.

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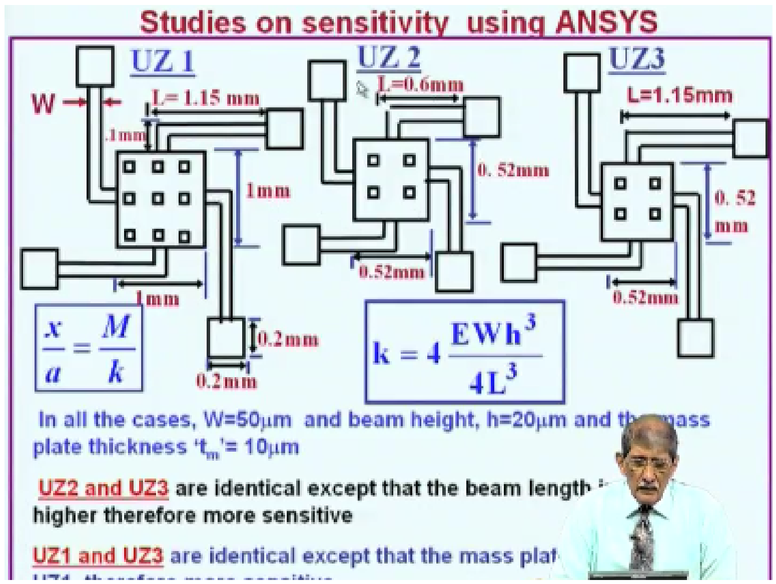

Okay now let us see, just take some examples, I have taken 3 structures called uz1, uz2, uz3, these are the 3 accelerometer structure that we have discussed last time, it has a membrane, square, mass gate supported by 4 beams like this sort of swastik connection, now comparing these sizes all the 3 masses, have okay same thickness 10 micron, T mass is 10 micron of thickness.

And the beam thickens H is 20 microns in all the cases, but what is varied is either the mass or the spring length, so comparinguz1 and uz3, you can see L length of the beam is same in both Uz1, and uz3 1.15 milli meter whereas H size of the mass uz3 is .52 milli meter and in uz1 it is 1 milli meter, so what implies is the force accelerometer is same as third one except the mass is almost double, compared to the third one.

So you can see that for X/A will be large one in the case of force one compared to third one and if you compare the second one and third one both are same mass size, but the spring is smaller in case of UZ 2 that means sensitivity is less flexible, so the sensitivity of UZ2 is smaller compared to uZ3, so what you can see is uZ1 is high sensitivity larger than uz3 because of higher mass, and uz3 is higher sensitivity compared to uz2 because spring is longer here more flexible. So you can see that highest uz3, uz1, next is uz3, uz2.

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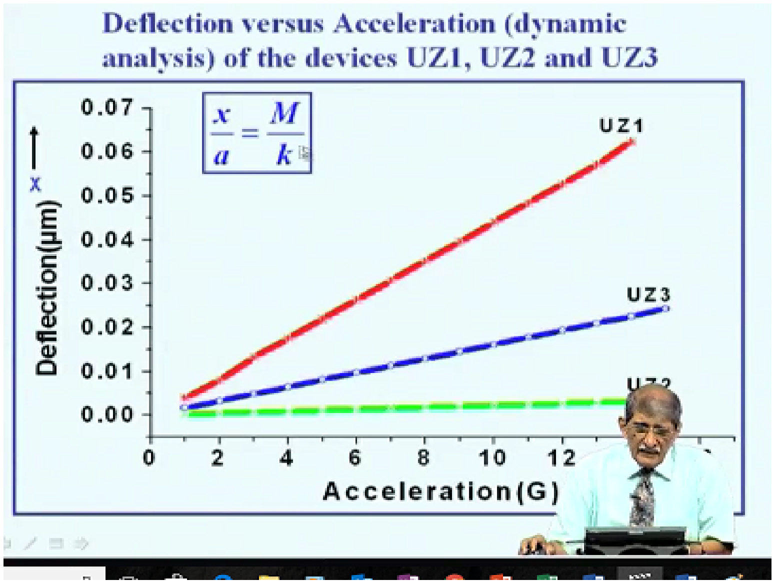

So these simulation by ANSYS is using to find the deflection, deflection is x , deflection versus acceleration, g czc is almost linear for 14g, acceleration to the gravity which is standard value , which all of us know , 980 grams for centimeters , acceleration is centimeter per second , okay 980 or 9.8 meter or second square , ao even for 14g, 1 to 14 is linear, it is higher sensitivity , uz3 is next, uz2 is least because the spring is less smaller , here the spring is large , mass is very large , okay.

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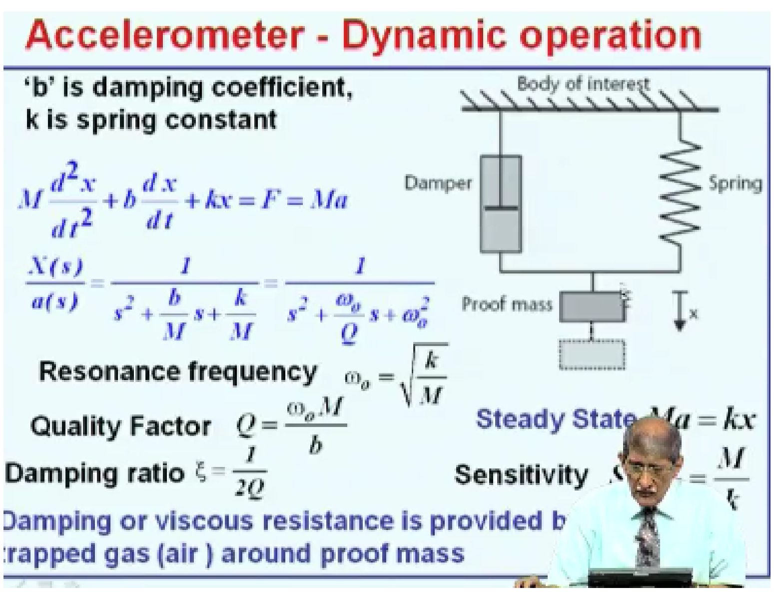

Now let us see the dynamic analysis or dynamic operation of the accelerometer, the steady state conditions we saw that the mass, the force=mass *acceleration steady state conditions, that means the pad force is pat value which ultimately gives = mass *acceleration but when the mass begins to experience the force It takes a while to come to a steady state or sometimes the force will be time being so then the force is given by M*d square x/dt square.

That is actually increases the acceleration + there is another parameter called the damping parameter which I described last time which comes into picture, which actually prevents the moment of the mass the way it likes, because it is like current flowing through a resistor, okay similarly there is a drop in the resistor, similarly here when the mass experience is damping, due to the air into the plate and the bottom.

For example into the plate and the bottom as an electrode or a frame, so putting those to wear or the move will be a air damping, so because of that, power damping is more if the velocity is more so air damping is promotional to the velocity which is dx/dt, so b *, b is the proportionality constant , D*DX/DT is the force due to damping and K*X is the restoring force, okay so you have greater of change of velocity mass * x square Dt square.

Second one is the damping force, third one is restoring force due to the spring and that is applied force, now to get the dynamic situation, you can solve this equation using Laplace transforms you can say X, see here I will divide, find out X divided by acceleration, okay I can write it as, I divide this entire thing by M X(s)/As) will be standard differential equation this is the present equation for accelerometer.

So M*d square/DX d square, I divide by m, so X displacement divide by a will be 1 divided by x square .b/m, I am dividing M*dx/dt, I represent by s, k/m, mi am dividing right , k/m okay , x you got there here , this is propositional to x, so this Laplace transform all of us know at X by acceleration, is 1 by this quantity , I can write it as X square+, you can write k/m as omega not square , I can write v/m as omega not q, where q is omega not m/b.

So you can replace here q/ omega not m.b, that will turn out to be q/omega not that quantity, I am not writing anything new other than the second order differential equation, so this would represent equivalent of a series response circuit, RLC circuit , RLC circuit will be X/ X, similar term, the term will be x square+omega not by Q. okay omega not is a reference frequency +omega not square, in RLC circuit , omega not square=1/ square root of 1/LC.

So m is equivalent of M delta,K is equivalent of 1/ capacitance , so the quality factor is q of , omega l/R or omega not L/R, l is equivalent of , or mass is equivalent of inductor, b is equivalent of resistor , so you can see performance of this is similar to RLC circuit, you can then expect that, if a plot X versus acceleration or acceleration versus frequency I will get a x/a to the plot versus displacement versus frequency then for a given acceleration you will see a resonance.

You also define other like damping ration 1/2Q, this is a standard definition, RLC circuit also the damping ration is 1/2q, 2q , omega l/r, same as this replace l/m, replace r/b, now you can see that sensitivity is x/a=m/k, okay higher the mass , the more it is sensitive , higher the K, less is the sensitivity m now you can see the resonance frequency omega not is square toot of k/m, higher the K, higher the frequency.

Therefore, if sensitivity is higher/k is higher and k/m is lower, so the accelerometer which shows higher sensitivity will show lower resonance frequency, you have to decide as a compromise between the sensitivity and the frequency, so if you can see, if I can make the frequency very low or if I am sensing very low frequency like earth quake, seismic frequency then k/m will be small, that means m/k will be large.

We can have high sensitivity, we can have big mass or getting high sensitivity, okay depending upon the application you can use your approach, the approach will determine whether you want a big mass or small mass, bigger mass for low frequency and high sensitivity, smaller mass for higher frequency may be over sensitivity, amplifier for that, okay damping various resistance is provided by trapped air or gas around the proof mass, it will move.

Now let us go back, let us go further, so this is a damping which comes prevents the spring to move further and the entire equation is governing the dynamic equation, you can solve it get the step performed, fix an response and everything , okay.

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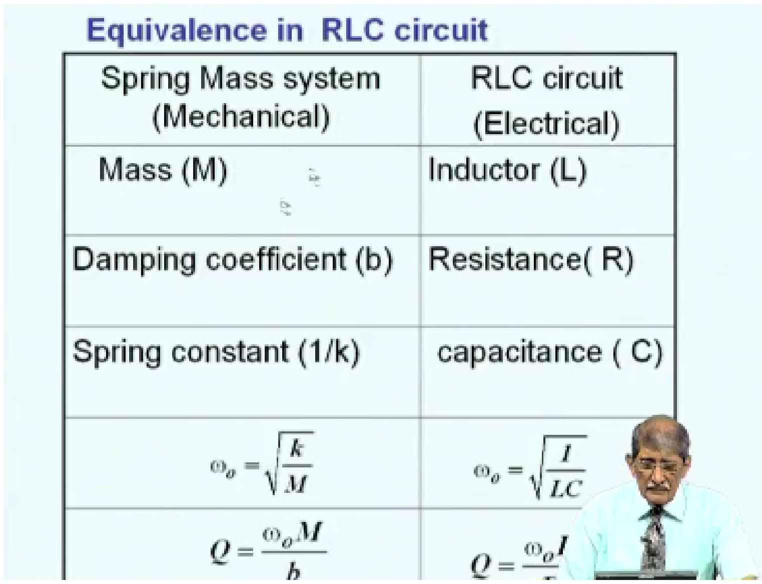

Now just to sum up what I said spring mass system, mechanical system, is equivalent to RLC circuit, M , in the system m=inductor of L, second order different equation governing L, R and C , here the resistance is governing instead of LRC, b m and 1/k, okay these 2 are equivalent, we use stimulator to relate such a system, where is the RLC circuit omega not is root k/m and in RLC circuit omega not is root 1/LC and quality factor q=omega not M/B and the quality factor in other case is omega not L/R because M and R are equivalent.

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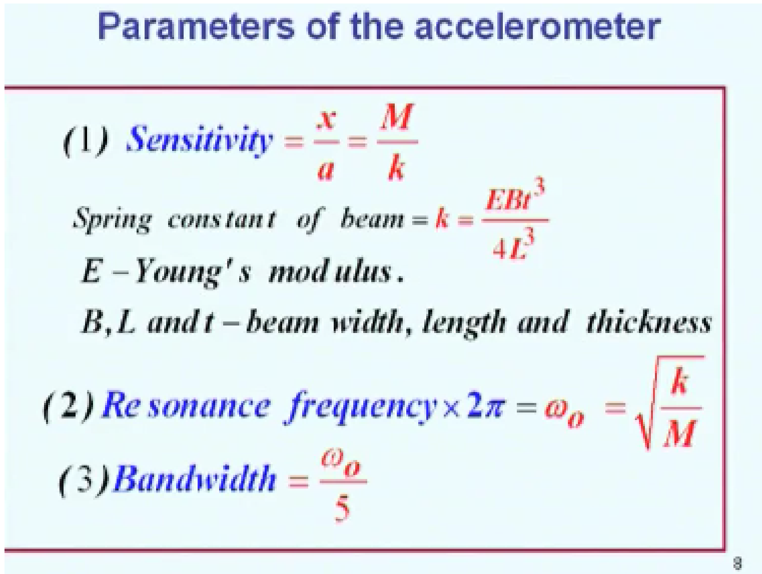

Now let us look at some of the parameters, so as I already defined sensitivity is one of the most important parameter that is displacement t divided by acceleration and it is stated by m/k ratio and spring constant is decided by the dimensions of the beam that you are using, in fact I have used t and L, resonance frequency is root k/m, omega not is resonance frequency*2 pi, bandwidth is one fifth of the usage.

We will see what does it mean actually, you have to operate the system in the region where the sensitivity is independent of frequency, so that for all the frequencies of vibration of the accelerometer you get the same sensitivity.

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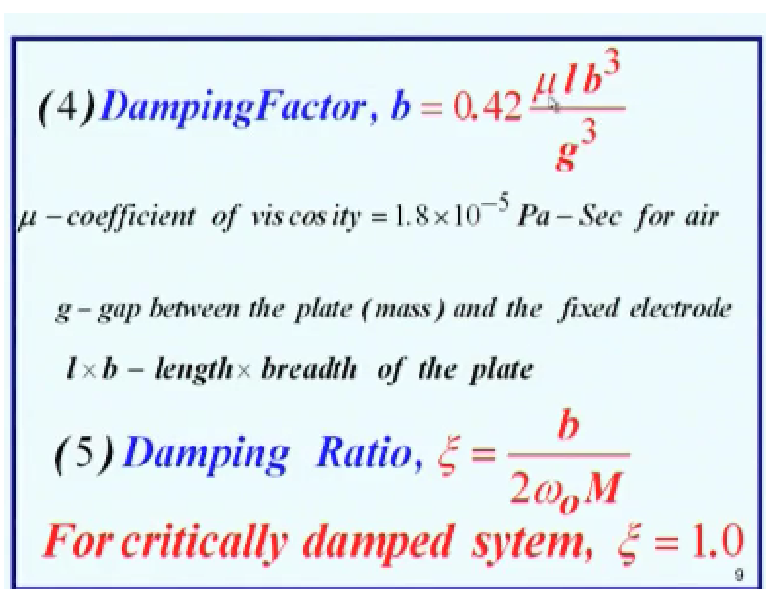

Damping factor as we have derived this it will depend upon the co efficient of viscosity if it is air that is a number then the gap between the mass and the bottom plate because after all the mass moves like that down, you will have that gap, smaller the gap, more will be the force extracted on the mass, prevent it moving, so the resistance will be more or the damping will be more if the gap is smaller and B is the, if I take mass of that size like that L*V.

V is the width, L is the length, LV Cube is proportional to that, so bigger size, if the mass is bigger, it moves like that, there is more air trapped in between, so if it moves, it prevents the movement , it is more difficult, if it is smaller the movement of air will be little distance it has to move, so that is why the damping factor B depends upon again the dimensions of the mass and the gap, damping ratio is of course is 1/2Q, q is the quality factor , omega not m/b is the Q.

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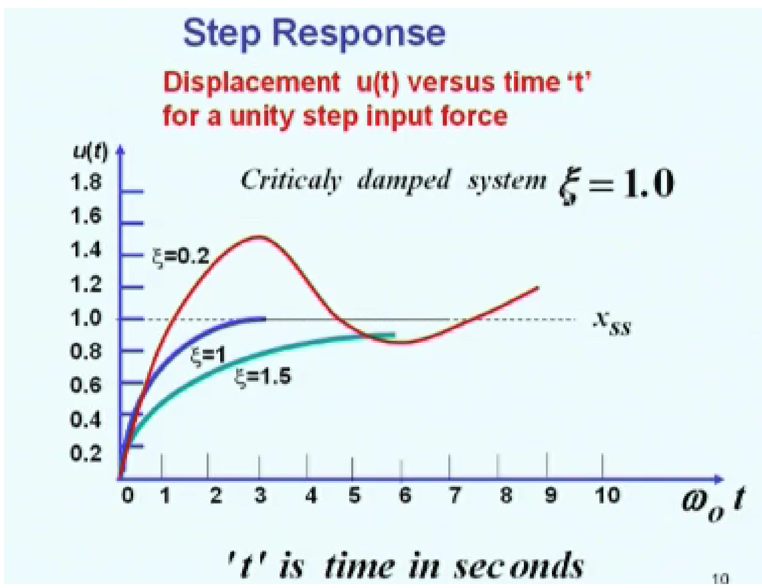

So now let us go further, if you follow that equation which is the second order differential equation, if you solve or a step input, depending upon the value of the critical damping ratio, if you give a step in out, if it is critical damping zeta=1, where zeta is actually 1/2Q, Q is omega not M/B, so that will very quickly come back to the steady state value, that is step input is 1, it will come to that value, whereas damping is small, under damped like RLC circuit.

It will go beyond the steady state value, because it moves much quickly and it will come back to the state and after long time it will come back to steady state, if R is not present it will not come to steady state, it will keep on isolating undamped oscillations, ZETA is more than one, old damped and it takes much longer time, it does not oscillate, but it will take much longer time to come to the steady state value, okay that is under damped, critically damped over damped.

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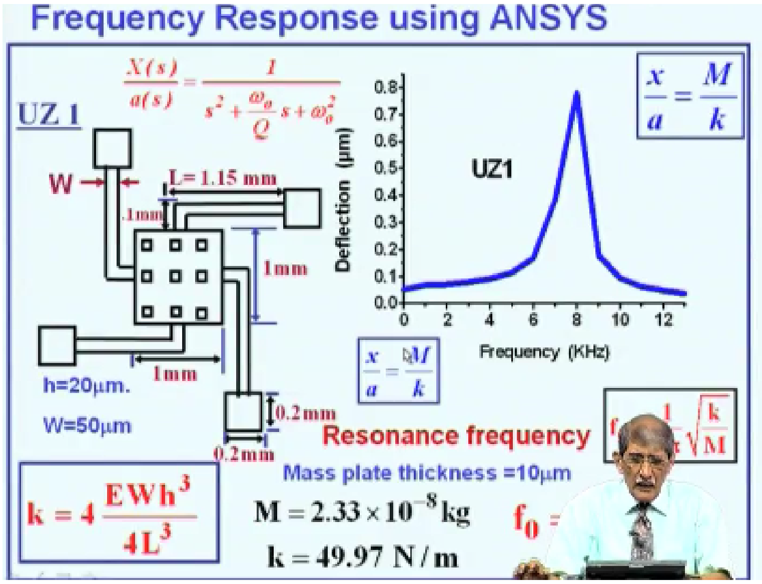

Now, let us see the frequency response, you are seeing ANSYS study, the sane structure which we discussed for sensitivity we will see. We saw if you remember, first I will go back quickly and come back, here we saw this one has higher sensitivity uz one, uz3 has less sensitivity, uz2 has the least sensitivity, in our discussion you can immediately tell that this must have lowest frequency resonance frequency, this will have next higher frequency resonance frequency.

This will have the highest resonance frequency, so let us see that, that is because of the dimensions, so for this dimension, the K is given by spring constant of the spring ig given by N smallest to the width* H thickness cube divided by L is1.15 milli meter, everything Is expressed in k constant, mass in kilograms and linear dimension in meter, you do that, K will be newton's per meter, so when you use this equation, frequency is 1/2pi root of k/m, you solve them in k consonants you solve them and then k is 49.97.

Newtons per meter and mass is this area which is 1.5 I am sorry 1 milli meter that is 10 to the power of –a to ten to the power of -3 meter square*thickness, thickness is 10 microns, 10*10 power-6 meters okay that is the value, density is 2330 kilo grams per meter cube or 2.33 grams per centimeter cube, so when you do that you get mass=2.33 *10 to the power of -8 kilo grams in kilograms,.

So the resonance frequency is square root of k/m, you get 7.37, you can see that, I used 4EWh cube/4L cube is the spring constant of 1 beam like that for 1 beam K is EWh cube/4L cube there are 4 beams supporting this mass, so rigidity is increased 4 times, so spring constant will be 4 times, 4*the spring constant of 1 spring or 1 beam, you receive this quantity, refer this 4, so when you do that you get substitute for that this k is the total value.

And this formula if we use I get 7.37 kilo hertz, in facet you can see that it matches closely with the simulator ANSYS slightly below 8 kilo hertz, okay, that is the bigger mass, the biggest mass, the longest beam.

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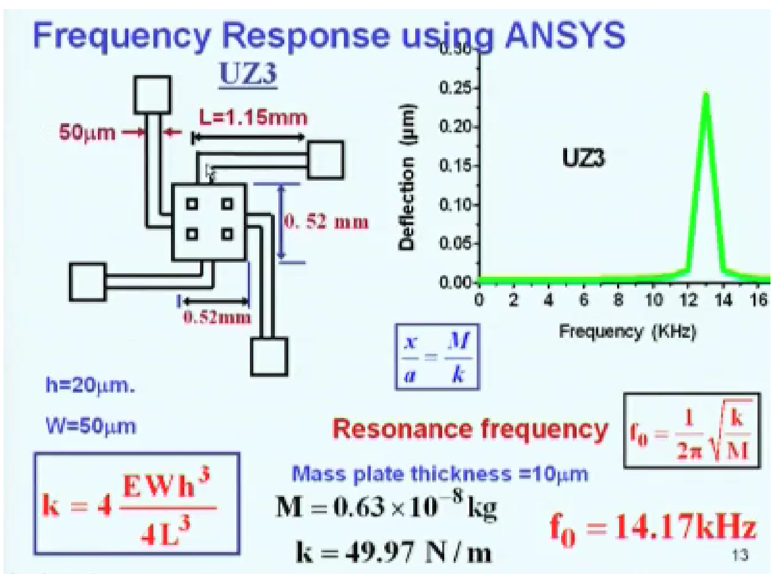

R: Now I will go to UZ3 that is the same length but the mass is smaller, okay by a factor of 2, that is m is 4 times smaller, okay here you can see M is 4 times smaller the frequency will be root of that times it is double, if you get seven, it will be like 14, you can use the same formula that UZ3 has got a mass which is smaller 2.33 and here it is 0.63, one 4th of that, mass is smaller, and K in both cases is 49.97.

So the ratio or the resonance frequency is using the same formula it is 14.17 which is actually double that, you double that because mass is 4 times smaller, so frequency is thrice larger, let us see compared to uz1, uz2.

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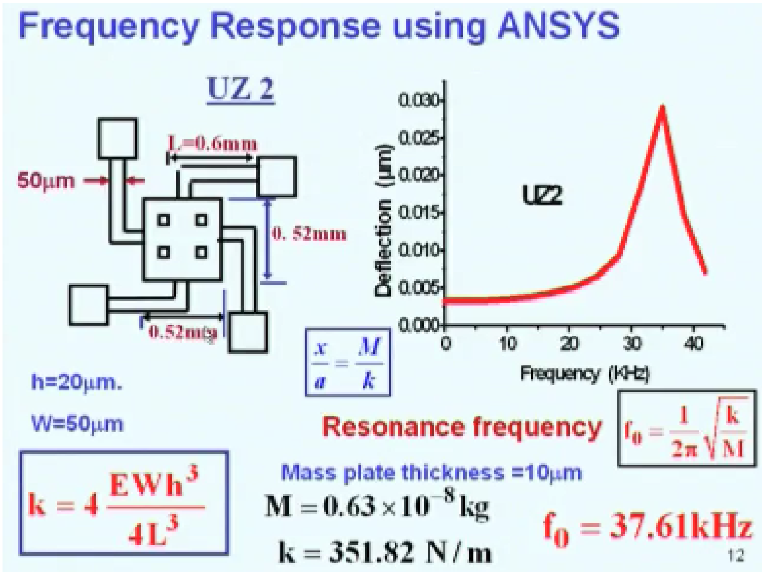

Uz2 you can see, compared to these 2 uz2 and uz3, mass is same for both but k is 0.6 uz2 that is smaller, L is smaller, so K is larger, so you can expect the frequency to be higher, uz3 is 1.15 and here it is 0.6, almost half, so it will be about 2 times higher the frequency compared to this, so you will get that 40.7*2 root , you will get about 35 kilo hertz as the resonance frequency, so this is to show that.

Whatever you calculate with analytical expressions your k and m and estimate the resonance frequency practically matches with the resonance frequency, what you have to note is in all these cases, you can see I will take one example, the deflection or the sensitivity is practically constant in these frequency range, if I take this, 7.3 kilo hertz as resonance frequency, you will operate the accelerometer somewhere here, one fifth of that.

Okay, that will be here in this range we will use where the reflection is constant for various frequencies because your acceleration may be over a certain frequency range from very low frequency to one kilo hertz, so the bandwidth will be somewhere here, so if you take a higher frequency one where the resonance frequency is 35 I can use that up to ten kilo hertz frequency because the sensitivity or deflection is constant.

So you need to operate the accelerometer in this range, so your design will be such that, what is your bandwidth, your bandwidth may be 1/ one fifth of this that is about 1 kilo hertz, okay and them it will reduced to that much, you can see if I go for lower frequency by making the mass large, you can see somewhere here 0.0025 or 0.002, whereas in the case of 1, that is less than 0.1much smaller, mass is larger, I am sorry.

In this case frequency is higher, sensitivity is low in the other case UZ1, frequency is low and sensitivity is high and range is also reduced here, here the range is increased, this is the general idea about accelerometer, the key point that I would like to emphasize is the bandwidth is about one fifth of resonance frequency , resonance frequency is higher , if the beam is shorter and mass is smaller , but the sensitivity is smaller if the resonance frequency is higher, okay

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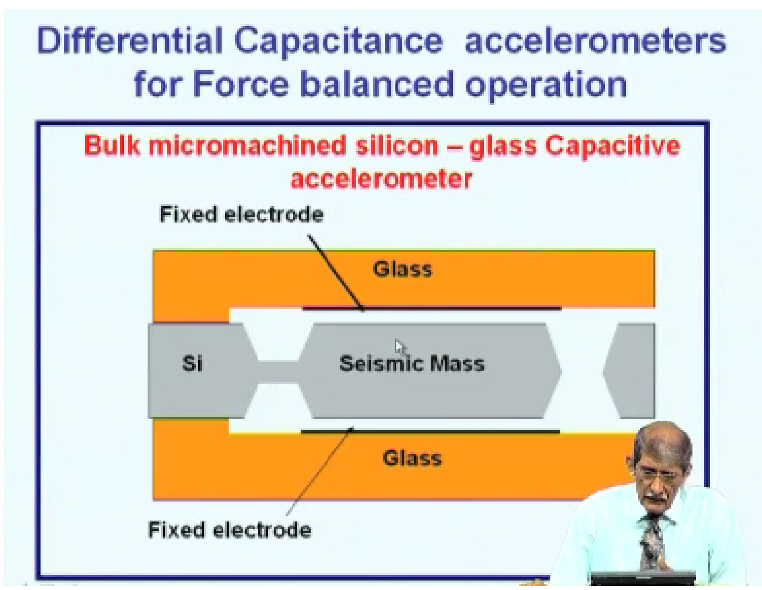

Now let us go into some of the differential capacitance accelerometer, as I mentioned if you want higher sensitivity and lower frequency your mass must be higher in that case it is better to use thicker masses, okay so bulk micro machined factors are used, this thing is a silicon, you release this mass by that is a vapor which was there originally reach out these portions reduce the thickness in this region.

That will be the beam and all-round the mass , your electrode will grow all-round the mass and the mass is like that , all round the H and the mass is held by the spring to the main body , so the mass can move like that and you can see the other side of the p, now part of this thing because , if it grew here you can see some portion of silicon this side main frame , that is what we see here, so you can use this as a differential capacitor because the mass is on plate.

And the glass can be brought genetically which we have discussed earlier, genetic bonding of glass, we have silicon here, I am not going through technology of that, I am going through the final structure, I am going to have metal contact here, how you take the connection out, we have described here, it is a schematic diagram, so this mass is the one which can move up or down depending upon the force that it experiences.

Supposing if it gets little dropped gap, gap between the top electrode black here fixed electrode and the mass goes down, capacitance goes up, the capacitance between the bottom electrode and this mass will decrease because the mass moves up, there the capacitance between the 2 decreases, now you can actually make use of this step of 2 capacitors by applying a voltage +v to this and- V to this one +v to the top electrode and –v to the bottom electrode.

Then the voltage at the center will be C1-C2/C1+C2=V, if C1=C2 the voltage fluctuation is 0 now when the delets upC1-C2 goes up, there will be voltage developed here, okay, so you can make use of this voltage electronically, we can see that later apply certain voltage electrostatically proceed backward, find out how much you apply, it will be very clear when you go through analysis of that.

So what you do is when it deflects up apply voltage to this electrode deflect to the other electrode further to the ground, so that the mass moves down back to the original position, how much voltage you applied to push it back is the measure of the force experienced by the mass, it has moved up due to the initial force, you use electrostatic force to pull it down, when the electro static force is equal to the initial force it has come back to the neutral position.

So you can measure the electro static force which is measure of the applied forces, the advantage of this you can use this for a wide range of accelerations because even at high accelerations the deflection will be minimal because of applying electro static force continuously to push it back, okay this is silicon and glass but some problems are there with this silicon and glass because of the thermal mismatch etc., so you can make all the 3 layers by silicon like this

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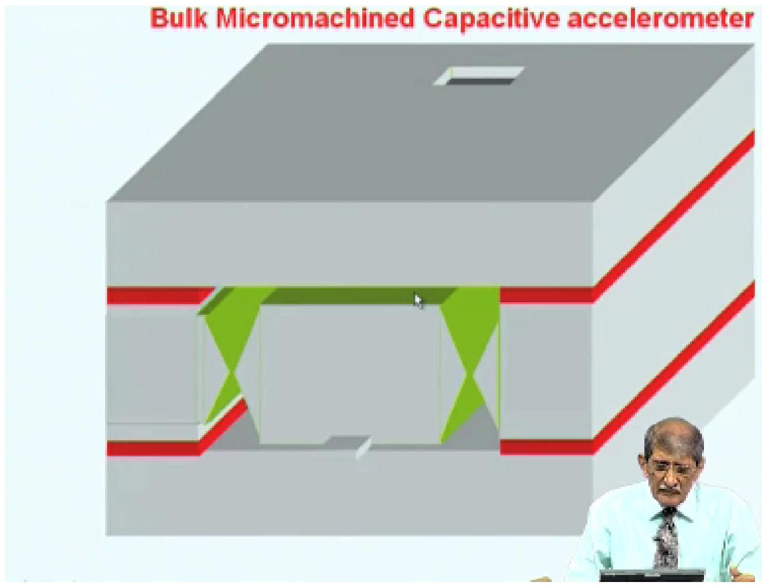

This is a silicon sample, you have used bulk micro machined technique, it is in this shape because of the KOH searching, top side and bottom side, what you do is, first you edge a depression which is about 2 microns and then from both sides and then dope these portions where beam should come, dope them very heavily around so that it is wont be edged by KOH, so protecting all the other portions, edge this portion using KOH.

So you edge the group all the way by using KOH, I am not going through technology but the structure will be obtained because you edge all the way down through this KOH edging by the group, but this portion is cannot get attacked by KOH because this is heavily doped with more on that is edge top, there are 1,2,3 and similar on the back side 4, so that mass will be held by means of , if this is the mass it will be held like that on both sides from the top.

And for the other side it will held from the bottom, so which means actually it will be rigidly held so that it will be held, it will not wobble in the direction, that is for rigidity, you do that, this is uniaxial accelerometer, so this is the mass and you can see this beam is a spring which holds to the top, it is a spring which is connected rigidly to the bottom, now to realize the capacitance, what we should do, we will see a gap here top layer of the oxide and bottom.

I can bond a silicon vapor onto that like that, if you have missed it, you can see that, vapor is bounded from bottom, now you can see there is a gap between the mass and the bottom, that is the capacitance and this is mechanically connected from this bottom plate is connected to the frame through this oxide electrically isolated, similarly we can have one more vapor bonded from the top, so this structure is complete.

So you have got this gap here which is about 2 microns, this is one particular design and this mass size is 1 milli meter, thickness is about 200 microns, suppose if we go to frequency mass and the plant size if you go back this is about 200 micron length, 50 microns wide and about 10 microns thickness , that is the swain so this differential capacity is used for measuring accelerations, let us go back further, go further down, that is the capacitance accelerometer , okay.

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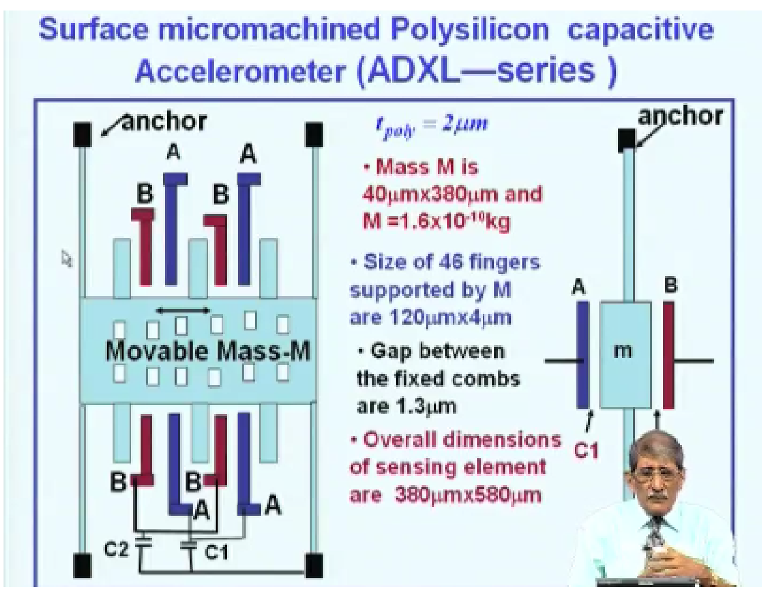

Now if we go to a type of accelerometer which is realized by surface micro machine and capacitive sensing and differential capacitive sensing, so here, this is a very popular known ADXL series commercialized by unlock devices, they have spent several years to standardize several complications with the final cost in fabricating this type of device, what have we fabricated this accelerometer.

This is top view of the accelerometer, they have also made electronics along with that to convert, to obtain force balance, balancing application system, post balance system using the electronics along with this, so what you have here is a mass, this is the top view with a hole, the hole is, you may recall that in all this surface micro machine structure you provide a hole so that you can edge the oxide below that and also it will provide damping.

Damping in the vertical direction if required, so this color here light green, this is actually the proof mass, that is the seismic mass, the mass of the spring mass system, the mass has this 123 coumbs on both sides 6 coumbs which are shown, fingers, the mass has fingers on both sides, the size of the mass is about 40 microns wide, 380 microns, length is that for your information, that type of ADXL series.

Okay you have got this, as supported by 1234 beams which act as flexible flankers anchored black regions, 4 regions, that means mass cannot move in that direction, but mass can move in that direction, because it is anchored there, so when it is subjected to acceleration, the mass can vibrate in this correction, now you can see these fingers are movable, I have shown only 3, 6 fingers supported by mass and these fingers are actually there are 46.

In the actual design and width of about 4 micron gap okay in between the 2 fixed beam there are 2 or rigid or fixed course, they are anchored, they are not movable, A and B are the longer one and the shorter one, they are the 2 fixed beams, so what happens is when this mass moves to the left, I can see this, take a look at this B here, B is fixed, mass moves towards the left, mass between this particular finger goes up, that means the capacitance goes down.

Okay gap is decreasing, similarly A is fixed, so the mass moves towards the left, the gap between the moving finger and the fixed finger A reduces, so the capacitance goes up, okay, so if the mass is moving towards the left side the capacitance between the finger A and the moving finger goes up, capacitance between the finger B and moving finger goes down, now what we have done in the design is, all these fingers blue which are actually marked A.

There are only 2 of them, they are connected together, okay between finger A and this mass there is the capacitance, okay this finger A and this mass there is capacitance , so lumped together I can put it as a capacitance C1 between A and the mass , mass is that fingers , between A and the mass , between A and the fingers totally put together there will be capacitance C1 and you can see if the mass moves towards the left, the capacitance between A and the mass.

The mass moves towards the left, capacitance between, the gap between A and the mass goes down therefore C1 goes up, similarly all the shorter fingers which are fixed marked b and marked by red, they are all connected together like this and the capacitance exists between the B and this moving finger, each of them has the capacitance between the moving finger that is the mass, that is C2.

So if the mass moves towards the left, the gap between B and the moving mass increases C2 decreases, so here there is lump equivalent representation, mass is movable one because of the reason, these 2 are rigid, this moves to left, capacitance C1 increases, C2 decreases because the gap increases, now let us see how this is made use of, for so that is the principle of the capacitance when this experiences force to the left.

Okay, one of them increases, other one falls, so the theme is to bring them back to the neutral position and find out how much voltage you will supply to bring them back to neutral position and that will give you how much electrostatic force applied to bring it back to the neutral position and that electro static force neutralizes compensates the applied force, okay

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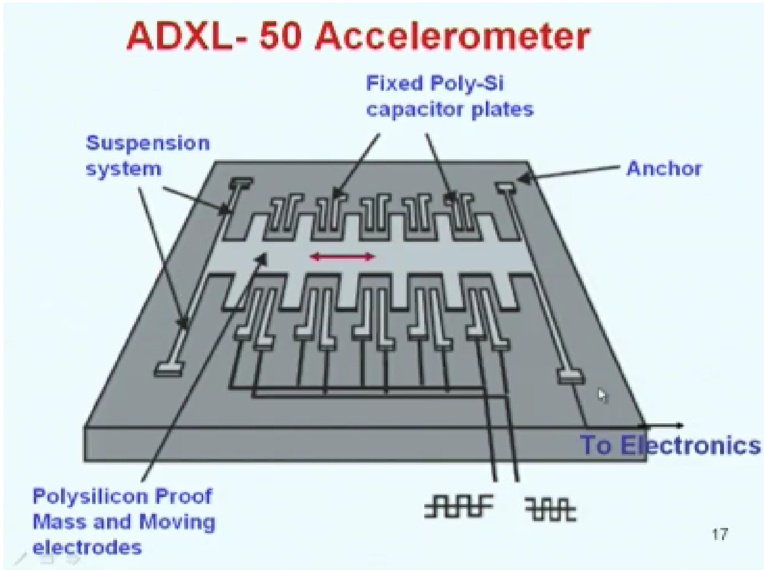

Now let us just look at the structure, this is the same structure, I have put it in a more detailed way, now the overall dimensions of this sensing element is actually 380 microns *580 micron, this is very small and thickness of the polycrystalline silicone, these are polycrystalline silicone and top thing is made up of polycrystalline silicon, that will be about 2 microns, now you can see thickness of the mass is very very small.

And you can see the mass of this system this is 2 order of micro systems and that of bulk micro machined that we saw which was about 10 to the power of -80 kilo gram, here it is just about 10 to the power -10 kilo grams, much smaller that means you can see the sensitivity is very lower one thing , number 2 the frequency is higher compared to those masses, okay here the spring constant also will be smaller , which will to compensate for the smaller mass, because finally it depends upon M and K ratio, okay

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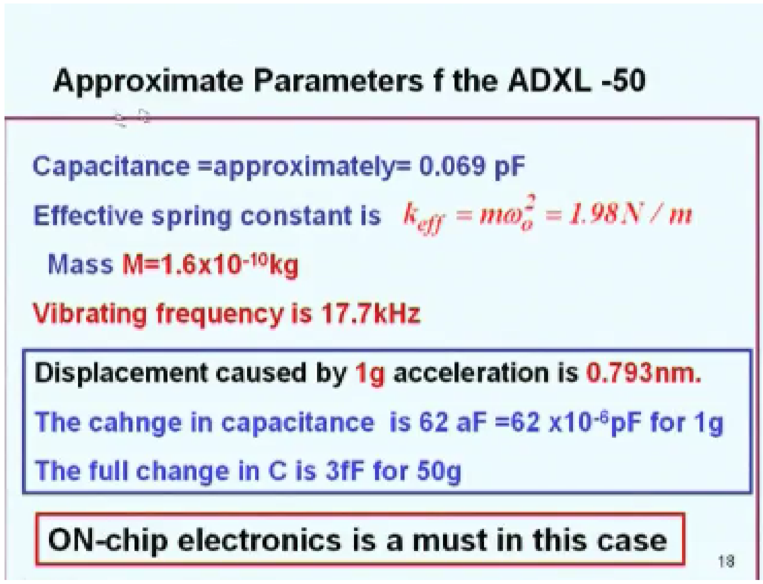

So these are the approximate parameters for his thing and the vibrating frequency of that making use of that effective spring constant, mass of this one and spring constant of 1.98 and 17.7 kilo hertz, now the displacement caused by 1g is 0.793 Nano meters very very small or 7.9 Armstrong, so the change in the capacitance is something like 62 atto farhertz that is 62*10 to the power -6 Pico far hertz, very very small that means you need on chip electronic for sensing this. Okay

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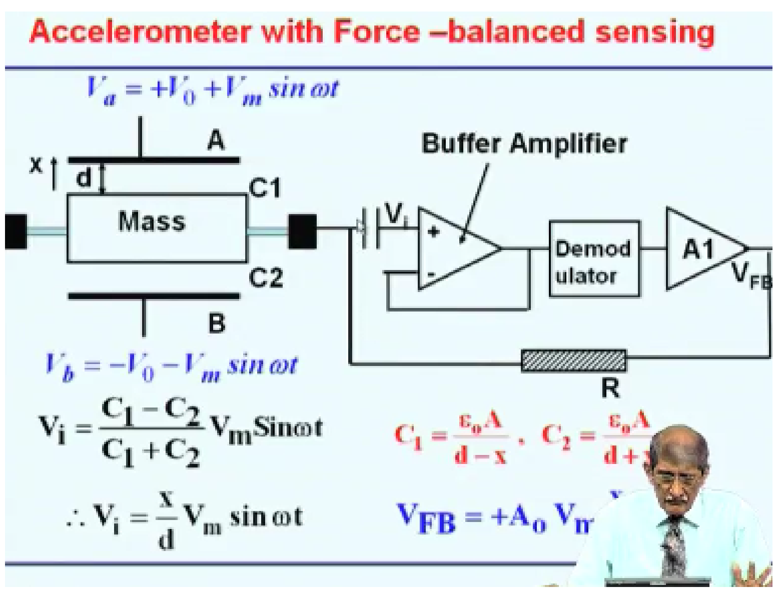

Now Let us take a look at how this works, so you can see this is the mass, this is the capacitance C1, this is capacitance C2, you apply VA=+VC V0 +Sin omega t, on the bottom side exactly opposite we have to type –V0-V sin omega T, so the voltage here at the center will be if this is Va and this is –Va the voltage at the center will be VI=C1-C2/C1+C2, if C1=C2, the edge =0, there will not be voltage at the center+A and –Abut when this moves up.

Okay D is the original gap it moves up by X, new gap is D-X, the capacitance C1 will increase by epsilon 0 Area/D-X, so it reduces C1 increases and C2 will be epsilon A/D+X, C2 falls, so C1 increases C2 falls , therefore there will be voltage which is actually C1-C2*C1+C2 vA, that is the total voltage , if I put a capacitor here the whole thing will be C1-C2 at this point will be C1-C2/C1+C2* V0 +VM Sin omega T but if I put a capacitor here.

The dc will be blocked and vi will be only the added quality that will be C1-C2/C1+C2 V M Sin omega T, okay, now what we do is you amplify the signal demodulate it, convert it into DC, okay you get a feedback voltage here, so the feedback voltage will be actually because demodulator it will remove the AC component and then you will get through this you will get a feedback voltage which is actually, whatever we have there *k that is A not.

Now VI here is actually when you substitute this quantity and when you take X=very small, you substitute this C1 and C2 in this equation here, okay Vm Sin omega T remains there, so you substitute and take X less than D you will get this Vi=X/D*VM sin omega T that Is the quantity there and feedback voltage what is applied DC will be n not *VM*x/d sin omega t goes off, ac component goes off.

So you can see I am applying full voltage to that, okay, so what happens if I apply + voltage here, already there is a voltage, now I increase the voltage to that, that means the difference to the voltage will be reducing that means the mass will be pushed back, okay if I apply + here this is - the difference in the voltage will increase therefore this will be pushed back. so the total force acting on the mass will be now.

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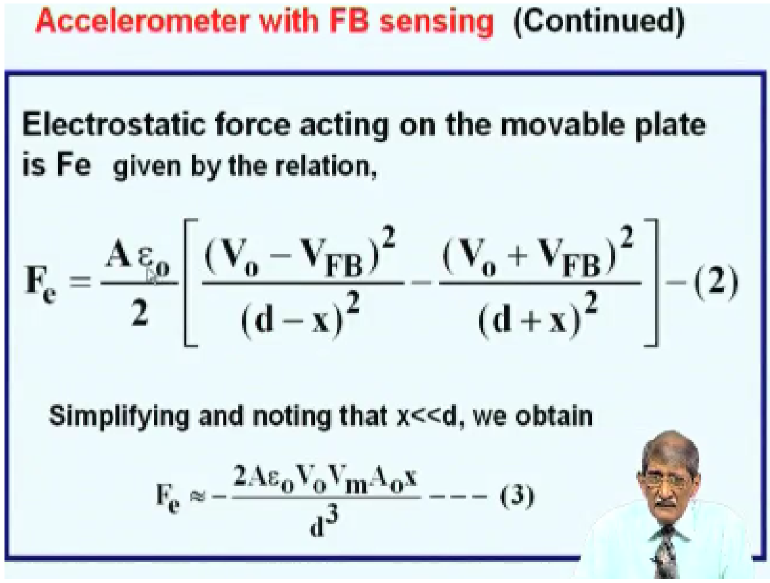

Electro stats force of Fe= Epsilon area *that is half FB square/D, half fb square is energy, half Fe square is the force, the force is actually Epsilon 0* V square, V is V0 original voltage that is DC voltage – the flat band voltage, so on to this DC voltage was 0-the flat band voltage, so the voltage decreases here and the bottom will be V0 +V flat band voltage that increase, so total force voltage on the top will be like this.

Quantity we are using half epsilon area *v square/F square- this which is acting on the bottom electrode, simplify this and you will get electrostatic force on this quantity, not note this electrostatic force is also equal to applied force mass acceleration, I repeat the exact quantity *mass *acceleration. , whatever I have written here by simplifying this I have put here

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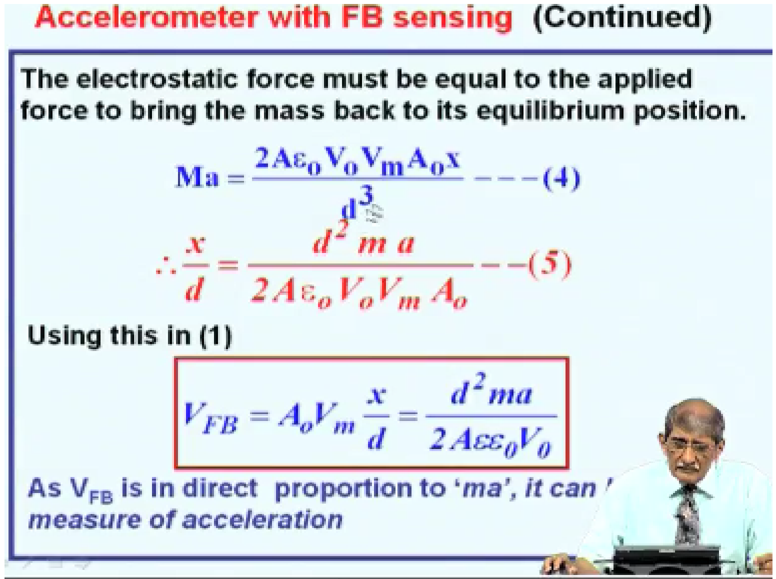

So then X/D, if I take D square on to that side, I will get D square*MA divide by whatever is the numerator. So you can see the displacement x/d is proportional to mass*acceleration, everything is D and MA everything is parameter of the accelerometer x/d is a known quantity, in fact if I can determine by this quantity, if I know v Fb, I can determine x/d which gives me mass*acceleration with x/d I can find out mass*acceleration that is the force, but x/d you can see this thing here.

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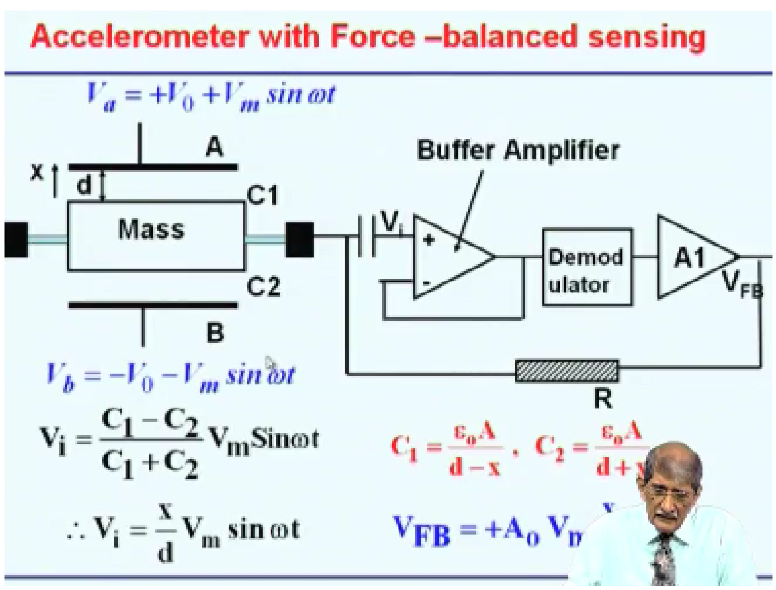

We saw x/d is related vfb =A not Vm X/d from this simplification feedback voltage. So if I measure feedback voltage, okay either VM has applied voltage here, I can get x/d , so measure feedback voltage and vm is known x/d is known , if I know x/d,I will know m*a force, so you can see that my measuring the feedback voltage here required to bring the mass back to neutral position, okay that will be brought back to the neutral position that will give me an idea of measure of the acceleration.

I will just quickly run through this If you not clear because I just went through that quickly C1-C2 all these are understood.

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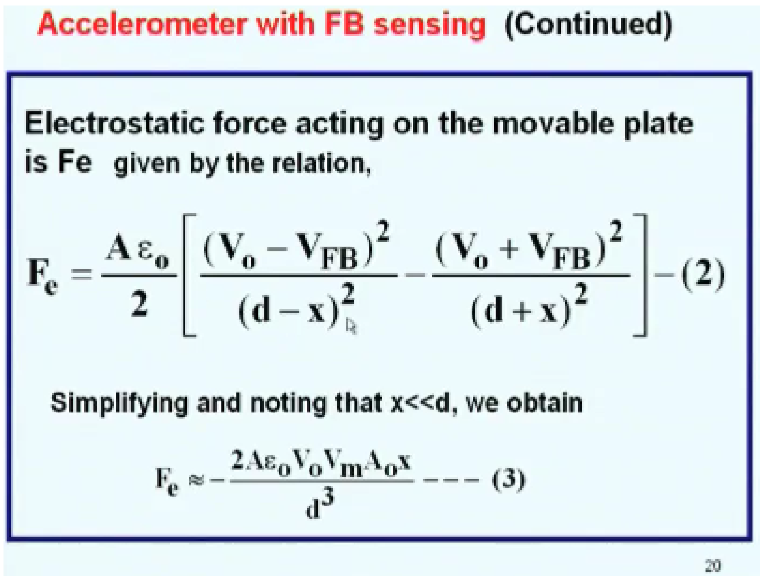

This quantity may be the one which with you will have difficulty, this is half*capacitance Fe= A divided y , energy is half fb square , this is the force , half fb square/d square d- x the whole square , voltage applied is actually whatever dc voltage was there - the feedback voltage because that is +. So that is why I get that quantity and in other case in the bottom place this has + voltage this has - V0.

So the voltage that is applied is force acting is -, v0 +v fb difference is sum of the 2 this is - and this is + difference vfb+v0, vo +vfb divided by d+x the whole square, I get this one and I simplify this I get this entire thing like this, okay, I will just go here. So using this I have found out, just running through this again, this is electrostatic force, this is equivalent to mass * acceleration.

That is what is written here and here x/d, x divided by d is Ma *d square take it out on the other side divide by this entire quantity before I get the feedback voltage is related to this relation by this I have seen right in the beginning I can get knowing the feedback voltage I can get the acceleration. So feedback voltage vfb is in direct proposition to ma, it can be used as a measure of acceleration, okay

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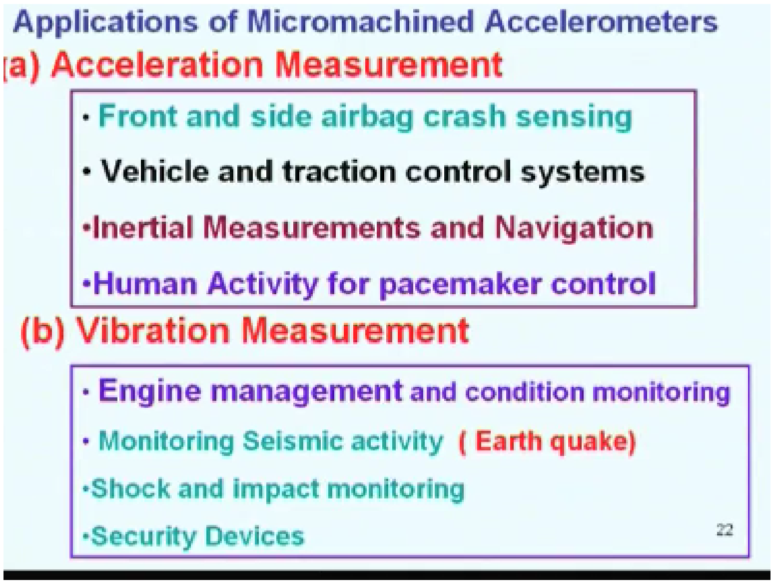

Now let me just go through the applications very quickly, the micro machine accelerometers can be used by using the acceleration measurement for some applications, some other application for measuring the vibration frequency, from the acceleration measurement, vibration is actually the frequency, we can measure the frequency which is actually load k/m, so we can decide what is the mass and what is K, okay, acceleration is a force.

So one of the popular applications in which accelerometers is used is the air bag crash sensing, in almost all the cars in America have these accelerometers which are used to deploy air balloon. Okay which will, air bag, air bag means air balloon which will just open up when the car decelerates or accelerates quickly or when it hits and comes to abrupt rest, so this sudden deceleration will trigger the accelerometers.

Which will trigger the voltage activator which will deploy a balloon, so that balloon will actually come, if you are sitting in the front seat, the balloon will just open up and prevent you from hitting, driver is sitting here, balloon will hit the dashboard and that was the one which leads to the fatal accident, so to prevent that this air bag blocking from coming forward, so air bag is used in cars in USA.

In India also some of the cars have come now, okay this is one of the applications, the accelerometers with electronics forced by balancing circuit fabricated or made by analog devices is used for this airbag sensing that is airbag crash sensing, it can be used for other vehicle traction control systems, it is also used inertial measurement and navigation, for example a missile or a inertial navigation system.

You know to locate the position you can use Saturometer with electronics, acceleration will tell you what is d square X/ dt square, integrated once Dx/Dt, integrated twice that is X is the position, so position can be tracked and accordingly correction can be done, all these navigation systems or these safe applications these accelerometers are very popular often used, notice you need to have very small files, very big because that add on to the pay loads of the space craft.

These accelerometers are also used for bio medical applications or pace maker, okay, the pace maker will actually give out a pulse, okay , just to keep your pulse rate at required rate depending upon the physical activity , so that is the bio medical application , then you can put it under situation r bio compatible , you cannot use a huge accelerometer , you should use a micro machined accelerometer are definitely very popular for bio medical applications.

And even universal applications and the car also, other applications are vibration measurement, health condition monitoring of the engine can be monitored by using the frequency of vibration sensing the frequency, if there is a defect generated in the engine the frequency of vibration will change, that is one way of monitoring the health of the machine or the engine very popularly used. Then the other applications will be, it can be used anywhere using single applications.

Where there is support, there is AC rack, you can set the vibration depending on the vehicle we can sue on bridge and since that frequency of vibration of the accelerometer, you can say well about that, other application that is popular is, you can see that this is called seismic mass, implied that you can use this for measuring very low frequency. You can sense the earthquake that is the seismic activity, we sense by suing the accelerometer.

So those earthquakes are very, very low frequency not to the large mass, may be for those applications micro machined accelerometers are very popular, very useful, these are some of the very popular applications of accelerometers, shock and impact monitoring by changing the frequency, security devices for security reasons also can be made. We can think of many other applications, even for angel of incidence etc., we can use it.

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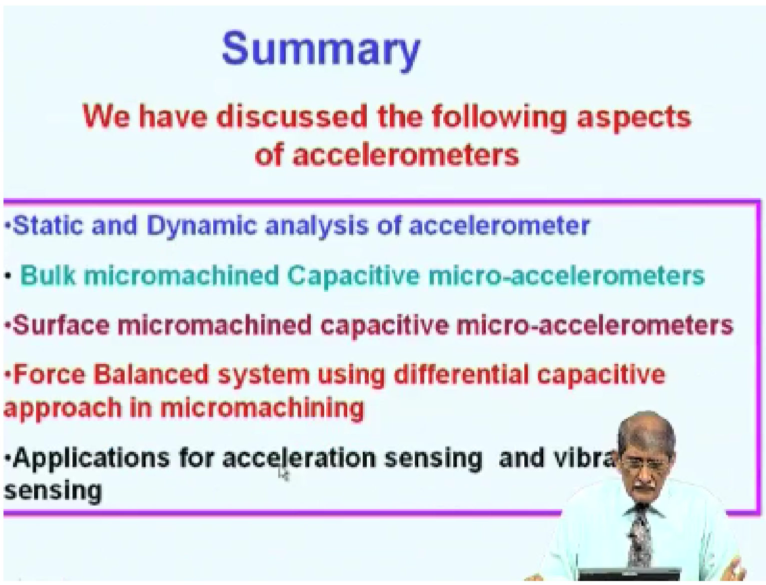

In Summary we have discussed static and dynamic analysis of accelerometers with electronics accelerometers and also we have discussed bulk micro machined and capacitive accelerometer and I have presented the surface micro machined capacitive accelerometers , both bulk and surface micro machined and also how force balanced system can be sued for differential capacitive approach for micro machining, we also pointed out some applications accelerometers for sensing acceleration and vibration, thank you very much.