Fundamentals of Electric Vehicles
Technology and Economics
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Lecture 5
Mechanical Design – Part 4

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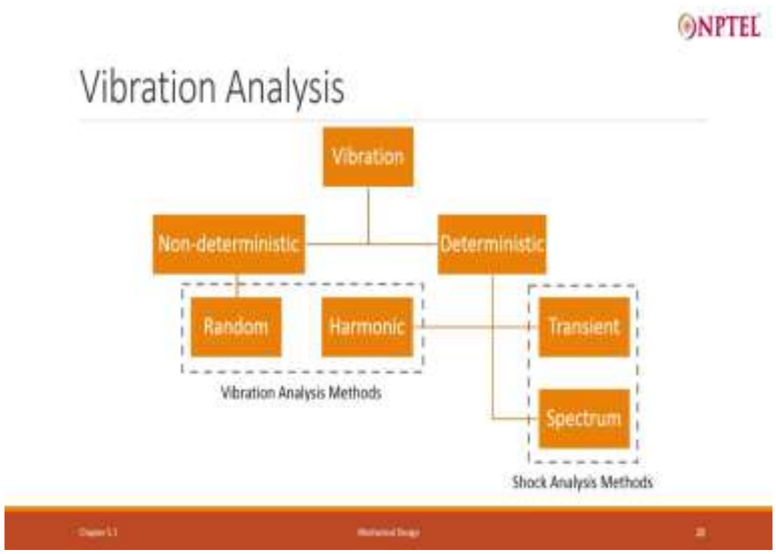

The next the important topic in a mechanical design is vibration analysis. So, we will be talking on that, so vibration is basically two different types; one is non-deterministic and other one is deterministic. What is the difference between non-deterministic and deterministic? In deterministic vibration you know the response function, you know the amplitude time of the response function as well as the frequency.

However, in non-deterministic function, we may know you may know the frequency you may know the time but you will not know the amplitude of the function, since you do not know the amplitude that is why its become non-deterministic. In deterministic general you will get a nice function like force function or response function, like force F equal to F0 Sin omega t you know the F0, you will know the omega, you will know the t also.

In non-deterministic vibration you will also find the similar equation, but you will not be knowing the F, F naught, for certain, so what you have to do in that case, you have to go to a statistical analysis, you have to do the main mode all with the given data set and then you have to find the equivalent function and then you have to start doing non-deterministic vibration.

Deterministic vibration is basically transient, harmonic and spectrum, three different types of vibration comes in deterministic type. In non-deterministic random, both are same non-deterministic you cannot determine, random means it can be anything. What would be the example of a random vibration? In nature air bridge, bridge you can say earthquake it is very difficult to either find out the direction or magnitude if you are in outside.

How do you find out? Generally we keep on putting one instrument it collects whole the data or every hour data and then we find out what would be the average or mean and then we say, okay, this was the mean velocity, during the day. Movement of the cloud, in the cloudy day the sunlight could be example of random vibration I do not say it is random, random nature I can say.

In this vibration analysis when we do the random analysis as well as harmonic analysis we say it is a vibration analysis method, however this transient and the spectral we say it is a shock analysis, abuse. So, vibration itself will have two parts, one is the simple vibration and another one is shock vibration, shock is suddenly you drop something. If I drop something from here to ground the force experienced by the object is for very small time, but very huge, impulsive.

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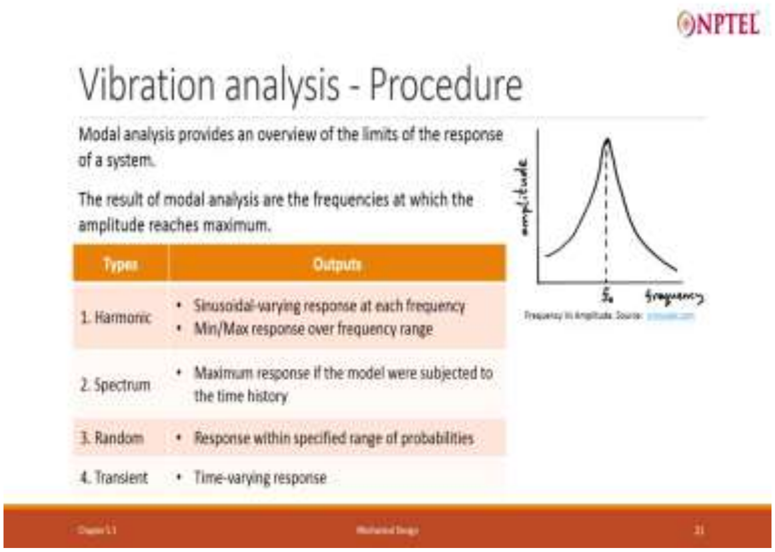

So, now we will move the vibration analysis procedure. The first thing in a vibration analysis is to do a model analysis, what is the model analysis? Generally, you try to find out a frequencies where the amplitude become maximum, in other word we say that as a natural frequencies also, the natural frequency on which the amplitude general the frequency at which amplitude become maximum is known as natural frequency.

Any idea what is the train, the train railway train, the natural frequency of that, a bogie, recently it has come in news several time. And what is our natural frequency? It is approximately 2 hertz, when you go to bed, it is a basically you are vibrating at 2 hertz and that is your natural frequency and you sleep nicely and the similar same thing is of a train bogie, the natural frequency of a trained bogie is approximately 2 hertz.

So, you go to sleeper class or AC or first AC, you get a nice sleep in the train most of the time, it is because of the frequency. So, the result of model analysis is the frequency at which amplitude reaches maximum and those are known as generally natural frequency. F0 you see here, this is the result of model analysis where my amplitude becomes maximum. Now, what we have talked about harmonic spectrum random and transient.

In harmonic vibration it is basically a function same function same sinusoidal function basically sinusoidal function is running continuously so my force is changing continuously, but it is the same, in one cycle if you see it is the same, so we also say it is a steady-state vibration analysis.

If my frequency is not changing my amplitude is not changing we can still consider it is a steady state condition.

The spectrum analysis what we do in the complete time let us suppose one vehicle is moving for 1 hour and there is different vibrations, so instead of checking each vibration and the corresponding each in frequency and corresponding amplitude what we do? What is the maximum amplitude during that time frame or the time history? If once I found out what is the maximum amplitude, amplitude is nothing but if you want to relate it is a deflection what we have talk later that is what is amplitude deflection maximum deflection.

So, if I know the maximum amplitude in a time history of 2 hours or 3 hours or 5 hours, I can find out if things will fail it will fail at that moment only, instead of doing the analysis of at every frequency or every natural frequency because from model analysis we will get the natural frequency or the frequencies at which the amplitude become maximum. Now, random vibration; again it is a statics and probability problem you get different response then you club all the response you do simple average, moving average or mean mode, median, those type of analysis.

And then you find out what for this particular period I will do this function after this I will change this function, so that becomes random analysis. For random analysis it is one of the toughest one all our road vibrations comes into random analysis, because we do not know that know smooth surface same smooth surface, every millimetre the surface is changing and because surface is changing we are getting different vibrations at every different level.

So, that is a random vibration, what we do? Basically we check the road load we take we put the instrumentation, we see all the amplitude, we record, then we come back, we analyse and then we put either in simulation or experimental what are the things has been failed during that time.

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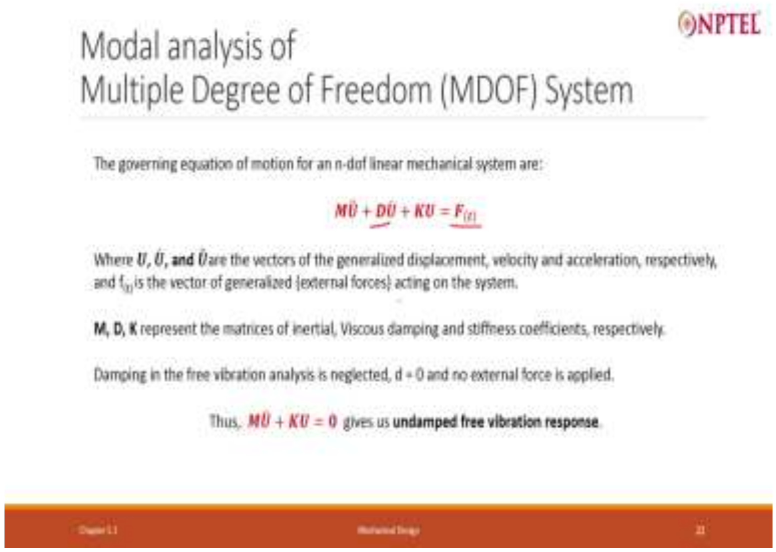

The transient is time varying response, but again sinusoidal, sinusoidal response, but time varying, amplitude or frequency or both can keep on changing, but we know how it is changing that we know, in random we do not know. So, next this is about overview of a vibration the next thing what I am going to talk is model analysis of multiple degree of freedom, the simple governing equation what is that, MU double dot plus DU dot and KU is a function of force.

Where U double dot represents the acceleration matrix or acceleration, U dot; velocity, U; displacement, M is inertial or mass factor, D becomes viscous damping and the K is stiffness, we say. Now, in this case if I am talking about un-damped vibration we do not want damping, what will happen? D become 0, this D will become 0.

And we also do not want external force this also 0, my equation reduces to MU double dot plus KU equal to 0 that is nothing but un-damped free vibration, a simple pendulum in vacuum where you do not have any frictional resistance at the top, you can say this that is example of un-damped vibration.

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So, we will move next, free vibration, so mass-spring system mostly vary present the vibration in mass spring system where the spring stiffness is k1 the mass is m1 and this is the direction of displacement, what would be the natural frequency or you can say angular frequency is square root of k1 by m1 and that comes 2 Pi into f, f is natural frequency in hertz.

So, we can write also natural frequency angular frequency divided by 2 Pi, so the natural frequency is 1 by 2 pi into angular frequency here we have angular frequency is nothing but square root of k1 by m1, m1 is the mass, k1 is the spring constant, so natural frequency becomes 1 by 2 Pi square root of k1 by m1 simple solution.

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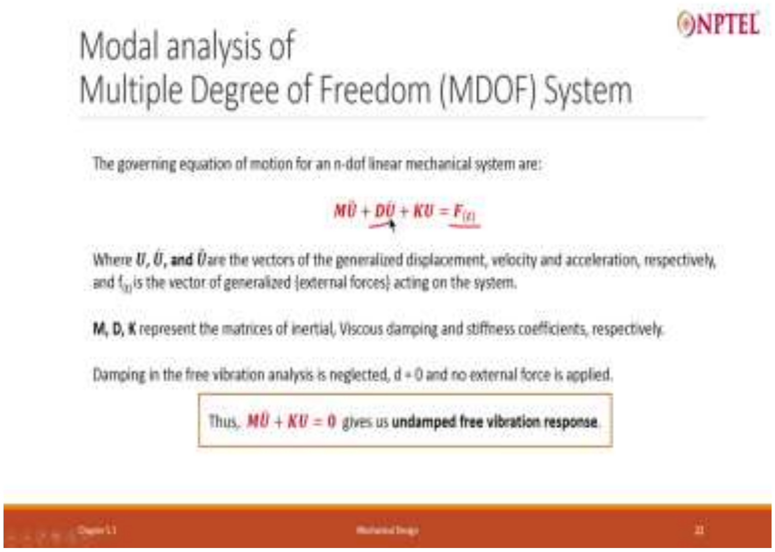

If you see this is my generalize MDOF system where we have acceleration term, velocity term and displacement term, multiplied with inertial term, viscous damping and spring constant. Now, what we have done that I am saying external force let us assume the external force is 0 and viscous damping is 0, so that becomes un-damped free vibration.

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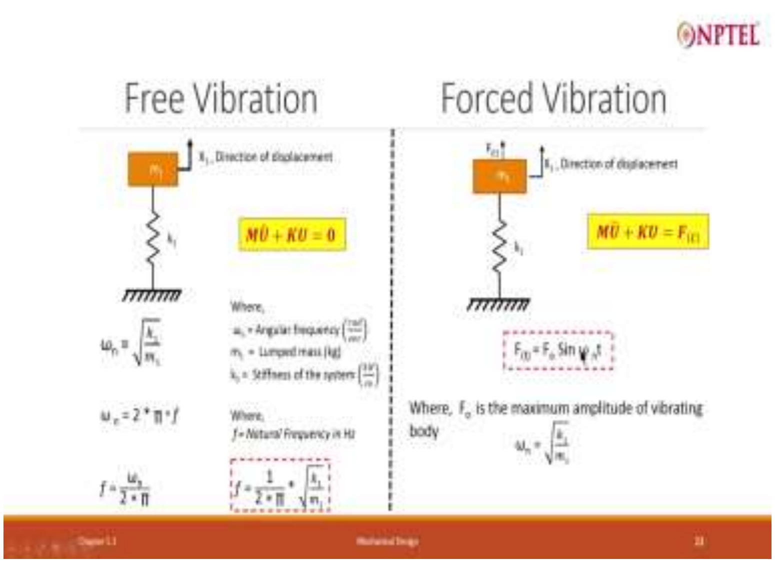

So, the equation reduces to M do to U by do to U square plus KU equal to 0 and then we are trying to find out the frequency and amplitude, so frequency we know, amplitude would be whatever the direction whatever displacement comes that becomes amplitude. Now, force vibration, obviously damping is not there here, in the vibration what will happen? This equation is un-damped forced vibration, where force is a function of time.

And what is the force? I always said it is a sinusoidal function. So, Ft is nothing but F naught is the amplitude of the force Sin omega n is nothing but anger frequency and t is the time. The F naught is the maximum amplitude and the frequency is omega n is again k1 by m1 only, I will show you the next slide. In that I will give you a assignment question and you that assignment question will give you the feel how the vibration works out.

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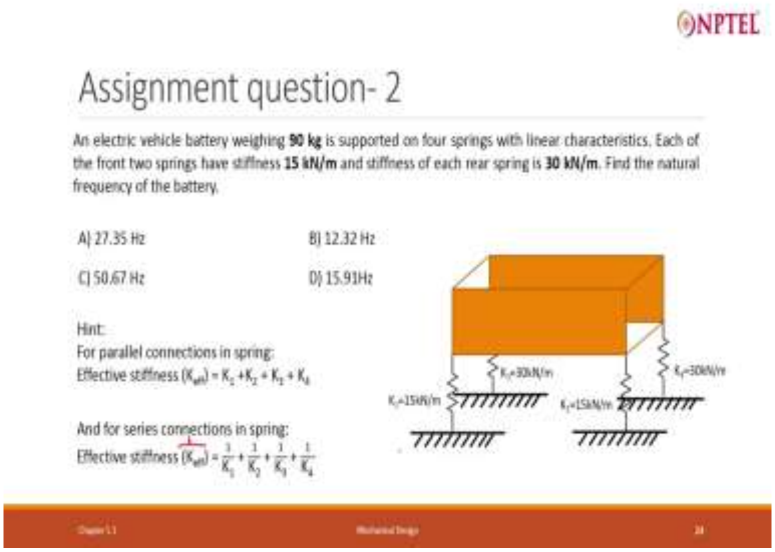

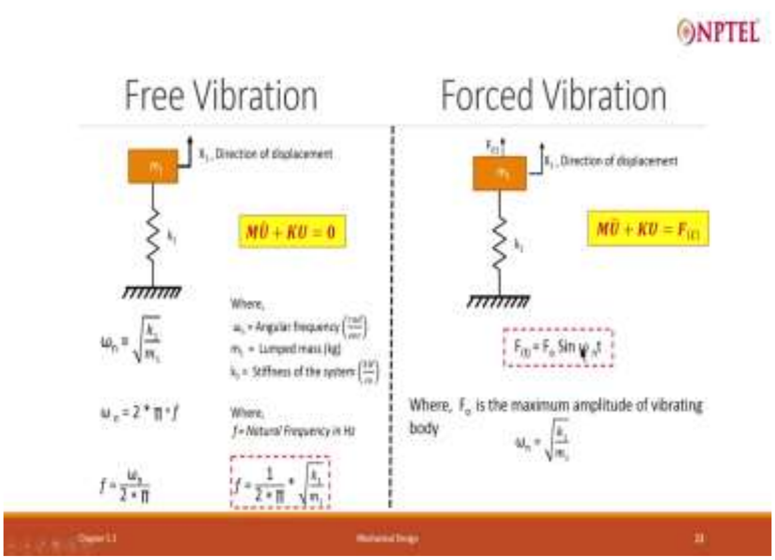

So, what I am saying here and electric vehicle battery my battery weight is 90 kg, so what is m is 90 kg supported with 4 linear, 4 spring with linear characteristic, so either you put rubber pads or you put vibration isolator, so this vibration isolators are nothing but it will have a spring dashpot arraignment, so it can damp but what I am saying you damping terms I am removing here, just for simplification.

So, there is four spring attached to it, even in bike if you see in the front there is a spring and there is a viscous damping by some fluid, so you do not get the same force applied to you it will try to damp, the each spring has the different stiffness you see k1, k2 is same k3 and k4 are same.

So what is the natural frequency of the battery means at what frequency the battery will oscillate?

Everything in the universe is oscillating, only thing that we do not know what frequency we have to we measure and then we find out, see here you have a spring the battery pack is kept over four spring of different stiffness, we wanted to know what would be the natural frequency. What we have to do? So, remember again parallel and series connection of electrical resistance, effective stiffness in parallel is nothing but the sum of the stiffness.

Effective stiffness in series is nothing but 1 by k1 plus 1 by k2 plus 1 by k equal to 1 by k1 plus 1 by k2 here it is 1 by k. And from here now this springs are in parallel or series you have to find out what it is, once you have find out find out 1k equivalent. Then use the equations here, angular frequency is root under k1 by m1, M you already know 90 kg and then you find out the natural frequency F, that is what is this problem about.

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Now, test standard, what are the test standards we use for our automotive application in India, I am talking about India. So, basically we use three test standards, one is harmonic vibration test standard that is nothing but AIS 048 2009, but second standard remain same but we also use for shock abuse test the same standard AIS 048 2009. And for random vibration we use SAE J2380 in India mostly. If we are able to pass these three test standard we can get the certification that our by our battery pack is good enough to move on the road, mechanically.

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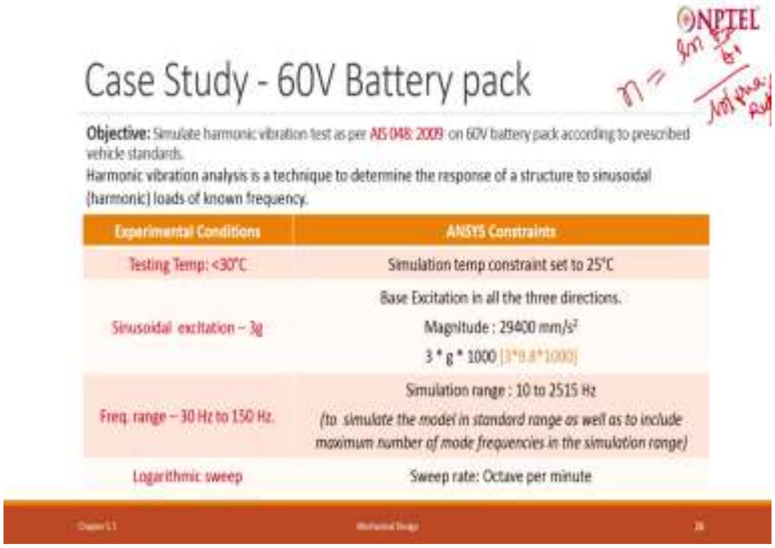

Now, I will show you one of the case study done on the 160 volt battery pack which we have already designing which we have designed in the mechanical section. So, what is our objective? The simulate harmonic vibration test as per the standard AIS 048 2009 on a 60 volt battery pack according to the prescribed vehicle standards. As I just said earlier the harmonic vibration and analysis is a steady state analysis, steady state response of a structure subjected to sinusoidal loads.

Sinusoidal load is what? F is equal to F0 Sin omega t, the F0 remains content omega remains constant and then it keeps on going in time but even though it is known as the steady state because force is in sinusoidal form that keeps on repeating, the number of cycles 5 cycle or 10 cycle or 20 cycles or 30 cycle, so its basically gives us a steady state response.

What are the test condition? Generally, the testing temperature has to be less than 30 degree, in simulation, you can set up any temperature 25 degree, 10 degree, 15 degree or what is sinusoidal excitation? It is of 3G, G is nothing but acceleration due to gravity. So, the base excitation in all the 3 directions should be 3G and that what magnitude comes out 29400 mm per second square, 3G into 1000 that is what, the frequency range, what frequency range we are looking for?

As per standard, it is between 30 hertz to 150 hertz, but if you see the components generally this 30 hertz to 150 hertz would not be sufficient, you may not get even a first natural frequency between this range, so generally during the test as well as simulation we extend it to the larger range or larger frequency.

Then logarithmic sweep, sweep rate octave per minute. What is octave? Octave is the way to select the frequencies, that on because it is a very difficult to do, do either test or simulation on all the frequencies, so very difficult. So, we select a frequency in some particular manner on logarithmic scale, so if I am saying 1 by 1 octave that does mean from 30 hertz of 50 hertz that I will select a frequency of 30 hertz, 60 hertz and 120 hertz.

The formula become like this octave number n is nothing but ln f2 by f1 divided by ln frequency ratio, so where f2 is the upper frequency limit, what we have upper frequency limit here? 150 hertz and f1 is lower frequency limit, 30 hertz, now octave or ratio frequency ratio we want to go by 1.25 or 1 or 1.4, accordingly we will select the frequency.

So, for 30 hertz if I have to go 1 by 1 octave in that case I will select 30 hertz, 60 hertz and 120 hertz from this equation, the equation what I have talked. If I have to go 1 by 3 octave then I will select 31.5 hertz, 40 hertz, 50 hertz, 63, 80 and then 125. So, this sweep rate or octave is nothing but instead of selecting all the frequency like 30 hertz, 31 hertz, 32 hertz, we select particular frequencies only, so that its takes less time to either test or simulate and is the scientific way of doing this one octave per minute.

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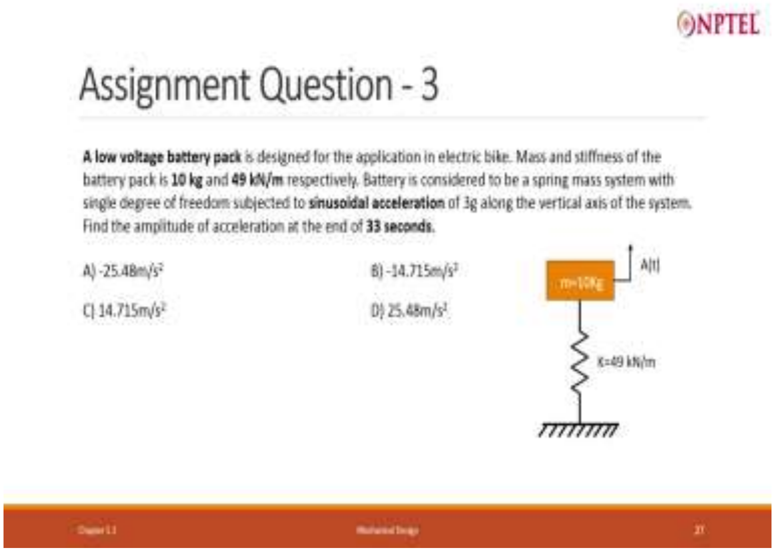

Now, I will give you another question which we have talked just now sinusoidal acceleration of 3G, forced vibration, my battery pack mass is 10 kg, spring stiffness 49 kg, sorry 49 kilo Newton per meter, single degree of freedom and the sinusoidal acceleration of 3G find the amplitude of acceleration at the end of 33 seconds, so what you have to do? You have to use the equation F equal to F0 Sin omega t, t you know, you know the mass, you know the k, so you know the omega you also know F naught that is 3G, 3G is basically acceleration, so you need to convert into F0.

So, what would be the amplitude of acceleration at the end of 33 seconds? So, you know t, you know F naught, you know omega, so you have to find out F, from the equation F equal to F naught Sin omega t. Since in harmonic we have used 3g acceleration so that is why this problem has come up here that is the force vibration.

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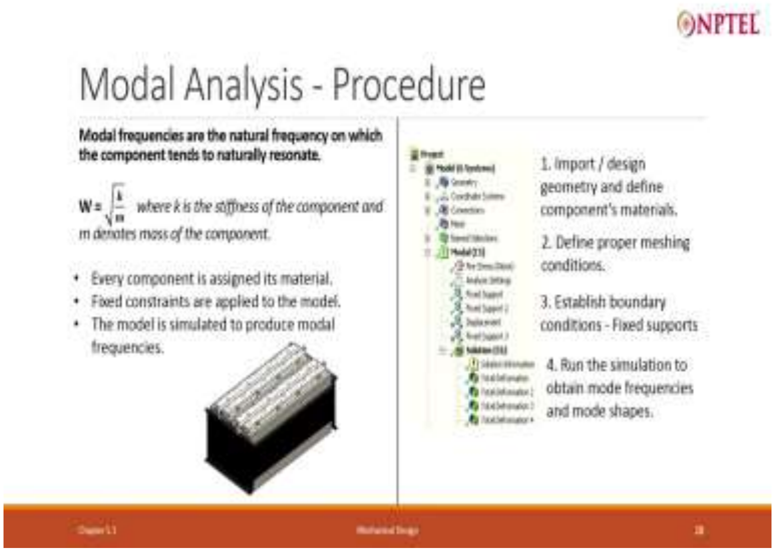

Now, modal analysis procedure; so as I discuss modal frequencies are the natural frequency on which the amplitude becomes maximum. So, in a set of in a frequency range, we find out what are the frequencies which tend to be natural means tend to be the natural frequency because what we are interested is the maximum deflection or maximum amplitude, how do we do a simulation or even a test?

So, every component is assigned its material, now in battery pack what we have seen, we have 7 components, we have end plate, we have base plate, we have side strips, we have bus bars, we have sensors, we have wiring harness, each has a different material, now there are constraints like if I want to put the battery pack somewhere so I will have the holding points or fixing points, so those becomes constraints that it cannot move in this direction.

Then we simulate to find out the modal frequencies, that so basic of a modal analysis, how it is being done in any of the software? First what we do, first we import the design, CAD design, we clean up that means if there is any discontinuity between the surfaces or if there is very-very sharp bends we try to make it a smooth, then we mess it, we convert the whole pack into a small-small elements, we provide the boundary conditions and then we run the simulation to find out what would be the frequency, either you use Ansys or you use Ebika the procedure remain same. Shall move to the next slide?

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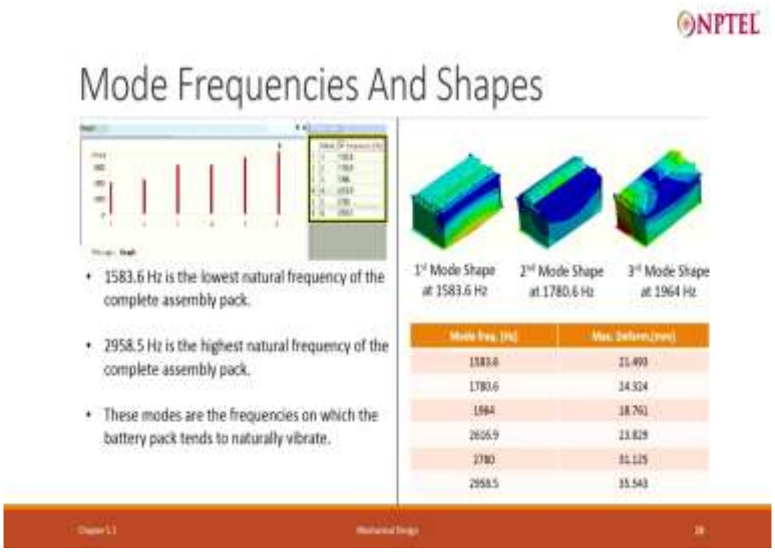

What we have tried the frequency between 1 to 2500 hertz, so what we are finding that we get the frequencies 15.8.36, so 1583.6 hertz is the lowest natural frequency we are getting, so in 30 hertz to 150 hertz we did not get any natural frequency and what we are interested that where would be the natural frequencies because at natural frequencies amplitude would be the maximum, the deflection would be maximum, deformation would be maximum.

2958.5 hertz is the highest natural frequency, so these are the modes where battery tend to vibrate naturally that means the amplitude would be maximum. The mode shape, mode shape what I am saying is after the deformation or the maximum amplitude maximum amplitude is nothing but it is a deforming how the battery is deforming.

So, when it is deforming? Where they stress would be maximum. So first mode shape at 1583.6 hertz, second mode shape at 178.9 hertz, third mode shape at 1964 hertz and you see the corresponding deformation we have also found out, but this is not at the base plate only it could be for anything.

However, my criteria is only 30 hertz to 150 hertz, I am going beyond the my criteria, we have selected a 5mm thickness there based upon that local criteria of 30 hertz to 150 hertz let us suppose. However, here frequency range is very high, my deformation the maximum deformation in whole pack is coming around 21 mm till 35 mm for the maximum frequencies what we have selected.

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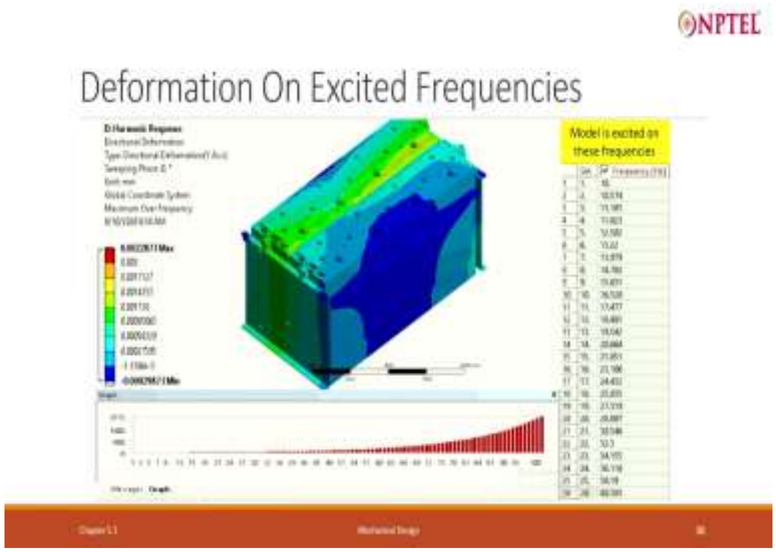

Now, once we know that then we need to know the deformation on excited frequencies, again, this what you are seeing is octave, we are not going for continuous frequencies we are going either 1 by 1 octave or 1 by 3 octave, we are not selecting all the frequencies, we are selecting some particular frequency by the octave method.

And then we are finding out the maximum deformation. And then stress developed because this is the stress which will give us the allowable stress that my material is going to be fail or not. This particular simulation has been done in Ansys. However, any software like Ebika or some other software the process remains same.

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So, with this I have finished my mechanical design, what we the I would like to summarize, so the mechanical design of battery pack lead to safe cost effective which is lightweight as well as highly reliable. Various factor what we have considered during the design of battery pack material selections, loading, a base plates, end blade, side strip, bus bar we have just discussed we have not gone in detail, in other section not as a mechanical, but when we will be talking electrical part, there we will talk in detail about bus bar may not much mechanical, but still we will talk.

What also we need to do bus bar and outer casting development? Base plate and end plate either we solve Kirchhoff equation for thin flat plate or we use the direct stress strain formula books what I had use is Rook book you can use any other books. We have also discussed what is free vibration, what is the force vibration.

The free vibration the external force is 0, in the force vibration we have a external force if that external force or excitation force or response function is not known then it is known as random vibration, if it is known then it is no deterministic vibration. In deterministic vibration what we have talked again harmonic transient and the spectral, we have also talked the different test standard. In India we use AIS 048 and SAE J 2380, any question you can if somewhere you have not understood I will try to explain back.

So what we have done, what we have done basically we have started from the battery pack development there we have defined the 4 categories; electrical development, thermal development, mechanical development and the BMS development, this is a 4th part of the battery pack, then we have try to understood the importance of all these force; electrical, mechanical, thermal, as well as BMS. And then we have a started the mechanical how to do the mechanical development of the battery pack.

In the mechanical development of the battery pack we started designing the base plate by considering the number of cells from series and parallel connection and then we have also try to work out the end plate and the side strip calculation then we move to the vibration, we have sorry, we have also done the material selection SB methodology, a nice methodology for the cost weigh and the strength optimization.

Then we have moved to vibration analysis where we have discussed different type of vibration. Random, transient, harmonic and spectral method basically divided into 2 parts. Then next we have defined the free vibrations and force vibration.

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Then we have gone for the different standards what we use in India AIS 048 and one SAE standard J 2380. We have done a case studies the battery pack which we were designing of 60 volt that we have done a case studies where we have tried to see the modal analysis, deformation and the maximum stress. And with that we have ended our mechanical development. The next portion would come as a thermal development of a battery pack.

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The question was can we harness the vibration? We can do, but that is a again very special design and which we may not like to do it here, there are methods like piezoelectric and some other materials where it converts into electricity or something, material remains same. See what happens in a okay in any development process, it is always go two a steps ahead come back one step.

So, initially if I have selected ABS and then it is not able to handle the vibration analysis, so in that case, we may go back look up on the calculations there check that calculation is correct or not, the calculation is correct, is it able have we taken the consideration of this vibration there are not, if not, then we will consider that and then again deselect the material, it may be again ABS or something else.

So, it is, the development process is always iterative process, the first you do some assumptions based upon that you select the material, then you do the test as well as simulation, if it is passing well and good if it does not, because of what it is not passing? My criteria or my assumption, we come back we check again those assumptions we modify those assumptions and next it can go for several iteration, need not to be one iteration, it could be 10 iteration, it could be 20 iteration.

It could be even after the product launch it happens, you come back and change the material because and the product after the product launch your simple size becomes very big. Some of the things which you may not have been able to encounter because of limited sample size, when it goes into the market, now your sample size becomes very big, so it is basically iterative process any design and development is the iterative process, it is a valid for material, it is a valid for software, it valid for hardware, everything.

So, it is not like that one time I have selected that is only truth, it may fail because of the (assumption) because it may encounter something which we have not assumed here and then we come back and correct our assumption, so that it how it works out.