Machinery Fault Diagnosis and Signal Processing
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Lecture - 55
Experimental Modal Analysis

Well in this lecture we are we had discussed something on experimental model analysis. The fact that you would have seen that in during machinery condition monitoring many components will come under resonance because they are being excited at a frequency which happens to be their natural frequency. So, as a safeguard to avoid resonance conditions equipment or machineries are not to be run at their resonant frequencies.

So, what is this resonant frequencies and how do you find out experimentally the resonant frequencies mode shapes and their damping associated with this resonant frequencies is what we are going to discuss in this lecture on experimental modal analysis.

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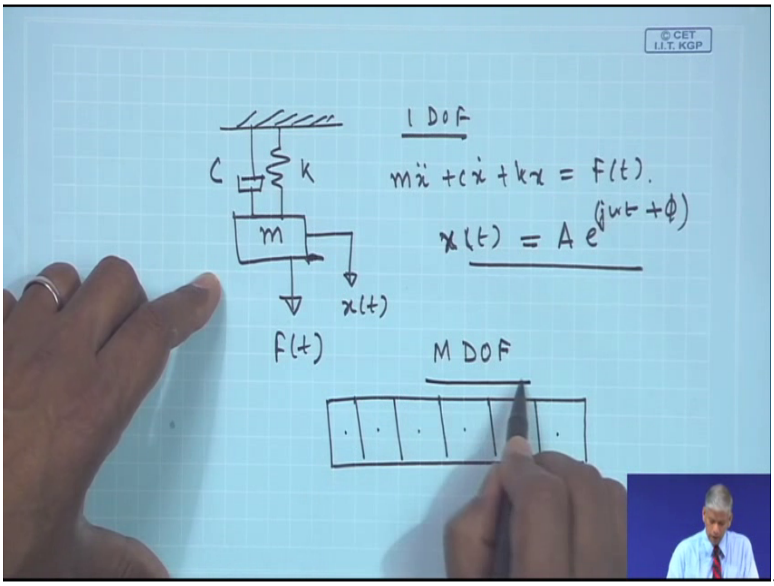

So, we have to determine natural frequencies, modal damping, mode shapes. Now if you consider a dynamical system for example, a mass spring dashpot or damped oscillator.

Now suppose this is excited by a force; so, this body is going to have a response. So, if I write the equation of motion for such a system now this x t of course, depending on the conditions you know I can write it A e to the power j omega t plus some phase difference ok; this can be a form of the displacement. Now when there are when there is a large system; large mechanical system imagine in such a such a system this was the single degree of freedom system.

Where in a body is only allowed to move in the x direction as shown in the figure as opposed to we will have bodies which can be divided into many infinite bodies and I will have a multi degree of freedom system.

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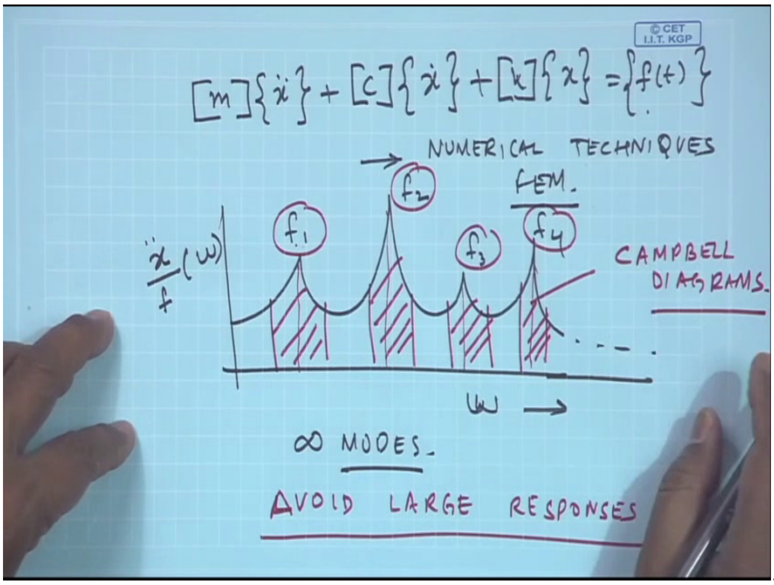

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Now as you would have seen in the techniques of Telamon method I can modal this body as a system given by this matrices. Through numerical techniques I can find out the responses of this body like FEM etcetera and then find out the natural frequency. So if I have a multi degree freedom system and if I look at the response x double dot by the force maybe in the frequency domain.

I will get responses like this; so, these are noting these peaks are nothing, but the resonant frequencies f 1, f 2, f 3, f 4 and so, on. So, there will be infinite modes and each one of them is a natural frequency. So, in machinery condition monitoring on machinery operations; we always avoid in the machines and these frequencies. Imagine the forcing function which is an external force is exciting the body at f 1, f 2, f 3, f 4; it will have large responses and this is what we have to avoid we have to avoid large responses.

So, designer would have taken adequate care in the design. So, that these frequencies are known beforehand and we may say that these are the safe operating zones and you avoid operating in frequencies around there are known frequencies. And this is what would have seen in rotor dynamics in CAMPBELL diagrams. We avoid operating at the resonant frequencies on this CAMPBELL diagrams plot and the natural frequencies versus the operating speed and the modes of the system.

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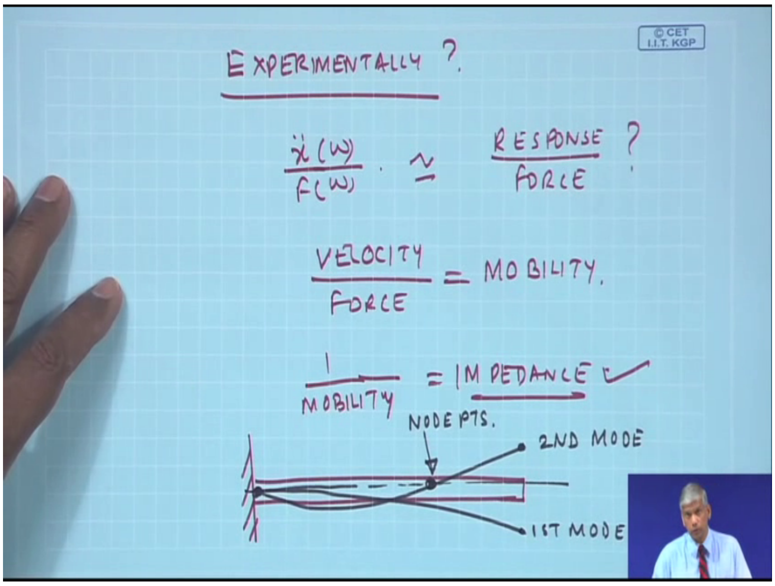

But question is how do we find experimentally these conditions? As you would have seen this response x double dot by F both in the frequency domain this is nothing, but a ratio of the response to the force to the force.

Now you would have seen when we talked about response this is response could be velocity by force which we call as mobility or inverse of that is the impedance. And you would have seen when we design a system and if it is mass spring and damping are known we can estimate its impedance.

So, wherever the impedance goes to a minimum we have resonant conditions and we can find out the natural frequencies. Now question is how do I measure this ? So, what we do and then once I know them I can also find out the damping and the mode shapes. For example, if I have a cantilever beam if I consider this cantilever beam to be a continuous system with infinite number of small masses. And I shall model them I will have the first mode something like this. And there is the central line and the second mode maybe this is a node point.

First mode, second mode; so, whenever we have 0 displacements these are not the node points and; obviously, this is a node point and these are all the free ends are the anti node points, but this I have just shown the two modes of a cantilever beam subjected to transverse vibrations. But if then there are many infinite modes the reason modes have help us is to find out the node points and there is a reason why any we need to do that I will give you another example.

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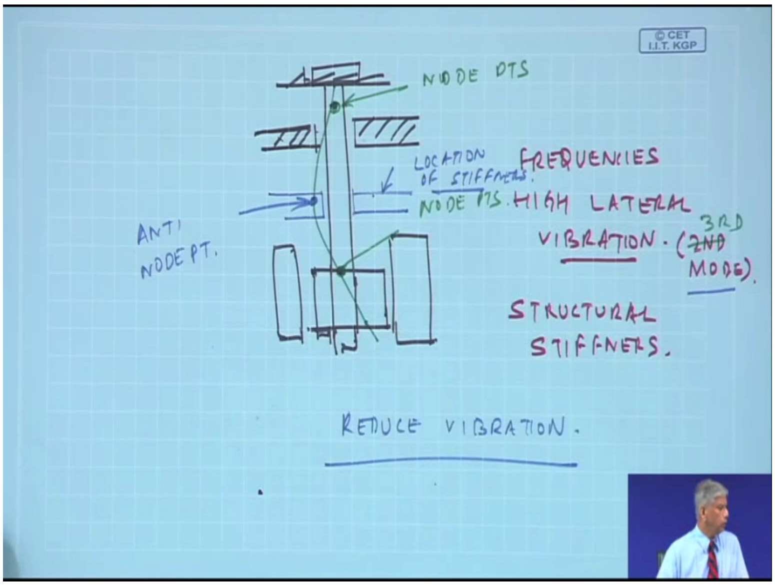

Imagine a vertical pump or a vertical shaft supported on bearing and this contains some rotor mass. And this is in a casing and imagine there are some support bearings and so, on.

So, this can be modeled as a cantilever beam and then the conditions in some frequencies that is high lateral vibrations. So, how can we reduce them? We can put structural stiffness; imagine this high lateral vibration is in its second mode; second mode means second or resonant frequencies. So, maybe the softest motion like this and get ok; in fact, I hundred at the third mode ok.

Suppose these are the node points. So, to erase the and this happens to be an anti node point. So, two errors the high lateral viruses are the anti node points; I may have to move some sort of a stiffener or bearing to this location. So, that will there as the vibrations; so, location of stiffeners which will arrest the lateral moment. So, modes has practically help us locate the stiffeners to reduce vibrations; well the first place we need to find out methods to reduce the vibration.

So, that we never operate at the modes, but even if for some reason we operate the machine at its resonance. We can remove certain of these resonances and vibrations are high frequencies by putting stiffeners around or near the anti node bonds. Now experimentally let us see how this is done.

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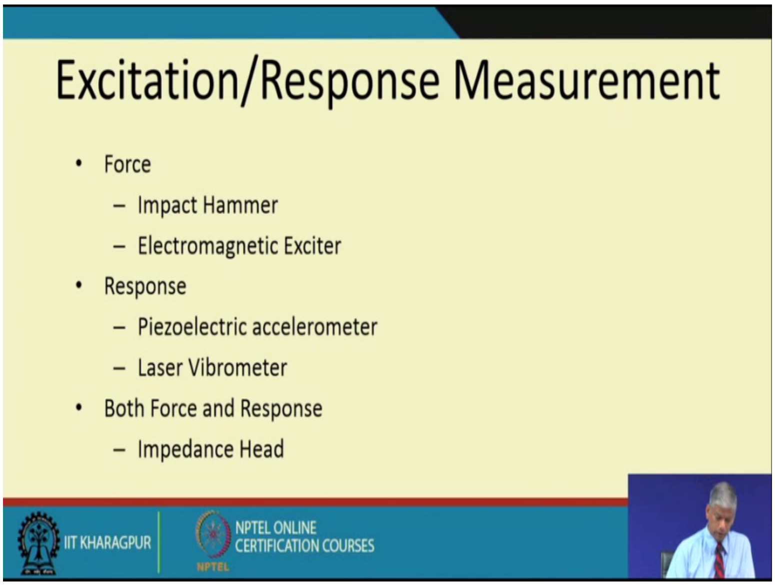

So, to measure the or export excitation and response to apply force; we can have an instrumented impact hammer or an electromagnetic exciter.

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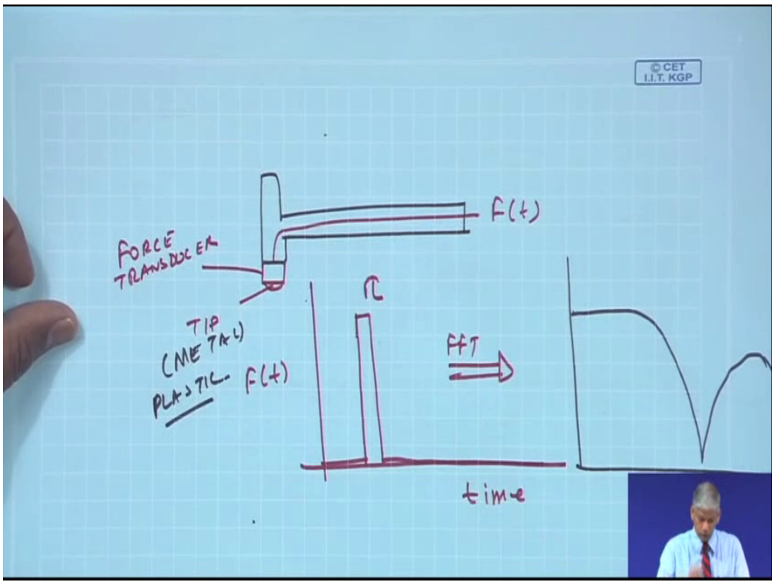

So, this hammer actually nothing but looks like in hammer and here on the tip we put a force transducer and there could be a some tip material and of course, we have the cables to give you a signal F t.

So, if you look in the time domain response of this force in time; this can be model as a step impulse of certain duration tau. Now if I do an FFT of this in the frequency domain it may look like this maybe I will draw another sheet and the frequency domain and so, on.

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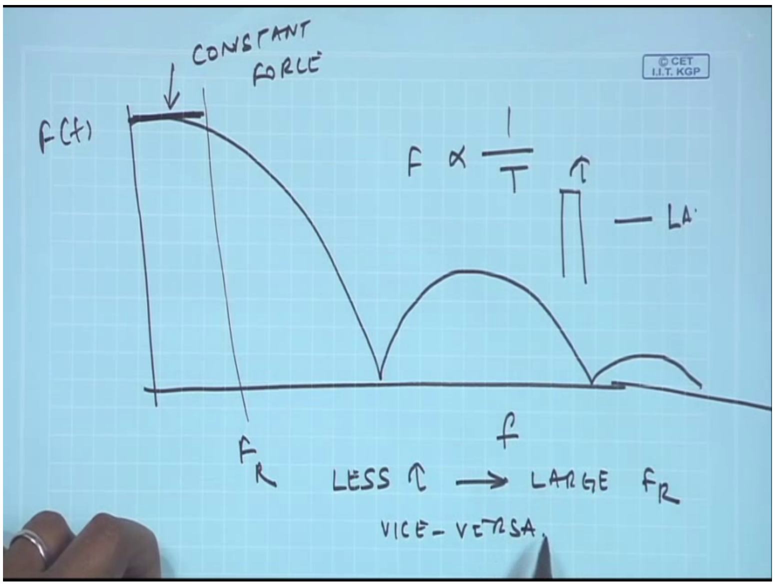

So, it is this to a certain extent; it is this is my frequency range of extradition. So, this is a flat force constant force as you know the frequency is inversely proportional to time. So, less time means more of this force and then what will what is going to happen is if the pulse duration tau is less, I will have large. So, less tau corresponds to large f r and vice versa.

So, that is why this tips which are available in force transducers can be of metal. So, that metal to metal the tau is very less or it could be soft plastic etcetera such tips are there. So, the idea behind force transducer is quickly I mean this hammer instrumented hammer its quickly I can excite of system up to a particular frequency range and where this is flat.

So, now any response which I will I will come to that. So, basically I am generating frequencies till F R by giving an impact.

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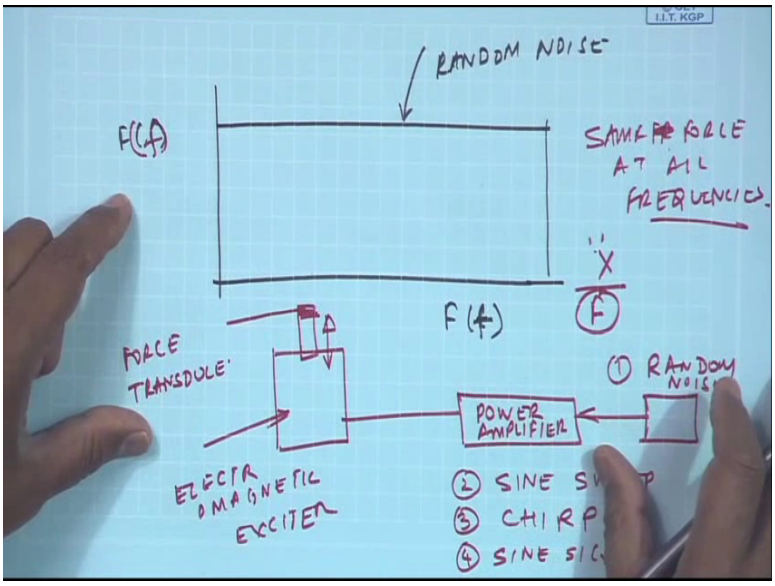

Another method of excitation is this electromagnetic exciter wherein I give a random noise and this is generating a flat frequency to a large extent. So, there are commercially available electromagnetic exciters which will be having a power amplifier to which I can give a random noise.

And this is my electromagnet on to which I can put a force transducer; the purpose is the same. So, basically I am through this random noise I am exciting the structure by a force which contains large frequencies and which has not same force at all frequencies.

Same force at all frequencies. So, since this is at the denominator and it is a constant force wherever the resonance or where their response is high it means its resonance because it is X by X dot by F which you are measuring and this happens to be a constant. So, wherever X dot has a peak it would correspond that it is resonance.

So, some of the signals which are used in such excitation one is random noise other is a sine sweep or chirp signal; these are some of the signals which are used which could be generated out of a signal generator and they will be amplified and they will be driving an electromagnetic exciter where this is going to vibrate at all these frequencies and then you can excite the structure. You can also I mean you can give it any signal, you can also give a sign signal, but only problem is if you give a sign signal it will only excited one frequencies.

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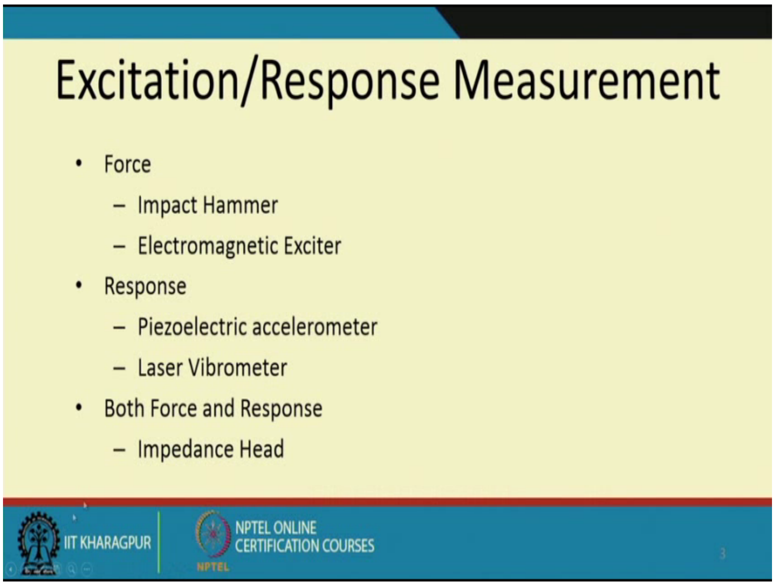

So, in summary; to give forces to a system I can whether I can either have an impact hammer or an electromagnetic exciter.

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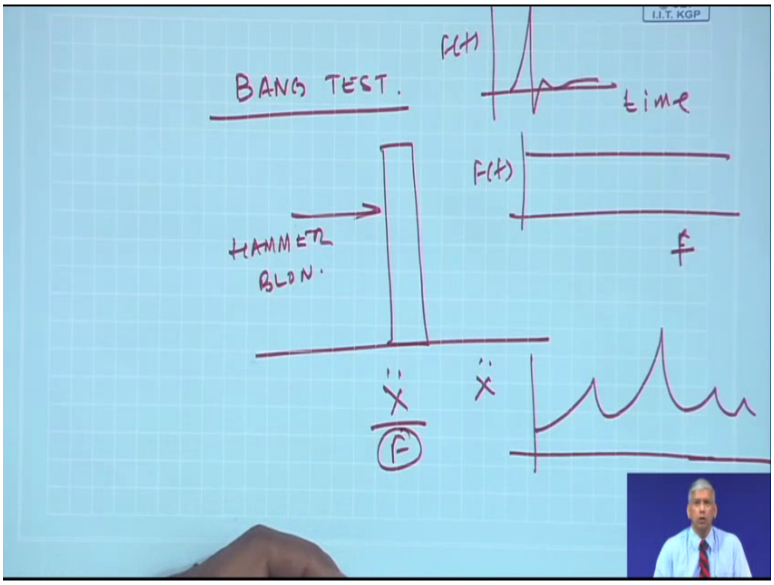

And you must have heard what is known as a bang test bang test is you know we just excite the structure with a blow; a hammer blow. Basically this means what? It is giving an impulse and in the frequency domain an impulse would look like a flat response. So, if I am measuring X by F and if this happens to be a constant.

So, just by measuring an X dot I can find out the resonance. So, in the industry they quickly use a bang test or a boom test to find out the resonance; where we do not require instrumentation to measure the forces.

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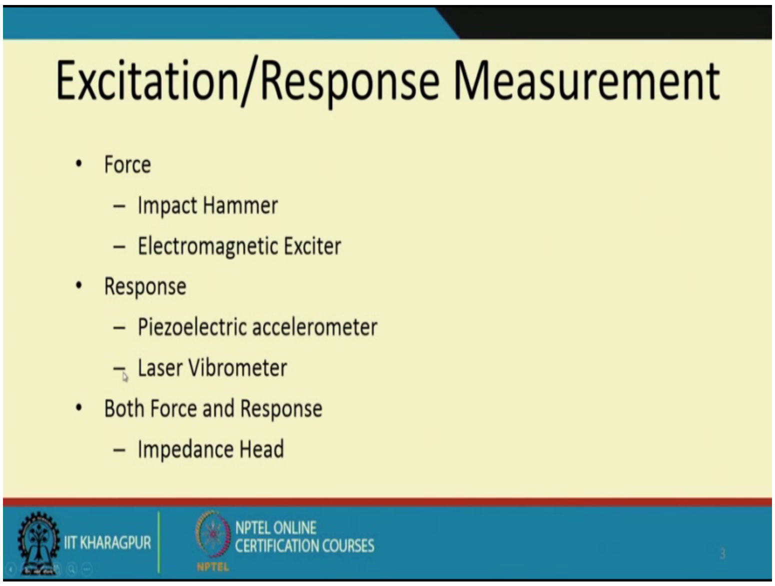

And of course, the response as you know we can measure by vibrations and the best way to measure vibrations is a throughout piezoelectric accelerometer.

But if the structure is very light very delicate, a heavy piezoelectric accelerometer would load this structure. So, we can use something what is known as a laser vibrometer where if we can focus laser vibrometer and measure the velocity by laser vibrometer.

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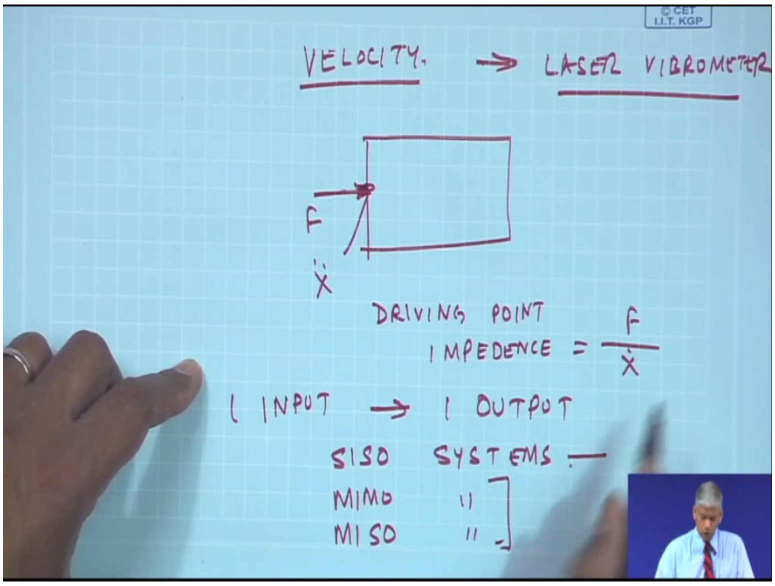

And we had seen this in one of our earlier lectures, but sometimes it happens in this structure when you are exciting. Because at this point on the structure where I am applying force; I can also get the response x double dot.

So, if I have a transducer close to this I can measure both X dot and F and that is known as the driving point impedance is nothing, but F by X dot, but then you know if you measure X double dot you can always integrate and get X dot such is required. And such systems where, the input is 1 input and 1 output; these are known as single input. single output systems.

Sometimes the systems are large I can have MIMO systems multiple input multiple output systems; or multiple input single output systems ok. So, this is there and then we can modeled it and so, on.

So, I am talking about SISO system signals and you all know we need to.

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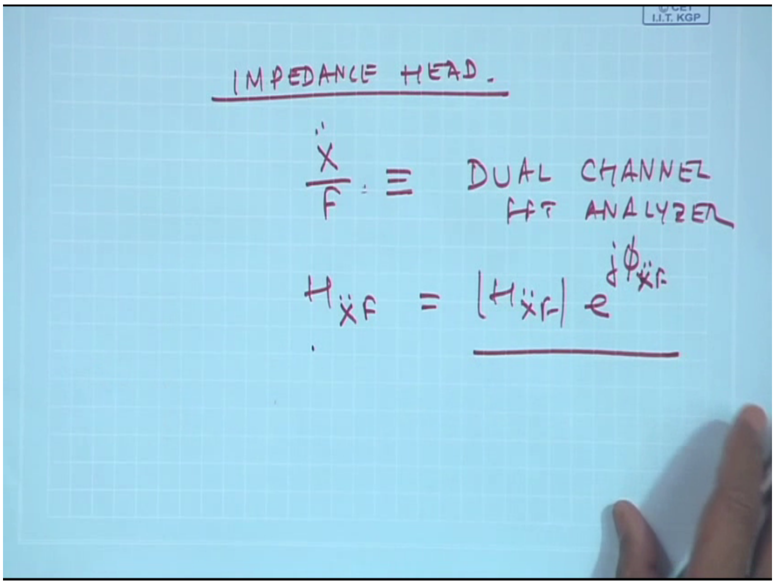

So, such transducers are used which can measure both acceleration and force at the same time and these are known as impedance head ok. So, we require either an impedance set or separately a force transducer and an accelerometer.

And then once we measure them question is how do you measure X dot by F. So, this has to be measured by a dual channel FFT analyzer. And this will measure the transfer function between HX dot and F. So, which will have a magnitude and of course, the phase.

So, this is a complex quantity; so, we can get the responses sort of X by F and sometimes to this is an experimental view; so, this is the DUT Device Under Test.

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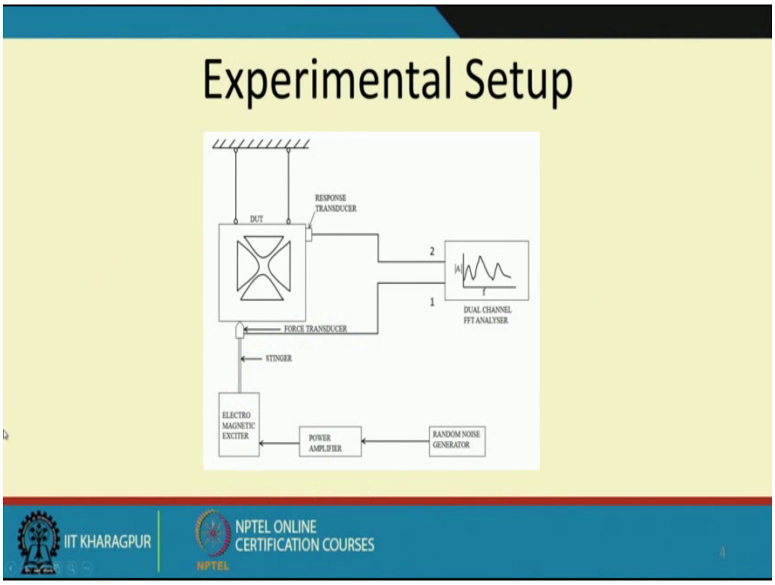

Sometimes through similar trail conditions we can hang them by strings, they are simply supported or they can be put on air cushions etcetera. So, this is my response transducer and this is the random noise generator instead of random noise generator; I could have a sine sweep, I could have a sine signal I could have a chart signal.

Because the signal needs to be amplified to drive the electromagnetic exciter, I need to have a power amplifier on to which is a thin number stinger which ensures that the force only goes in this direction because as you know the responses of dynamic systems are very directional.

So, I can measure X by F, I can move around this transducer and I can fix this force at one location or I can inclined in to excite many modes. And this response transducers could be roved around; that means, they are roaming and at each location I can find out the transfer function between response and force. And from the peaks of the transfer function or the change in the phase angle at the transfer function; I can identify where the resonant frequencies are.

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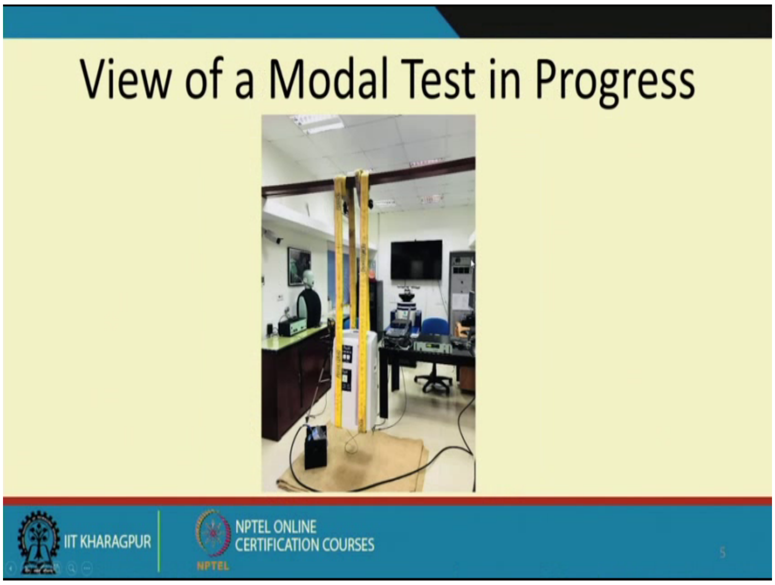

And this is just to give you an example of we are doing the model testing in our lab of a portable air conditioner. And if you will see here there is an dual channel FFT analyzer; this FFT analyzer has a signal generator which is feeding this power amplifier here.

From the power amplifier you can see the thick cable which is exciting the we feeding the electromagnetic exciter. And if you can see a stinger thin wire here and as a force transducer; so, we are means a given the force and this portable air conditioner is suspended from the ceiling by a flexible belt or fabric kind of belt here.

So, that we stimulated and at this end you can see a laser vibrometer which will be moved around to measure the vibrations. So, this is how a typical model test is done and some of them these structures are very large in number this is number of measurement points are very large in number and there are automated systems.

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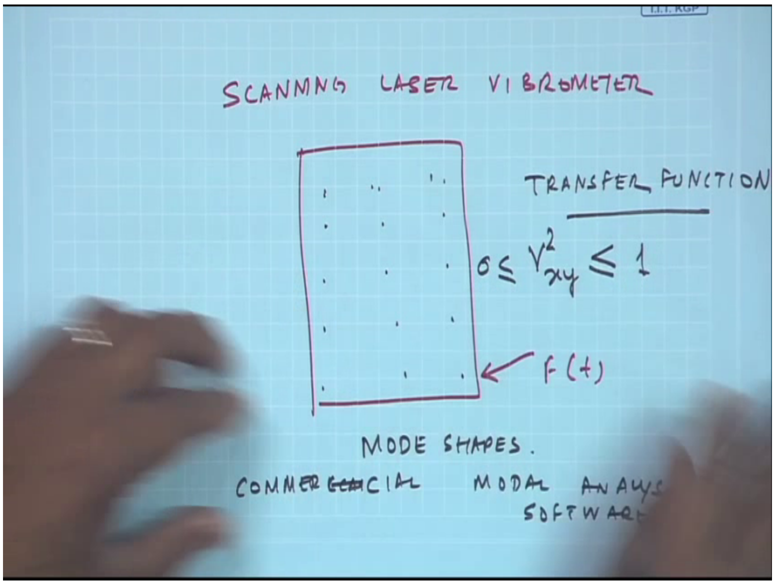

There are scanning laser vibrometers available. So, in one go suppose I have a panel and I am exciting it by some force F t. So, in one go it will measure the responses at all locations with the right phase reference keeping one as a phase reference and then you can get a entire picture of how this surface is vibrating.

So, from the basically the analysis of the transfer function; we can find out the resonances and this is how typically it is measured and this requires an elaborate setup. So, in the industry when we do not have such a system people resort to what is known as the bang test for the obvious reasons that the autocorrelation function of an impulse response is a impulse function is a flat response in the frequency domain; that means, the denominator is constant.

So, whatever is the response I measure I just put a bang and immediately I see the natural frequencies by the FFT of the response and this is what is very useful in the industry.

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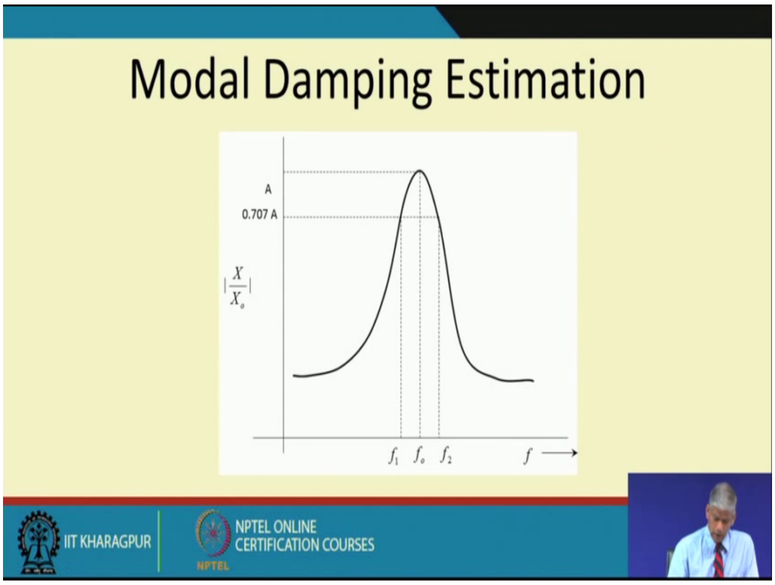

So, another important parameter and of course, you know by having the displacements at all locations; I can plot mode shapes. And today there are many commercial modal analysis software to do this.

So, once you have the measure data they will do nice animation of how the plate is say vibrating at its first mode. And another thing I must live when we are measuring transfer function, one has to keep the keep into account the coherence function. So, it is good that the coherence function their measurement is good.

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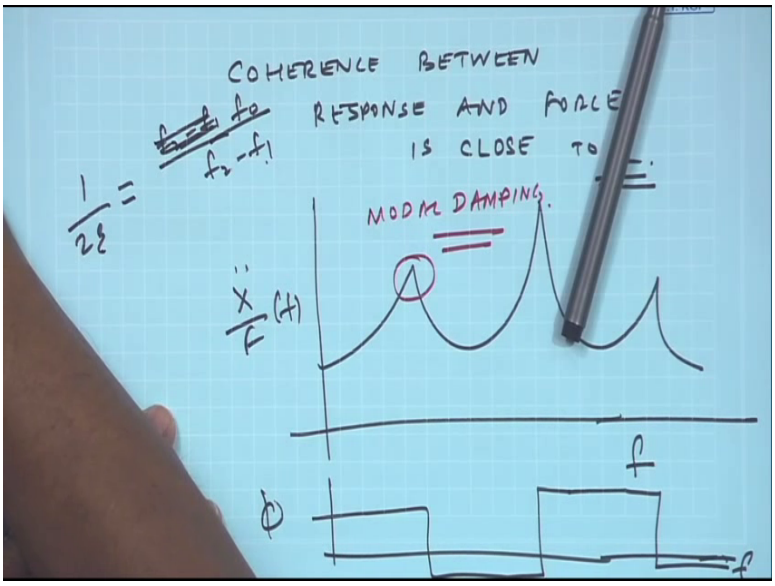

If your coherence between response and force is close to 1; so, you know you are doing a good measurement otherwise the effect of noise etcetera comes into play and then we will have a lot of problem.

So, basically from an F R F or the transfer function we can find out the and of course, you have to look correspondingly at the phase angle also and how they will change at 90 degrees. And you know how we can estimate damping by the half or damping method you know.

So, we can find out at every peak we can find out the damping and then these are the modal damping parameters by this response. So, we can have the 1 by 2 zeta is equal to f 2 minus f 1 sorry f naught by f 2 minus f 1 ok.

And then, we can find out zeta where we measure the peak amplitude and at the location point seven not seven we find out f 1 and f 2; so, this is also done. So, in by measuring the transfer function and we can find out the resonant frequencies looking at the phase angle and also by plotting the displacements or the responses at all the points around the body we can animate the mode shapes and at every resonant frequencies we can also find out the modal damping.

And this is essentially is done so, that to the operator we give safe guidelines as to what are the frequencies at which them will not or they must not operate the plant. And this is what we will discuss when we talk about vibration monitoring and paper mills in next week and then we will see the significance of natural frequencies.

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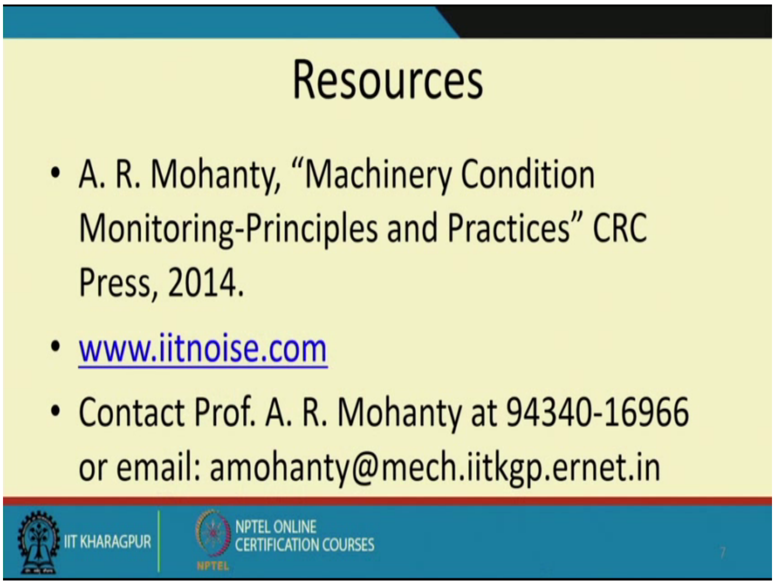

So, there is a rest of this you can find in my book.

Thank you.