Acoustics
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Module 6- Lumped Parameter Modelling of Transducers
Lecture 6
Models of Electro-mechanical Acoustics System

So in the last class we had talked in detail about how to develop complex models and what we will be doing today in the this specific class is essentially a follow up on that and will be actually talking more about specifics constructing actual models and also solving those. So in one of the earlier classes we had developed a lumped mass model, lumped parameter model for a suspension system for a car so will revisit that because we never solved it in that class.

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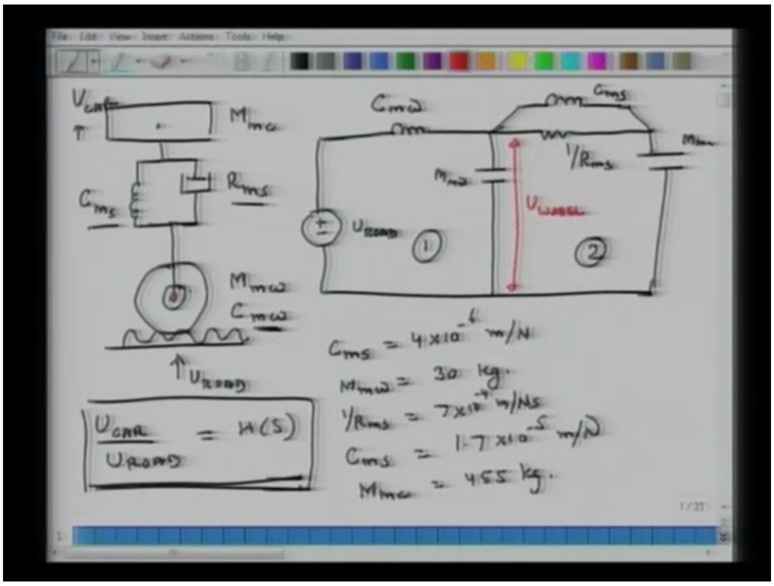

So to recap let's say you have a mass, this could be the mass of the car and since the car has four wheels I will only take one four, one fourth of the structure.

So I will consider only one wheel and the load shed by it. So the mass of the car or the one fourth mass of the car is MMC and this is my wheel which is moving on a road which could be uneven so as this wheels moves on the road it moves up and down and what I am interested in this particular problem is, as the wheel moves up and down the person sitting on this body, what kind of motion does he or she experience? That is what I am interested in. So what I am interested is that if the velocity here is U road, what is the velocity of the person? So I can call it U car.

Now between the car body and the wheel typically we have springs I will put a compliance member and also we have some times dash parts which dam the vibrations. I am calling this as CMS, S meaning suspension so it is compliance of the suspension (system) mechanical compliance of suspension and this is RMS that is mechanical resistance of the suspensions. Now the wheel itself has mass as it moves up and down it has some mass, so I assign it value moving mass of wheel which is W and its air inside the wheel which acts as a stiffness member.

So it also has a stiffness CMW, so again what I am interested is in is, if this an input motion because of the uneven of the unevenness of the road which is U road then what is the motion which is going to be experienced by the person sitting inside the car? That is what I am interested. So let's construct a lumped parameter model of this and I am going to use the mobility equivalence to construct it. So that is my input source U road and I have two masses and in mobility's equivalence we always ground the mass.

So my first mass is this it is MMW and this is my second mass which is mass of the car or one fourth of the car mass, so it is MMC and I am going to ground both of these also I have this stiffness or compliance element CMW and then I have suspension stiffness and suspension damping both are in parallel, so I put them in parallel. So here it is one over RMS and this CMS. Let's put some numbers on these terms so CMS is 4 times 10 to the power of minus 6 meters per Newton, MMW which is the mass of the wheel around 30 kilograms.

One over RMS is 7 times 10 to the power of minus 4 meters per Newton second, compliance of the suspension stiffness is 1.7 times 10 to the power of minus 5 meters per Newton and mass of the car or one fourth of its mass let say it is 455 kilograms.

Student: we have done this example.

Yes we have done only part of the example we never solved it, we did uhh only the break points. So will very quickly revisit those breakpoints and then actually start solving it.

So the first break (point), so what we are interested in is, this ratio U car over U road, this is my transfer function that is what I am interested in. How does this ratio change as my excitation frequency is change. Now we had learned in the earlier class talked about breakpoints, the first break point is associated with the fact that for some set of frequencies current will be more or less passing through the resistance and as frequencies go up in number.

Then that the current going through the inductor will become less and less and most of the current will go through is here through the resistor I have incorrectly labeled it. This is one over RMS and this is CMS ok. The other breakpoint is associated with this loop versus current going through the other loop, very quickly we call this loop 1, we call this loop 2 and also we assign another variable here which is the voltage difference across these two points and we call it U wheel.

Remember velocity of the wheel which is essentially velocity of this point is not necessarily identical to the velocity here.

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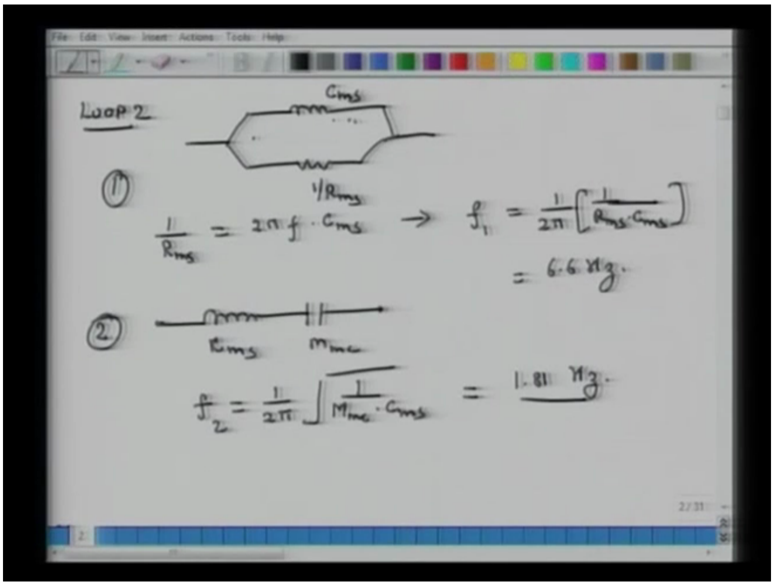

So we consider loop 2 and in loop 2, in loop 2 I have this parallel circuit. This is one over RMS CMS so as we talked earlier at low frequencies most of the current will go through the inductor as frequencies go up current will start going less current will flow through the inductor more of more will go through the resistance.

So the cross over point will be such that one over RMS equals 2 Pi F times CMS so this gives me the first breakpoint F1 is 1 over 2 Pi, 1 over RMS times CMS and that is 6.6 Hertz. Again below 6.6 Hertz more current will go through the inductor above 6.6 Hertz more current will go through the resistor, so this is first breakpoint. Second breakpoint is associated with the fact so above 6.6 Hertz the current going through this circuit will also have some sort of resonance, this is MMC. So let's compute the breakpoint of MMC and the compliance and let see where it falls.

So for this circuit which is essentially as current is going through this route let see if the resonance is below 6.6 Hertz or not, for this one my frequency is F2 is 1 over 2 Pie, 1 over MMC times CMS and when I plugin the numbers I get 1.81 hertz. So the point what I am trying to make it make is that below 6.6 Hertz most of the current in the circuit will flow through the inductor and within that range from 0 to 6.6 there it will cross a certain breakpoint again which is which corresponds to 1.8 hertz.

If this number had been more than 6.6 Hertz then this analysis would have been meaningless because current would have gone through this wouldn't have gone through CMS anyway. For third breakpoint what we are interested in knowing is what happens when current goes through CMW and MMW that is another inflection point.

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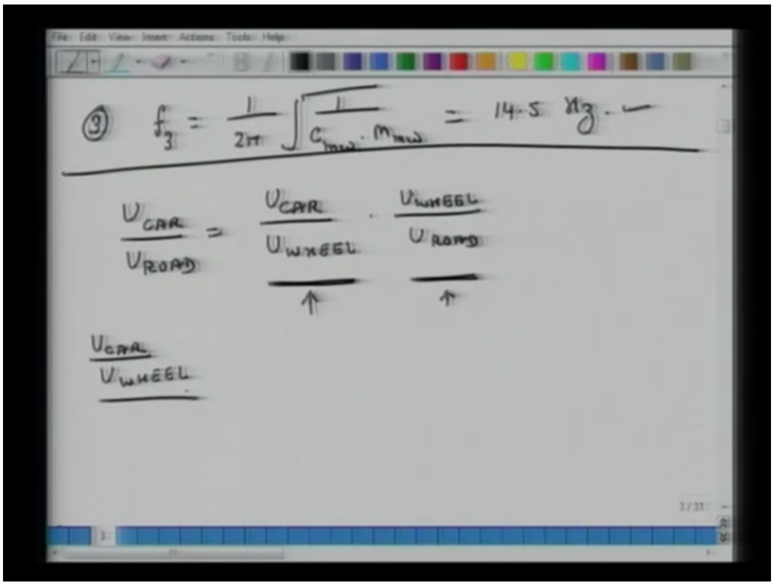

So for that one F3 equals 1 over 2 Pi CMW times MMW and that gives me 14.5 hertz ok. So these are my three frequencies, 1.8 hertz, 6.6 hertz, 14.5 hertz so I have to find in from 0 to 1.6 how is the circuit behaving from 1.8 to 6.6 how is the circuit behaving and from 6.6 to 14.5 how is it behaving and what happens above 14.5, so that is what we will do today and our aim is to find this transfer function, yeah,

Student: sir why we are interested in taking CMW and MMW we should have considered because (())(11:57) or pass through CMW so we should have considered the

MMW branch or the rest of the branch, so instead of considering CMW and resonance between CMW and MMW we should have considered (MM) between MMW and rest of the branch.

So we will see that how it becomes just hold on, so you, will see that CMW will be in the circuit regardless, right.

Student: So we have to consider this and this branch?

So just hold on to your thought, we will see that relevance. So what we are interested in is this ratio, so U car over U road equals U car over U wheel times U wheel over U road, so what we will do is in general our approach will be we will find how this transfer function is changing with respect to frequency and how this transfer function is changing with respect to frequency. Will construct board plots both of these, these two transfer functions and then we will add them up and then will get total transfer.

And in this context the (val) you will see the importance of 14.5 sorry will seeing later in detail. So what will start with is U car over U wheel this ratio.

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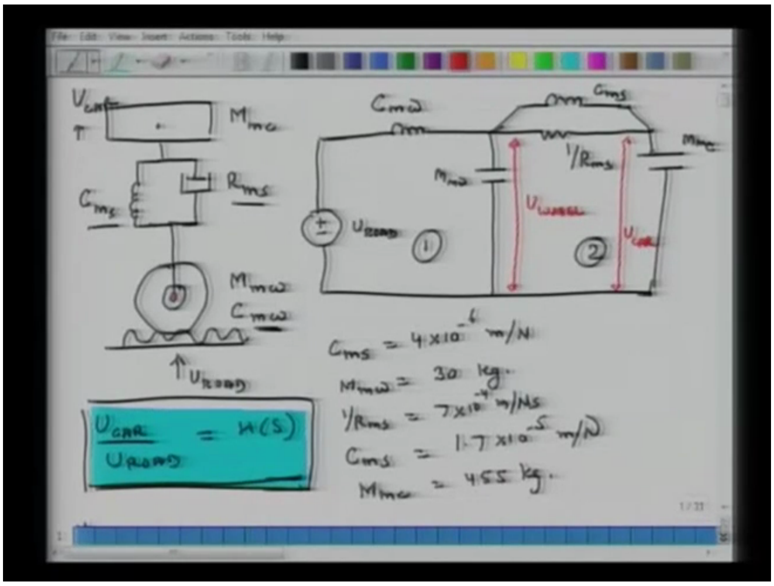

So again U car so to make it clear this is my U, U car so U car over U wheel in that context what we are interested in is essentially loop 2, whatever happens on loop 1 does not have a bearing on how the ratio U wheel over U car or U car over U wheel will get impacted.

Now the wave the reason why we are doing is this that if you don't have a computer you don't have to solve very complicated equation then you can get reasonably good board plots using this approach if you break the circuit in small pieces and analyze them piece by piece given that we have a lot of computers we have software tools which you can make all these circuits and this software tools and this software will solve for complex quantities very quickly.

But to get a physical inside test to what is happening that is why we are doing.

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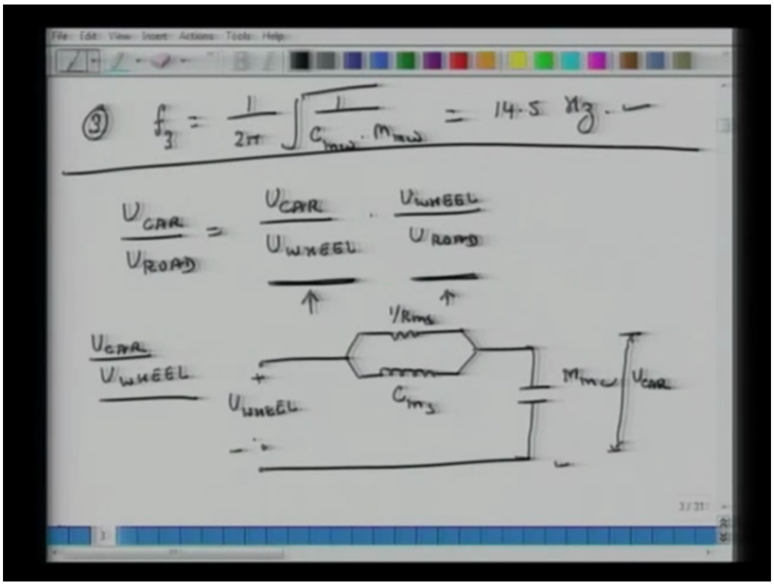

So to get my U car over U wheel this is my sub-assembly and what I have is MMC this is C suspension stiffness and that is my damping term, so switching screens so this is my U car that is my U wheel.

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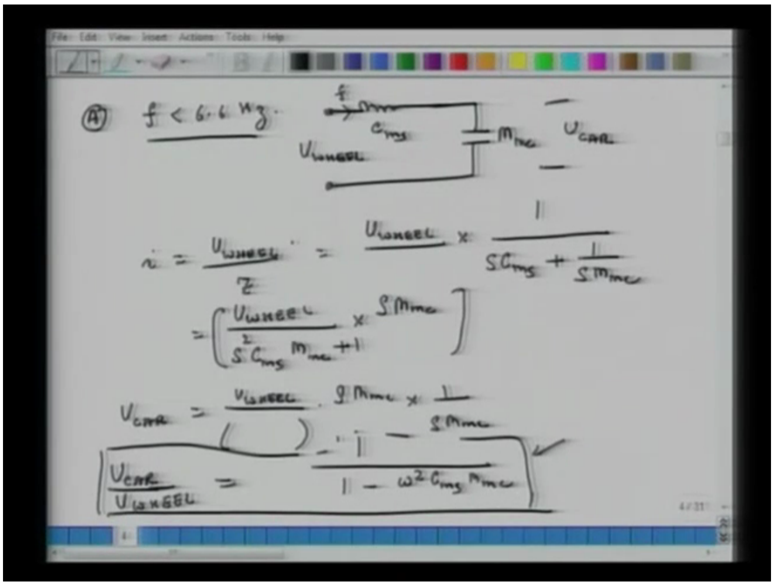

So let's see what happens above A if my frequency exceeds 6.6 hertz if my frequency is above 6.6 hertz if it is less than 6.6 hertz then in this circuit I can ignore the impact of CMS so all I have is 1 over RMS and MMC.

So then my distill down circuit becomes 1 over RMS and MMC CMS yeah this is U wheel and that is my U car, the through variable going through it is force, so the current which is analogous will be something like U wheel times divided by the impedance of this entire circuit Z, which is U wheel over L write the impedance here 1 over S which is my complex frequency J omega times CMS plus 1 over S MMC so I get that as U wheel over S square CMS MMC plus 1 into S MMC and my voltage difference across the (mov) moving mass of the car is basically this current times MMC times S the impedance offered by 1 over whatever that number.

So U car is this whole term U wheel over the whole denominator times S MMC (())(18:37) over S MMC so my U car over U wheel equals 1 over 1 minus and once I put S equals J omega I get omega square CMS MMC. So this is for frequencies less than 6.6 so now I make a plot of it say I will construct a board plot and a board plot has two parts low frequency S M to ten high frequency S M to ten. When the frequency goes low then this value becomes 1, so my 20 log of this value becomes 0, when this frequency becomes very high I get a negative slope, of how many degrees? 40 degrees because it there is a omega square.

If it was just omega times some number it would have been a 20 decibel negative slope, but I will get a minus 40 degree slope and the threshold the crossover point so my board plot will look like which I will plot it here itself.

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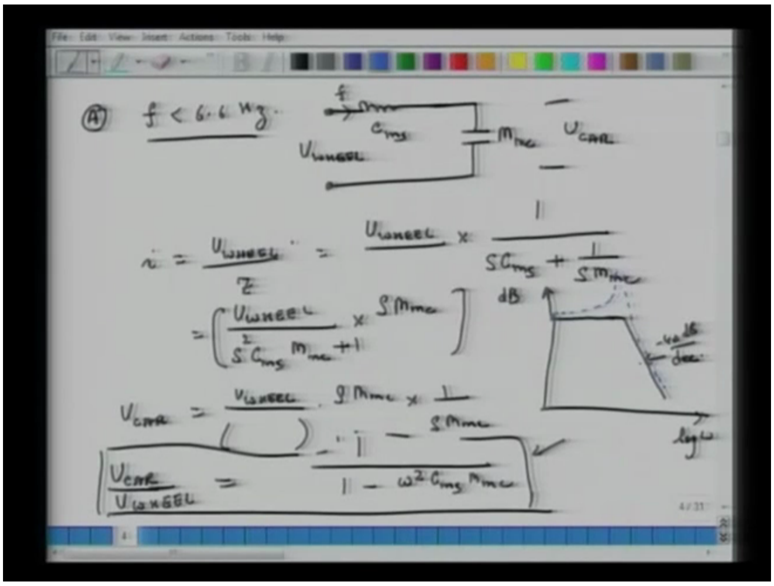

So this is my decibels log omega my frequency response will look like something like this and the slope is minus 40 dB per decade. My actual curve because at a particular value of when this denominator becomes zero my actual value will look something like this because there is resonance, what will be constructing is essentially the dark line which is (())(20:35)

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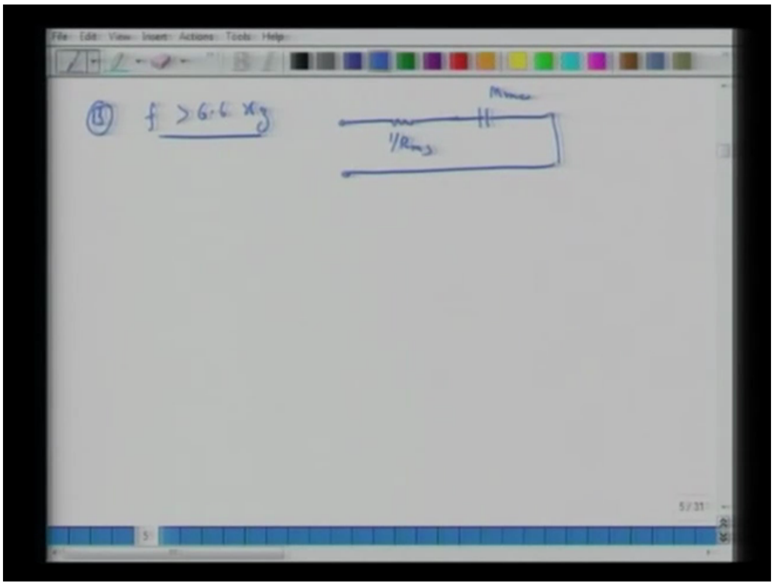

When frequency exceeds 6.6 hertz what will happen? I can drop the compliance term and include the resistive term. So my equivalent circuit will be, this will be my equivalent circuit. Can you infer what will be the shape of the board plot for this one, for this circuit, without going through the analysis, I mean we can construct you know we can develop again as we did here find the overall impedance and find the voltage difference across the moving mass, but just based on whatever we did here.

If I have an inductor and a capacitor in series I get a minus 40 degree slope, if I have a resistor and a capacitor in series, what kind of a slope I will get? Plus 20, 20, minus 20, or plus 20, plus 20. So the slope across if it was purely a resistor what will be the slope across it? It will be zero, right because there is no omega term here, if there was no capacitor or inductor the slope of the response term will be zero, because there is no omega term.

You have omega square so that (cont) generates a 40 degree, so it will be only 20 degree also what is this number? What is this frequency? And what is that number, is it 6.6? We calculated three frequencies right, we calculated three frequencies one was where is it, 6.6 hertz, 1.8 and 14.5, which one is this?

Student: 2.8, 2 Pi into 1.8

Yes I am just calling the frequency yes if you want to make it omega it will be 2 Pi.

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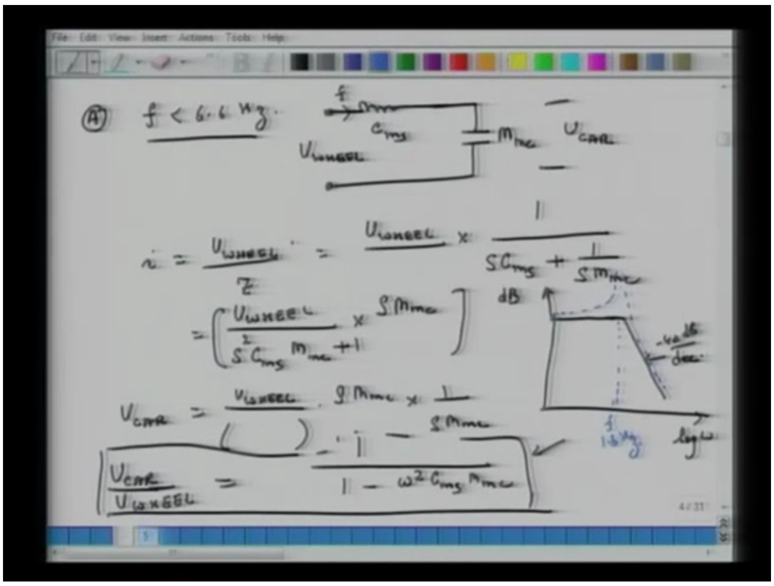

So it is 1.8 hertz so this is 1.8 hertz. It keeps on going with a negative slope of minus 40 degrees above 6.6 hertz as you guys mentioned.

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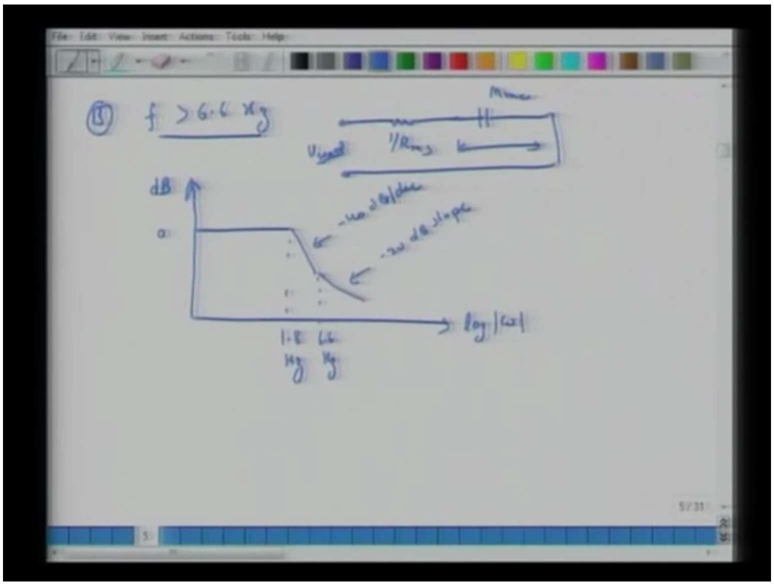

So I will construct this again, log omega this is decibels this is 0 dB, 1.8 hertz I have a slope of minus 40 dB upto 6.6 hertz and above 6.6 hertz I get minus 20 dB slope, here the slope is minus 40 dB. I am plotting a resistor and a capacitor in series yes.

Student: it should be constant after a while because it would be 1 upon S C plus R

What I am plotting is a ratio of the voltage difference across this element and the input which is U wheel, right, so they will be a omega dependency always because you U car is dependent on omega. So this is my overall plot upto 6.6 hertz now what we will do is so we have plotted this one U car over U wheel, now we will work on U wheel over U road.

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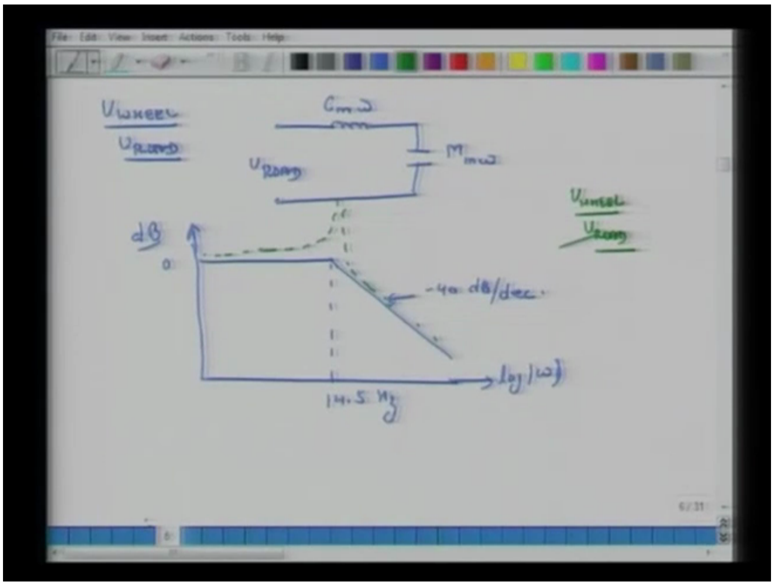

So U wheel over U road and the effective circuit for that is essentially this, so this is U road that is mass of the car mass of the wheel MMW and this is compliance of wheel. What will be the board plot for this circuit look like?

Student: minus 40

Minus 40 dB, right, high frequency or low frequency?

Student: high frequency

And low frequency?

Student: zero.

It will be a 0 dB same thing which we did earlier right. What will be this number? 14.5 hertz. This is my decibel scale I am plotting log omega on this one is 0 dB slope is minus 40 decibel per decade. The actual curve may look something like this because at resonance the denominator goes to zero. So this is U wheel over U road so I have a plot for U wheel over U road and I have a plot for U car over U W U wheel, so all I have to do is now just add these two up.

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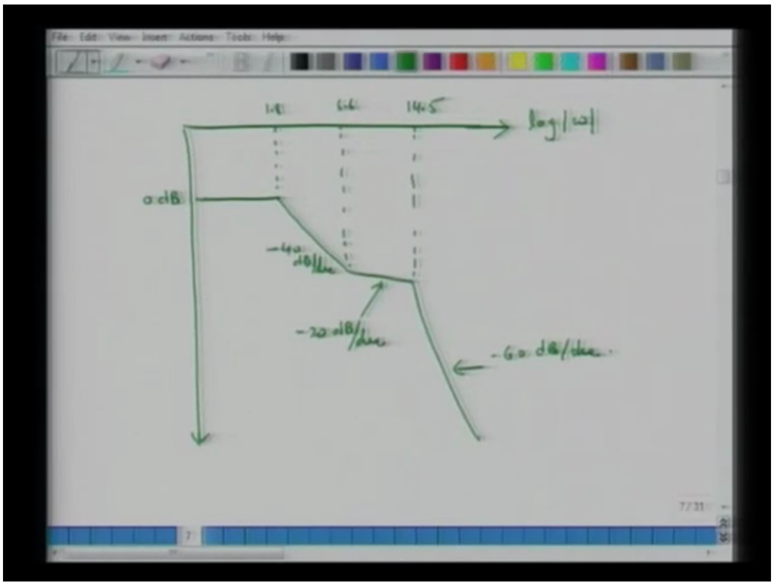

So my final plot looks something like this, I have three breakpoints 1.8, 6.6, 14.5 I have initially a flat line at 0 dB then I get a minus slope of negative slope of minus 40 hertz minus 40 Dc decibels then my slope is a still negative but it reduces this is minus 40 dB per decade this is minus 20 dB per decade and then I get a very acute minus 60 dB per decade. So what just picture is showing is that given the parameters which we had listed earlier in the mechanical circuit first thing is that you have virtually no attenuation at very low frequency it is all 0 dB.

Whatever is going in is being experience by the passenger and as frequencies go up you start seeing attenuation and that attenuation starts very rapidly increasing after this 14.5 hertz that is what you see. So you have to pick the right amount of damping right amount of stiffness as you are designing whether it is a mechanical it is a suspension circuit or an acoustic system what this is telling you is that you have to make that proper choices of some of these parameters, so that you get the right amount of damping.

It also tells you is that if the frequency of input signals which is essentially coming from the road is in this region let say your road is such that most of the frequencies are coming from 0 to 1.8 hertz then the suspension is doing not much, right, so depending on the road conditions you have to construct you have to develop or identify the right parameters of your suspension stiffness in suspension damping that is (what is says.)

So whatever you have to understand the topography and based on that you (com) construct the right damping and other thing you should think about is that and this will help you understand this.

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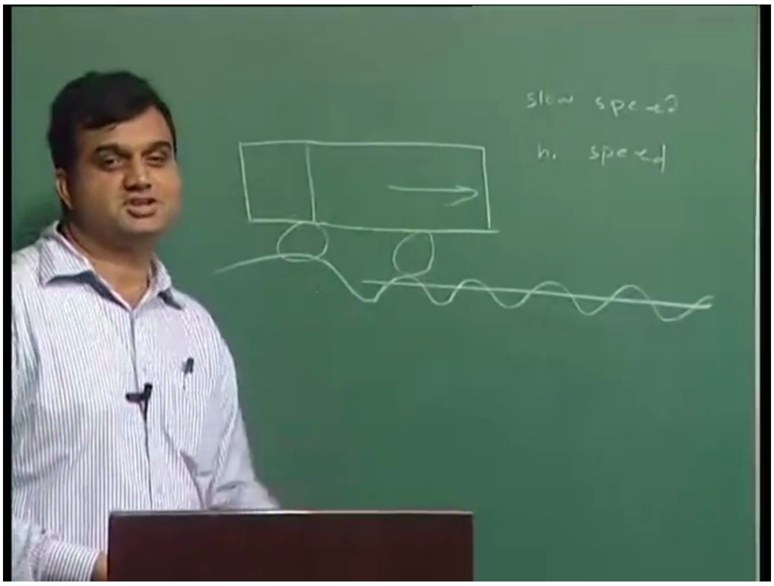

That suppose you are driving suppose this road this is perfectly flat road but in real conditions it is doing this right and your car is, car is going like this, the car is seeing the same amount of vibrations whether it is going at slow speed or at high speed, but the driver experience changes.

You can try it even on a scooter or a bike you try, you have a small bump when you hit and you go cross try to cross it with a high speed or try to cross it with slow speed and how do you feel? And why do you feel? you should think about it and figure out based on this understanding, at different speeds even though the amount of bumps and the frequency of bumps is same the perception of the person whose driving the car or bike or (most) motorcycle changes and the amount of vibrations he or she experience also change and it also depends on speed.

And what that has to do is it relates to the Doppler effect that as your moving at higher speeds the apparent frequency of these bumps which are coming from the road it goes high or low, it goes high. So that has a bearing and that you can relate that fact to this curve and figure out why you feel better at higher frequencies or at higher speeds or you will feel more uncomfortable at higher speeds you have to think about it.

So we have done one example and this one was overdue we had constructed this, the next example will today do is of a loudspeaker given that this is acoustics course. What we will talk in the remaining part of the lecture is model of the speaker and will also try to hopefully we will try to finish this solving it today itself atleast one model of this speaker.

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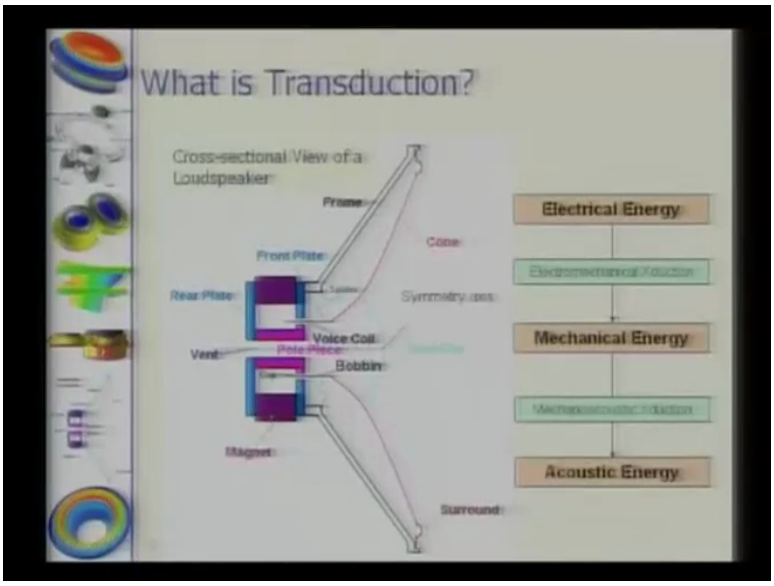

So what you are seeing here is a magnet which is sandwiched between two metal plates ok, the plate on this side is called the rear plate or the back plate and the plate on the front side is called it is on the front so it is called front plate, where this is the front of the speaker so it is on the front side so it is called front plate and between the front plate and the center you have this magenta or pink metallic piece this is also made of a regular steel which could be magnetized and there is a small gap between these blue front plate and the pink whole piece and in this gap you have this voice coil.

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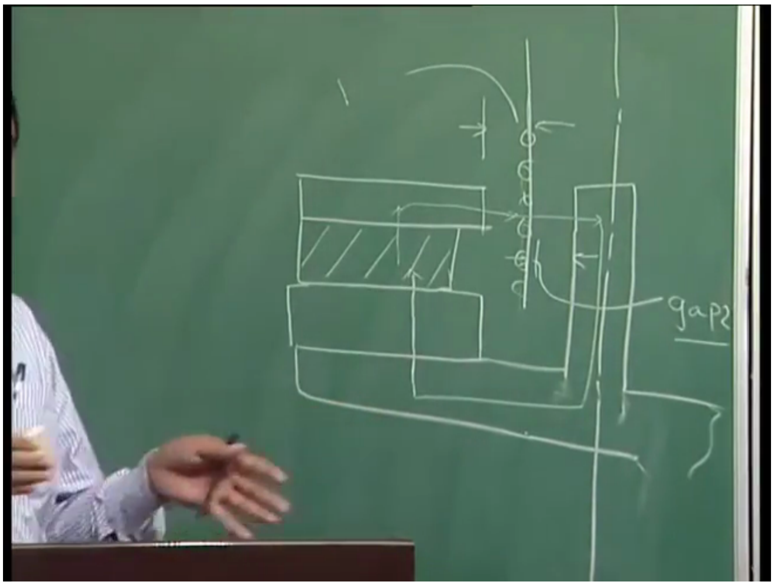

Just to zoom in you have front plate, you have whole piece here you have voice file on which the windings are there and here this could be a magnet and this cutting a cross section and this is your back plate and back plate is connected with the pull piece something like this. So the way the magnetic circuit works is, this is magnet it acts like a battery so you have magnetic flux lines going here then they can also go in here but here is much more resistive so they don't go there, so they get bend they come here they cut the voice coil conductor they come here like that this is how the circuit completes.

So it is analogous to like an electric circuit this gap if we try to minimize the gap as little as possible where the more gap you have the impedance to the magnetic lines will be higher and higher so typically this gap between the voice coil and this is about half a millimeter to account for tolerance is another things also. Also you have gap on this side so you have gap on front of the voice file and then also this gap is there this is gap 2.

So people call it outside gap inside gap that is also no not typically more than half a millimeter if you have big gap which it means that you have to put bigger magnet in this, is more stronger magnet then magnets are expensive so we will try to minimize the gap, so just wanted to give you some flavor of that. There is an electrical part current is coming in it goes through this voice coil winding. What will winding have in it? Electrically what elements will it have? It is a conductor so it will have resistance slight if you have to model it, you will model it as a resistor and then it is also a winding it can also be an inductor.

So people have modulated is typically resistor and a inductor in series that is the electrical side. Then the electrical side, the electrical energy gets converted to motion so the transformation factor that is what is DL, we saw it in the earlier class right and on the mechanical side, what do you have? This voice coil is moving up and down it has some mass right, so you can model it as a mass, also your seeing that this green element it is a suspension element it acts as a spring.

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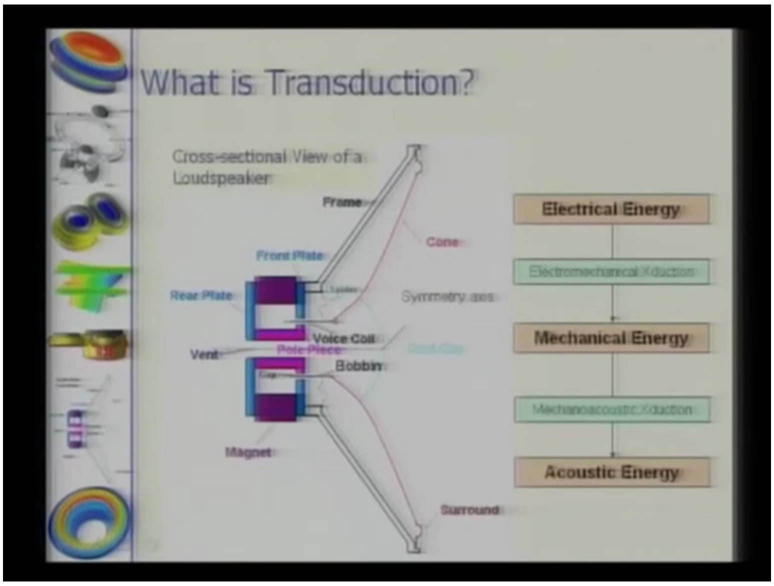

Similarly this curve here this curve here this also acts as a spring. So this is also, so these are two spring elements so you have mass because this voice coil is moving back and forth it is physically moving back and forth so it has a mass there is an inertia effect. Also this entire diaphragm is moving back and forth that also has mass so you have mass because of all these things your stiffness because of this spider and what they call the surround also spider itself has a little bit of mass, it is not luck much but it too has the mass which is not negligible so people account for that mass also.

So it has a mass it has a spring element in it and then also anything any mechanical thing moves piece of paper, rubber, metal does not once you strike it, it vibrates for a while and then it damps down because there is always internally damping so people put damping elements also. So on the electrical side there is resistor and inductor on the mechanical side there is you have to think physically how I am going to model it.

There is little (())(37:57) mass there is spring and there is damping and then this whole speaker could be mounted in an infinite baffle or in a tube or whatever, so once we go the acoustic side, what we will put? Radiation impedance because that speaker is going to radiate energy out into free field and that generates radiation impedance. So based on that physical understanding of the system will construct a lumped parameter system.

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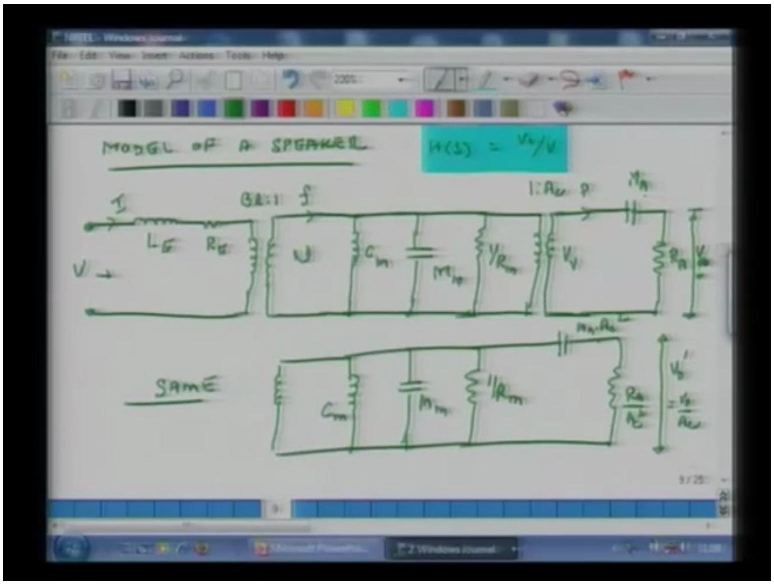

Model of a we call it speaker, so my input energy is voltage I can measure it 14 volts, 10 volts whatever it goes through when, this is the electrical element, electric side of the story. So I call it L E, electrical inductance and this is R E electrical resistance. Then electricity gets converted into motion, so what is my through variable here, on the mechanical side? If I use impedance analogy voltage corresponds to velocity of U, right, U and the through variable is force, turn ratio is B L is to 1, B is magnetic flux L is what? Length of what ? Conductor, which conductor? The total length of the wire, the total length of all these coils.

It could be in several meters, there is a springiness in it that I represent by mechanical compliance C M, there is mechanical mass MM and there is damping, ok, I have question here. Does it make sense to put CM, MM and RM in parallel, or should they be in series? Based on your physical understanding, this is the picture or the model, so should I put the mechanical elements spring, mass and damping in series or in parallel or should I put them in whatever, why should I put?

Student: we are talking about the magnitude

Magnet

Student: sir MM is the mass.

Moving, MM is what we call mechanical mass, MM is the mechanical mass MM which is sum of this voice coil it has some mass also part of this diaphragm which is moving back and forth.

Student: All the elements moves with same velocity, so we have to keep it in parallel.

So because we are using mobility model U across each of these variables is same and then this mechanical circuit is coupled with an acoustic circuit when the turn ratio here is 1 is to AC, what is AC? It is area of the diaphragm, right, area of the cone. Whatever area is radiating sound it is the area of that, what is the across variable here, in the acoustic lamp? Volume velocity and the through variable here is? Pressure, here I have ()(42:15)

And I am assuming that this speaker is mounted in an infinite baffle, what that means is there is an infinite wall extremely rigid there is a small hole in it and there is a speaker mounted in it and it is firing sound on one side on the other side there is vacuum that is what, so for that from standard texts the radiation impedance is I have to put an acoustic mass here and then I have to put an acoustic resistor, whatever is the energy dissipated across the acoustic resistor is something I will be listening to.

So what we are interested in is, V4 which is the voltage across this acoustic resistor. So given a value of V, what is the value of V knot? That is what I am interested in. So the transfer function which I am interested in is HS equal to V knot over V, this is what I am trying to find. We will make this circuit a little simpler not by dropping any element because you have not done any, what we will do is we will eliminate this transformation here and we had seen earlier in earlier class that if I want to eliminate this transformation my RA will get converted into RA divided by this term ratio square of terms ratio.

So RA over AC square my capacitor will get multiplied by that and my voltage will get divided by not square but just by AC. So what we will do is I will just construct only this part of the circuit. So this is MA times AC square this is RA over AC square and my voltage will become V knot prime which is basically V knot over AC and this part of the circuit is same. So if can find instead of V knot over V if I can find V knot prime over V I am fine. I can very easily transform that into V

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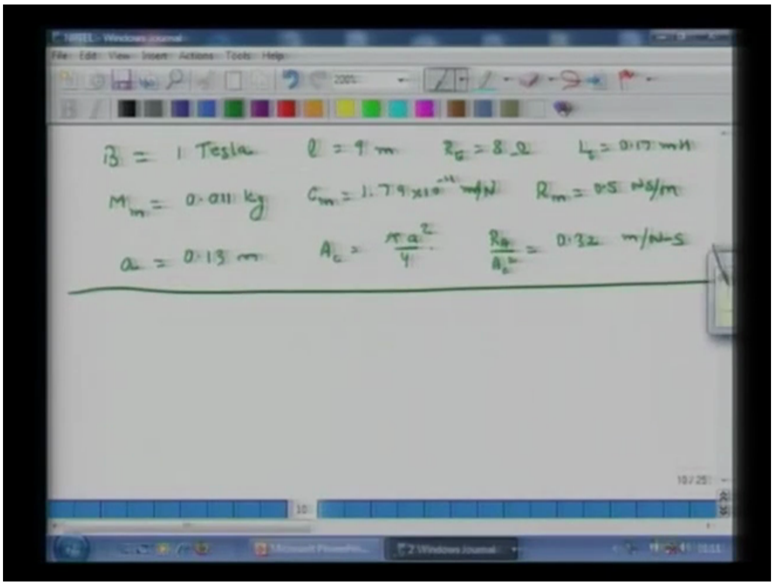

So now what I will do I will assign some values so my B, B is magnetic field density is 1 Tesla, these are fairly close to some of the real numbers if you and buy a speaker so what and I have drawn this from (()))(45:58) book it is about 10 inch big speaker, length is 9 meters these are long watts just gives you an idea there is a lot of copper while wounded, RE is 8 ohms and LE is 0.17 mili-henry's, moving mass or mechanical mass is about 11 grams, compliance is 1.79 times 10 to the power of minus 4 meters per Newton, RM is 0.5 Newton second over meter, A is 0.13 meters.

A is the diameter of the diaphragm so from that I can calculate AC, so AC is Pi A square root, did I miss anything? RA over AC square equals 0.32 meter over newton. So what will I do first when I start trying to analyze this circuit, what did you do in the case of this suspension system for a curve? Whatever are interesting points you have to figure that out, so the first one could be will just look at the electrical circuit, on the electrical side you have LE and I those are the two elements.

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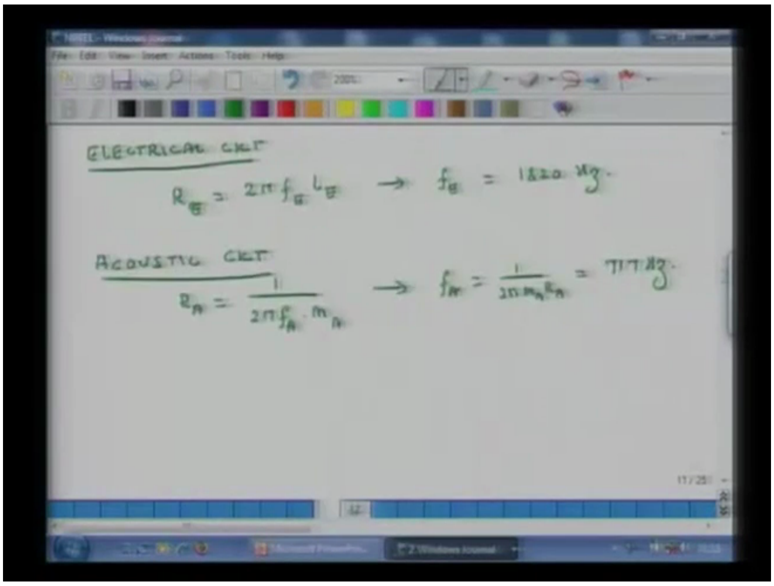

So they will be a certain threshold above which inductive part of the impedance will become significantly larger compare to the resistive part. So above that threshold I can only consider the (resist) uhh inductor in the electrical part below that threshold I can only consider the resistor as a very general agross approximation, so that what is the threshold? So that threshold will be when R E equals 2 by FE LE right, from here I get my FE equals 1820 hertz, so above 1820 hertz in my circuit analysis I will be ok as a first level of approximation.

If I can drop the resistor, below that I will have to consider the resistor and ignore I can ignore, second one is acoustic circuit and ofcourse if you have software you can do it you don't have to do all these things. So for the acoustic part what should I be doing? This is the acoustic, you have a capacitor and a resistance so I will do the same thing there, RA equals 1 over 2 Pi FA times MA this gives me FA equals 1 over 2 Pi MA RA equals 717 hertz.

So I started with the easy part the very few elements here they have very few elements here as soon as goes, now we look at the middle one, the middle elements are what are there in the mechanical, you have a compliance, you have stiffness that is stiffness you have mass and you have a dash part right, if my transducer is in vacuum again a extraction the role of RA and MA will be zero right the mechanical mass acoustic part I can ignore that right.

So if my system is in vacuum they will the mechanical part will resonate in such a way that it has two elements, mass and a spring right.

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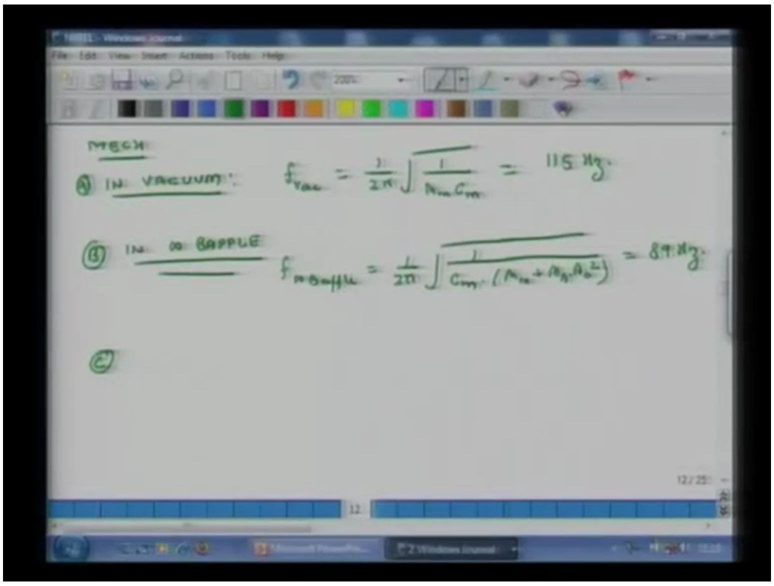

So natural frequency in vacuum with mechanical, in vacuum basically my F vacuum will be 1 over 2 Pie K over M, K is 1 over compliance so it is MM times CM is 115 hertz, what this physically means is that if I place my speaker in a vacuum and I strike it, it will resonate at 115 hertz, is the place it will free here it may not resonate because these are radiation impedance.

Second one is in infinite baffle when I place an infinite baffle I have MM and this MA times AC square in parallel right, so I can add these guys and I can find the total (len) final resonance when this thing is in an infinite baffle, you understand it? F infinite baffle is 1 over 2 Pie times as the compacient the compliance is not changed, the mass is changing, does everyone understand why is AC square here? Because we eliminated the transform.

So this brings down my resonance to 89 hertz. It is a significant difference that air in the system is acting as a mass and that brings down the resonance from 115 to about 90 hertz that is a very significant change in frequency. So you cannot ignore them like you know the role of radiation impedance. Third one this is again so this is my actual condition if I place my speaker in hand or I place it on a table then it what frequency it is going to resonate?

Natural frequency will it resonate at F vacuum, F infinite baffle or X (())(53:09) natural frequency, forget the table I can put it in hand or I can hang it in the air don't worry about table.

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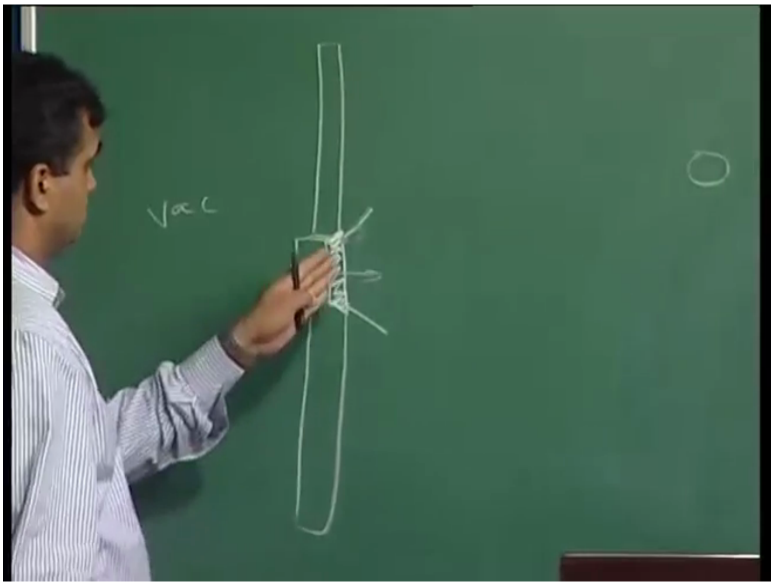

See what you have here ok, bad drawing , so this membrane is moving back and forth right, it has two surfaces one surface is pointing here let say my observer is here and this is vacuum. This membrane is moving back and forth it has one surface facing this side this way another surface facing this side right.

So this side you have the radiation impedance which we accounted for here by MA times AC square on this side there is no radiation, radiative impedance because there is vacuum, now if I place it in hand or I place it on a table both the surfaces of the same membrane they will see the same radiation impedance on back side and also on the front side, you understand? So instead of how many times AC square what will be the new number?

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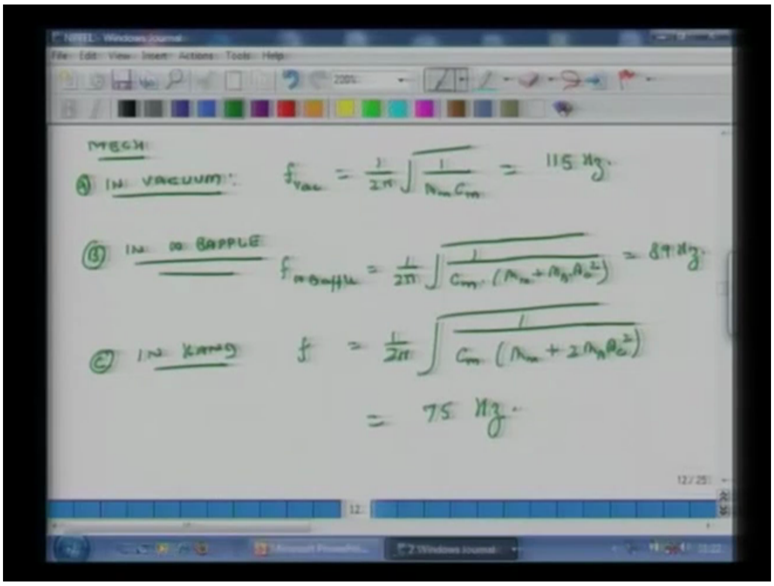

The mass this it will be twice that in hand my F is 1 over 2 Pi, 1 over CM times MM plus 2 MA AC square. So that comes to 75 hertz. So that is, so these are so what we have identify is this is something we will care about as we develop the board plot for the whole system we will also care about this one we will not hear about this one because the actual speaker is mounted in a infinite baffle. We will care about this one 59 hertz and again we will not care about this one because the actual mounting condition is infinite baffle.

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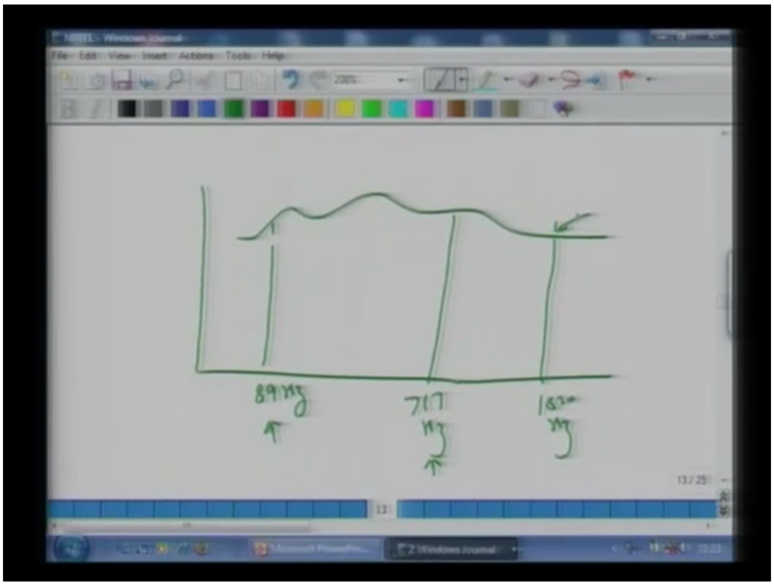

So my board plot will have it will be something I don’t know what it is going to be like but it will have several breakpoints 89 hertz, 717 hertz this is from acoustic circuit this is from mechanical circuit and this is from 1820 hertz and this is from electrical circuit at these three, these are the broad terms these are the three important breakpoints. We are short of time so we will not develop the actual board plot today but think about it that if you want an ideal speaker loudspeaker what kind of board plot would you prefer?

Should it be flat should it be going up should it be going down should it be wigly what kind of a board plot would you like to have an ideal perfect plots and why I will be good? What does it mean physically? Same sound return, so whatever you are getting in is being faithfully reproduced at equal levels for all frequencies. So bearing mind as we are developing that board plot and then will see the type of response we get for this particular system.