Machinery Fault Diagnosis and Signal Processing

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Lecture – 06
Basics of Vibration

Well, this week we are going to focus more on basically vibrations. As you know in the initial lectures I have told you in machinery condition monitoring 70 percent of the troubleshooting or the fault identification is actually done by monitoring the vibrations produced by these machines. Well vibrations as you know is almost a 40 hour lecture in any undergraduate curriculum in an institute, but you know we are going to give you the basics in about you know which time about 2 to 3 hours of lectures and we will be demonstrating to you and showing you how vibrations is useful for machinery condition monitoring.

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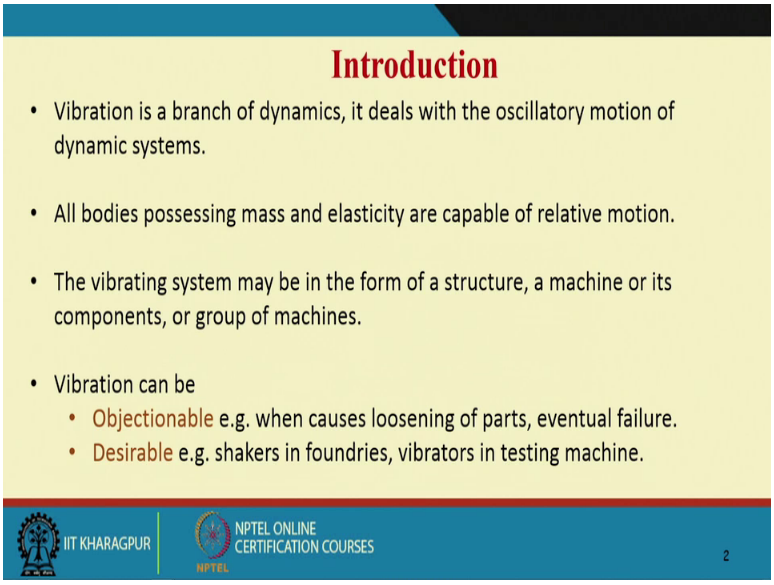

As you know vibration deals with the oscillatory motion of any system, so when I; before I go into the vibrations I will use some basic definitions or ideas. For example, if when I say a body this body is in space this body could be small big it is a material, but if this body is predominantly made to have motions, rectilinear motion in xyz and directions which are independent and rotations about xyz I will have this body has 6 independent directions of motion and each such direction is known as a degree of freedom.

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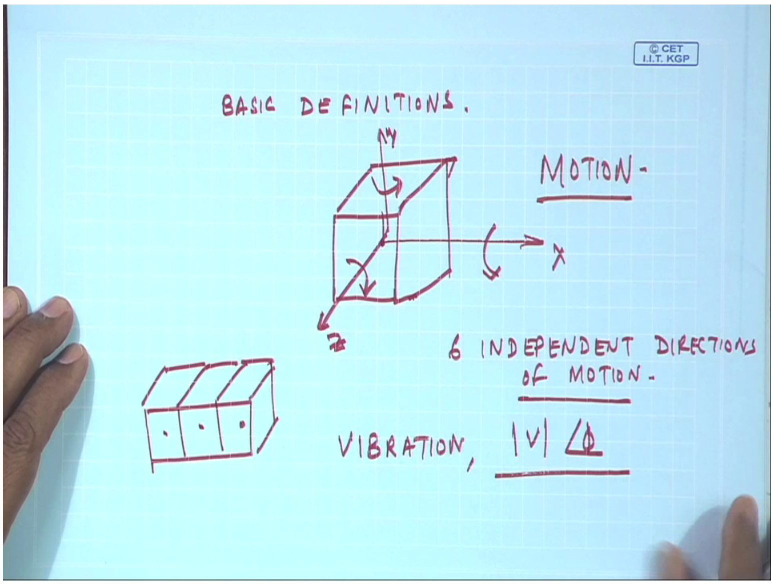

So, vibration definitely comes with a direction. So, vibration is a vector quantity. So, it has both magnitude and also phase. So, we will consider vibration in many a times as to whether we will have a body where we can divide into many small masses. So, this division is up to us. So, I can have theoretically infinite degrees of freedom in which this body will have motion. But it is this motion of this body which is about a mean position if you think of a pendulum, this, it is mean position, but then this pendulum will oscillate and will have a to and fro motion.

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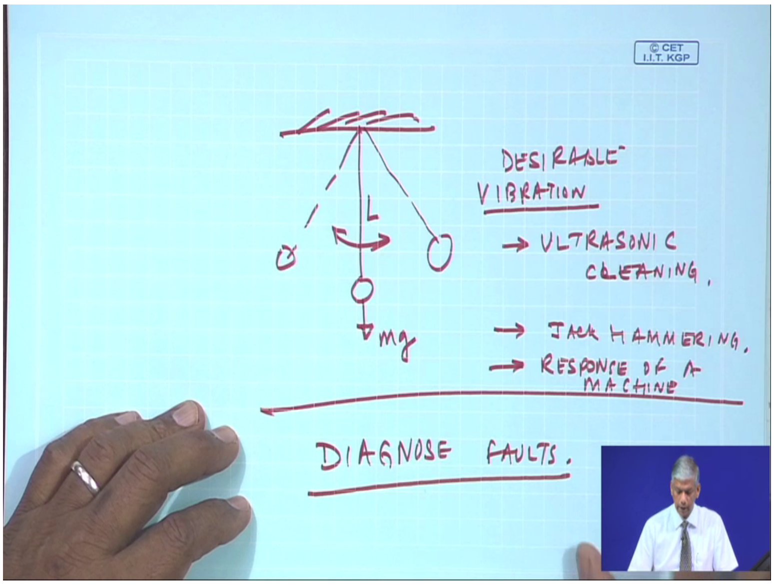

So, this is nothing, but this pendulum is supposed to have an oscillatory motion. So, all bodies possessing mass and elasticity are capable of relative motion. The vibrating system may be in the form of a structure machine component or a group of machines right, but vibrations can be objectionable that is it causes failure by fatigue etcetera. And sometimes we use vibrations for our help vibrations are desirable what are the desirable vibrations any practical examples are there, for example, ultrasonic cleaning of components, jack hammering etcetera. Of course, the most important thing in terms of condition mounting is response of a machine, machine in order to diagnose faults.

But then there is lot of undesirable vibrations as in vibrational clause fatigue failure, will create human discomfort and so on. We will discuss this in one of the later classes and show you examples practical examples where vibration is desirable and vibration is desirable.

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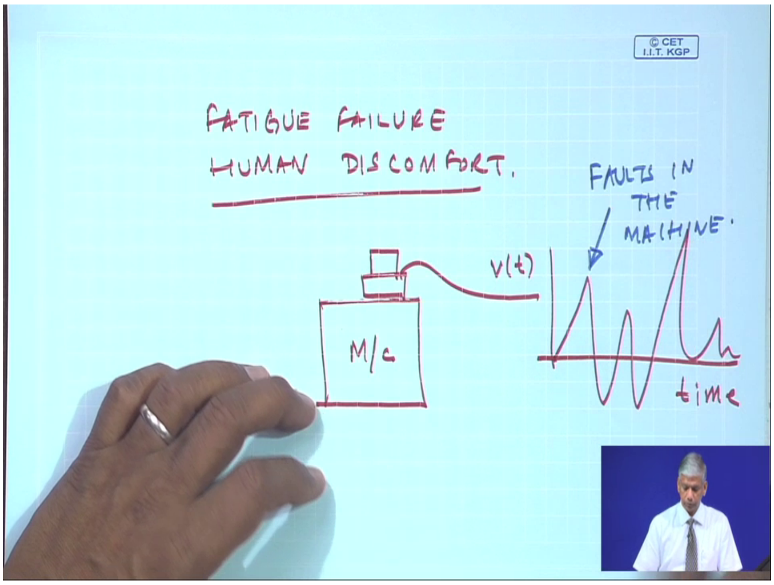

But in machinery condition monitoring we have a transducer on a machine and we get this vibration signal v t something like this. So, it is by analyzing this signal which we will discussed the techniques of analysis later on we can find out what is the faults in the machine.

But one thing I must tell you when I draw a body if I consider this to be a rigid, so all the motion is about its center of mass. So, I can relate the vibration of the body of the motion is the body of about its center of mass, but nobody in reality is rigid it they can be they are elastic because they have Young's modulus mass they have stiffness etcetera.

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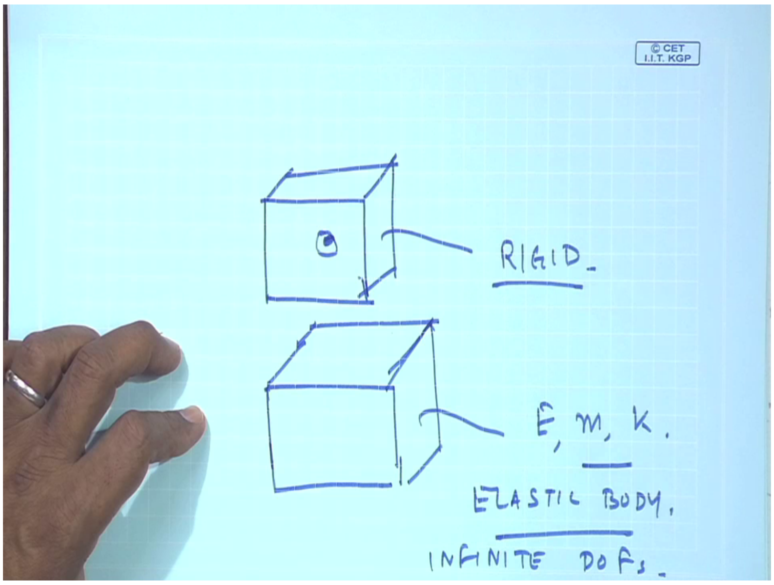

So, in elastic body or body which will deform they will have infinite degrees of freedom for the sake of understanding we will be right now considering the rigid body vibration of a body of mass m about its center of mass.

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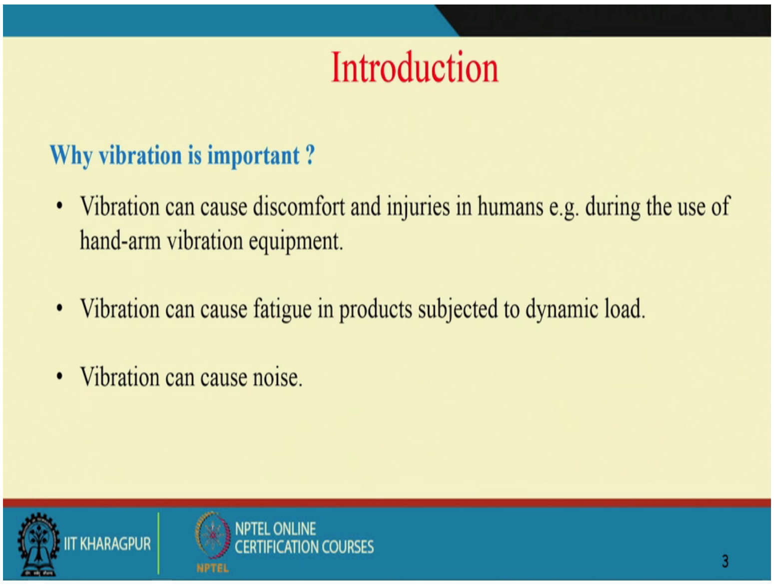

So, why vibration is important, (Refer Time: 07:22) vibration can cause discomfort injuries in humans during the use of hand arm vibration equipment. You must have seen in the people holding jack hammering equipment in order to break concrete etcetera, at their hands they will be exposed to high levels of vibrations and they may have enormous disorder. Vibrations can cause fatigue in products and then they may break or fail; obviously, vibrations in a structure cause noise are a panel like a car body panel.

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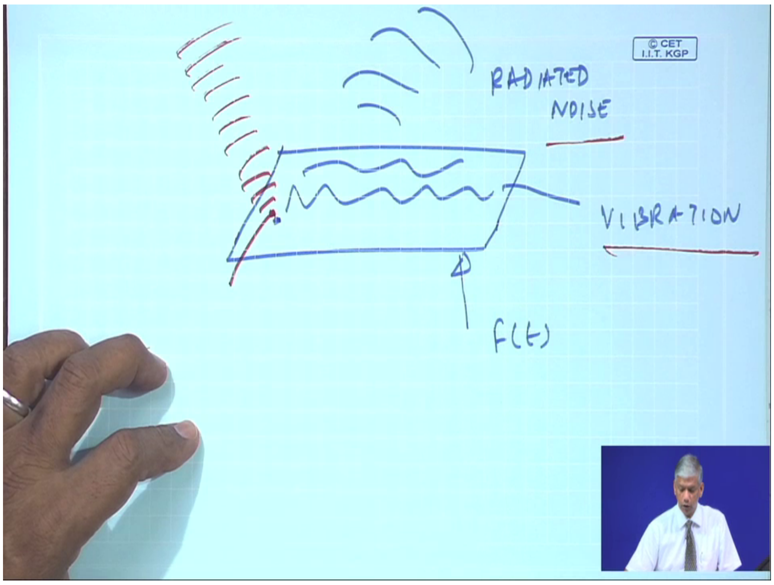

If there is some force there will be vibrations of the surface and this vibration is going to radiate noise, so vibration in radiate noise. I am sure all of you would have experience this, any panel etcetera or in fact, any matter which vibrates will generate certain noise because what happens if this surface as a motion you can imagine the air molecules next to the surface will also have the same motion and once the air molecules are in motion they will generate the wave and this happens all throughout. So, vibrations generate noise. In fact, in many of the noise control approaches you will see people reduce the vibrations to control noise.

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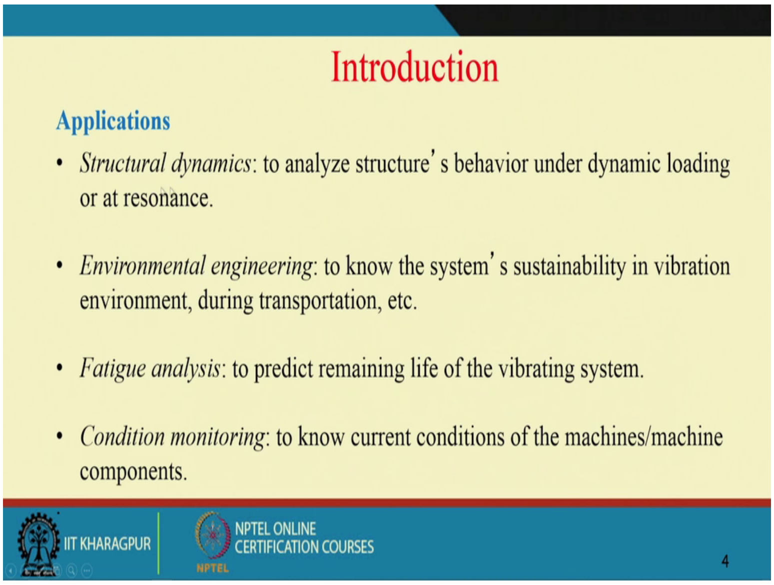

So, lot of application of these vibrations in structural dynamics to understand the dynamic loading at resonance, to know the systems sustainability in vibration environment, fatigue analysis and of course, lastly which is important for us is know the condition of the machine components because of the vibration it is producing.

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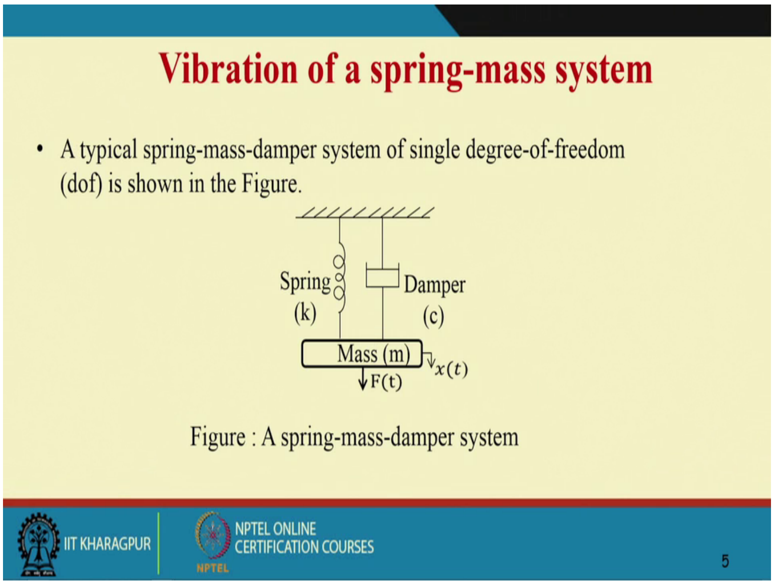

Now, let me take the case of a single degree of freedom system where this is a body rigid body of mass m it is only allowed to move in this x direction as shown here. So, basically though if it was in space it could have moved in 6 degrees of freedom. But I am only constraining the remaining 5 and allowing it to move in the vertical direction. So, this is suspended by a spring of stiffness k a damper of coefficient c. So, if I write and then it is subjected an external force or in the many times I will just give an initial perturbation to this mass and see the motion x. So, this now studying what this motion x looks like.

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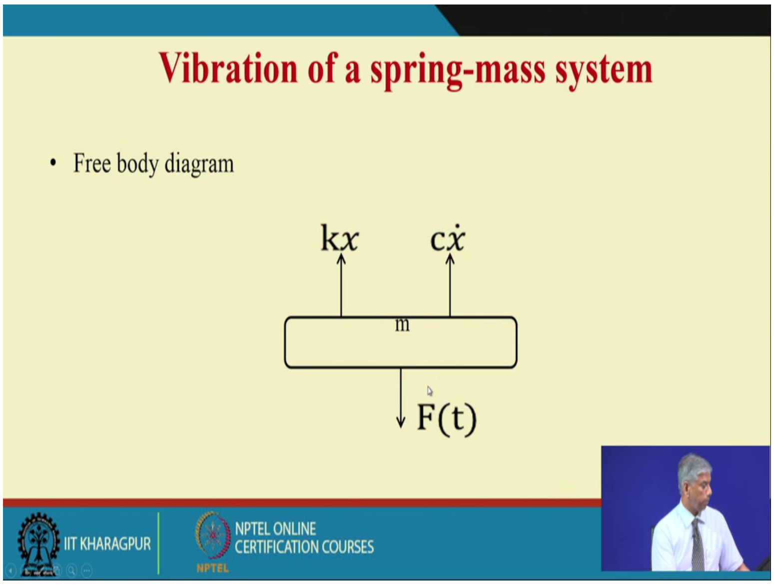

So, if we look at the free body diagram of this body there is a resultant force and then there is of course, the body it has not been shown because it has been balanced by the static deflection. So, the net force will be shown this way wherein the net acceleration of the body is given by this expression where f is the external force ok.

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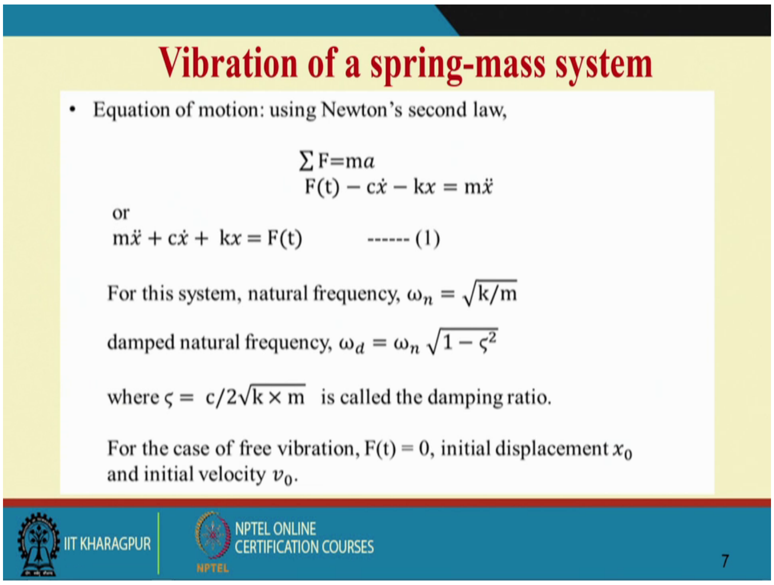

So, I have mx double dot plus cx dot plus kx is equal to F t is the equation of this motion now there can be many solutions to this equation differential equation and this is the first order linear differential equation.

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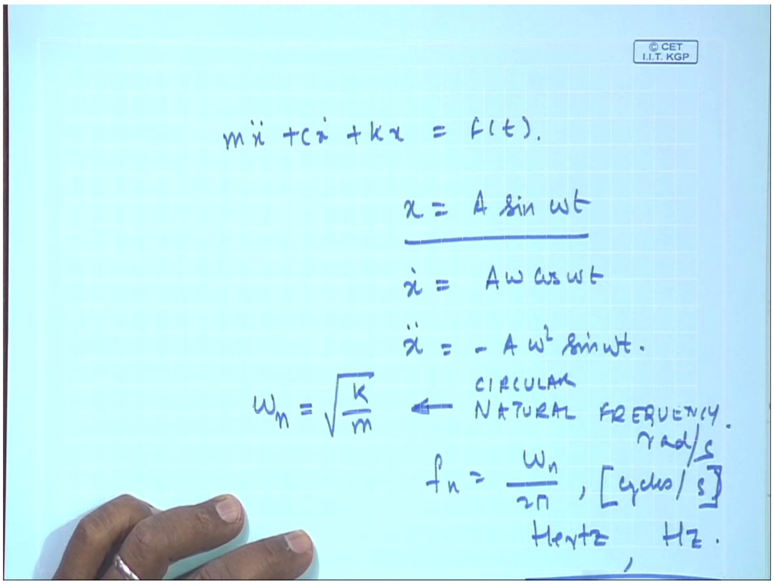

So, x is equal to A sin omega t can be a solution to expression and if I substitute x dot is equal to A omega cosine omega t and x double dot is equal to minus A omega sin omega t, in the above equation I will come up with an expression where omega n is equal to root over k by m and which is known as the natural frequency of the system. It is a circle on natural frequency where fn is equal to nothing, but omega n by 2 pi and usually units is radiance once again and for fn units is cycles per second or it is written as Hertz or capital H small z.

So, this is the natural frequency of this body rigid body of mass n and so on.

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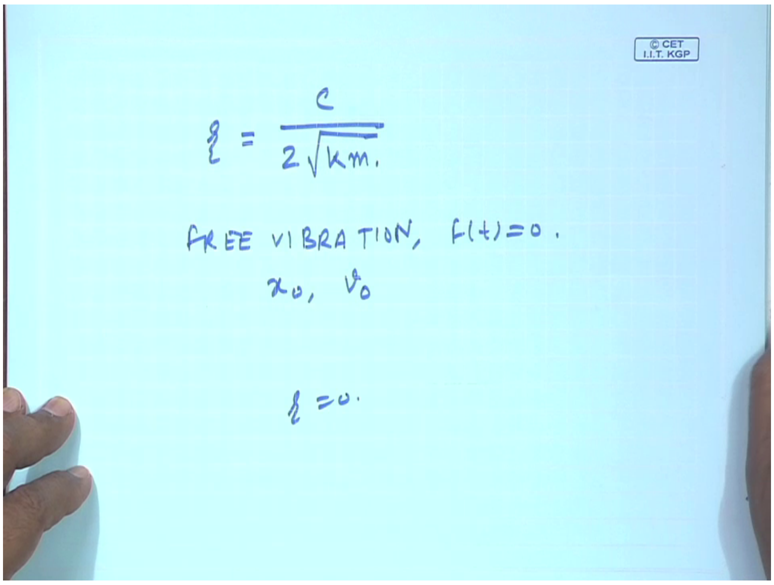

There is an expression called damping ratio it is given by c by root over 2 km. We will see certain cases when initially for the case of free vibration there is no force. So, F t becomes 0 and we have certain initial displacement x naught and v naught.

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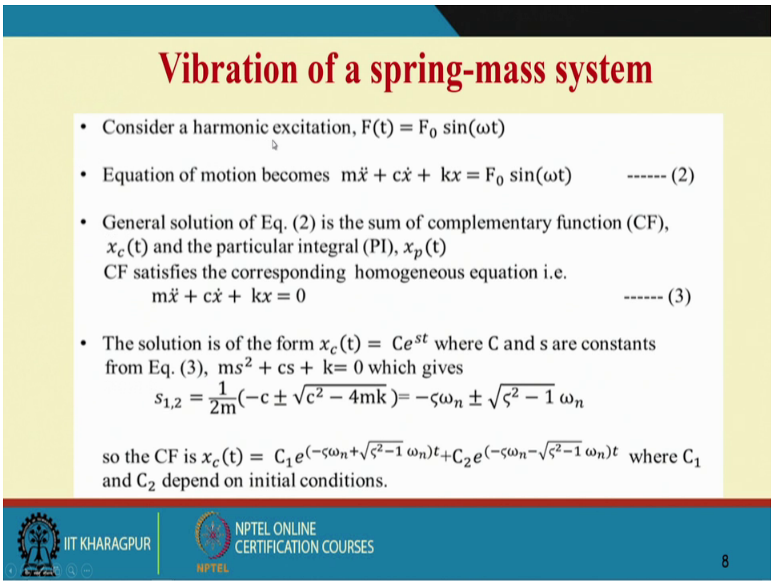

And then we will see the solutions to this in the, but then if I given harmonic excitation why is it called harmonic where because the external force is a function of this sin omega t or cosine omega t. So, this becomes the equation of the motion to the system. So, equation 2, will have two solutions two parts to the solutions, one is the complementary function another is the particular integral. So, the complementary functions satisfies the homogeneous equation when the right hand side is equal to 0.

So, we can find out the solution, where xc is equal to c if the power st where c and s are constants and if you plug it in we will get the complementary solution like this - C 1 e to the power minus zeta omega n plus zeta square of minus 1 omega n t and so on where C 1 and C 2 will depend on the initial conditions x naught and v naught and thus we can find out the solution complimentary function solution to this differential equation.

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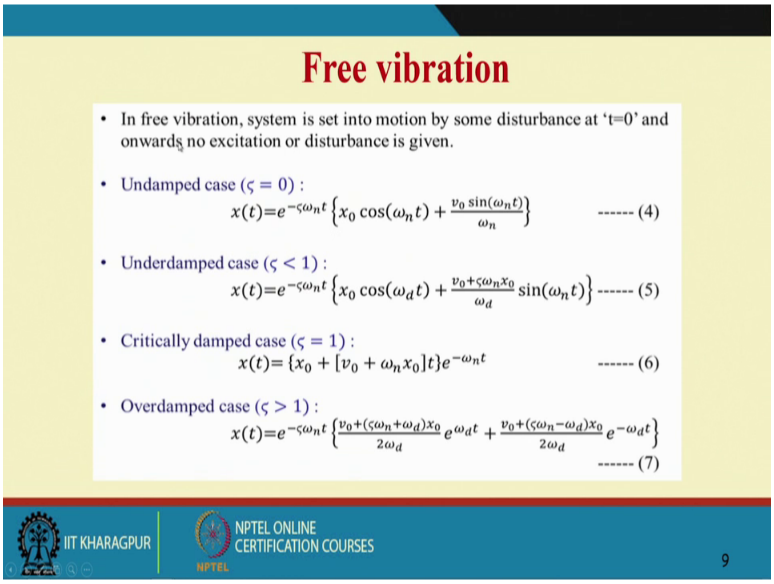

So, in the free vibration case at t is equal to 0 we will give there is no excitation or disturbance and there will be few cases when we have zeta equal to 0 undamped case because damping does not exist. So, this could be one solution and then underdamped case critically damped and overdamped case. We will see the plot of these responses of this body to this kind of damping scenarios.

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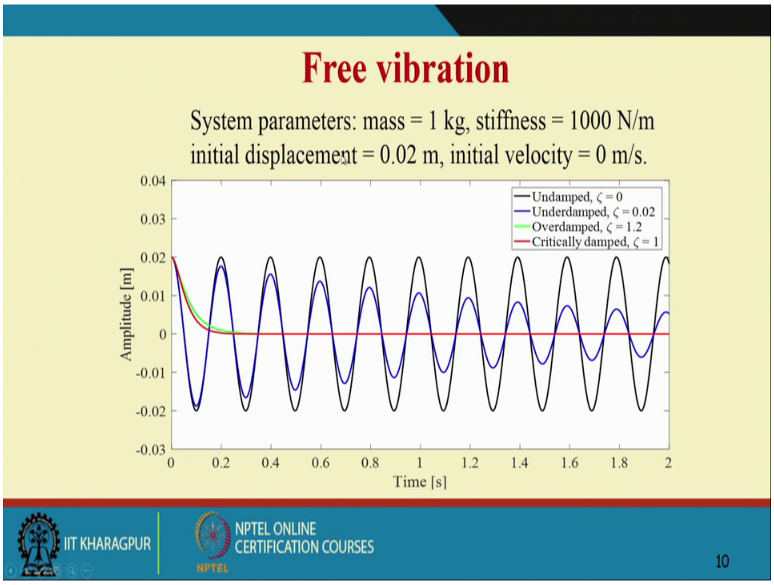

So, this is the free vibration of a body of mass, 1 kilogram stiffness k is equal to 1000 Newton per meter initially displacement x naught as 0.02 meter, v naught initial velocity as 0 and these are the flat for few different cases of zeta. So, we will see the case of an undamped motion the black line you will see the oscillations do not die which time and they are perpetually existing. Well reality does this does not happen because there is inherent material damping in every body and in fact, the joints in the systems and. So, try give damping, so this will reduce and for the underdamped case zeta is equal to point 0 two you will see the blue curve and so on and just for the critical damped case or the overdamped case there is hardly any oscillatory motion.

So, usually in practice we will see many of the vibrations response which will measure will follow the curve of in a free vibration will follow the curve of they under underdamped case when zeta is equal to 0.02 or some other value of zeta which is less than 1. And this is for the case of a free vibration; by the way in machinery condition monitoring you will see because of a defect there is always a force onto the body. So, the force could be something like f 0 sin omega t where omega is the external forcing frequency.

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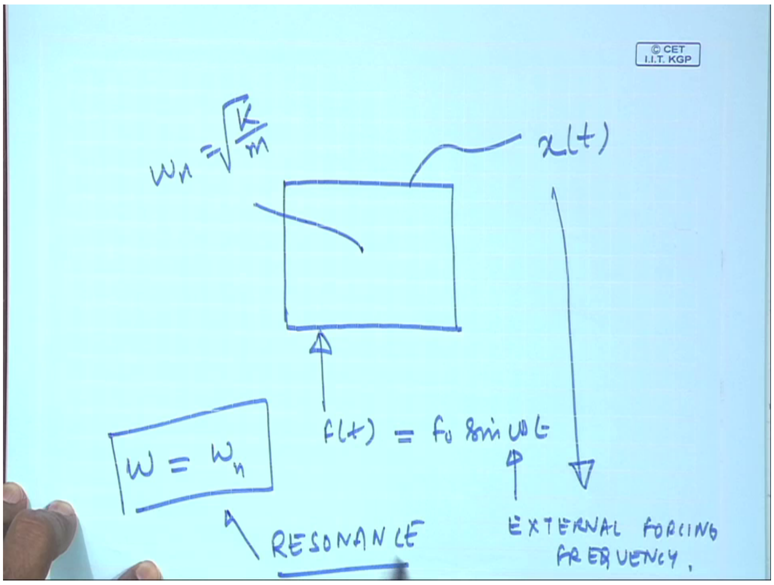

So, we will see this response will actually be at a frequency equal to omega, but this body has certain stiffness and mass, so it has a natural frequency. When the external frequency omega is equal to omega n we will have a condition of resonance and this has to be avoided at all.

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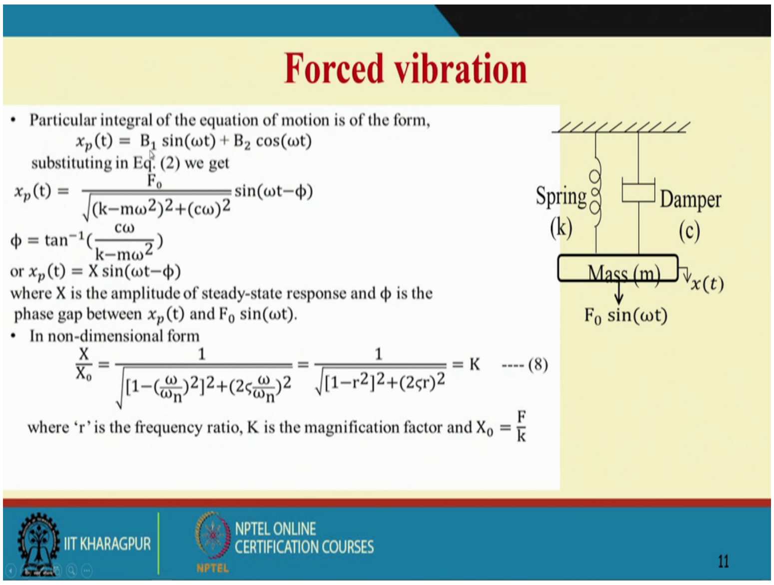

We will continue the discussion to the force vibration for the particular integral solution. So, I can have a response like this you want sin omega t plus B 2 cosine omega t. If I substitute this I will have the particular integral in this form given by a phase, phase is nothing, but the response between the forcing function the phase difference between the response and the forcing function. So, in non-dimensionalized term this is very important that X by X naught is given by one by one minus r square square root plus 2 zeta r whole square where r is equal to omega by omega n and zeta is equal to C by 2 root over k times m and omega n is equal to root over k by m.

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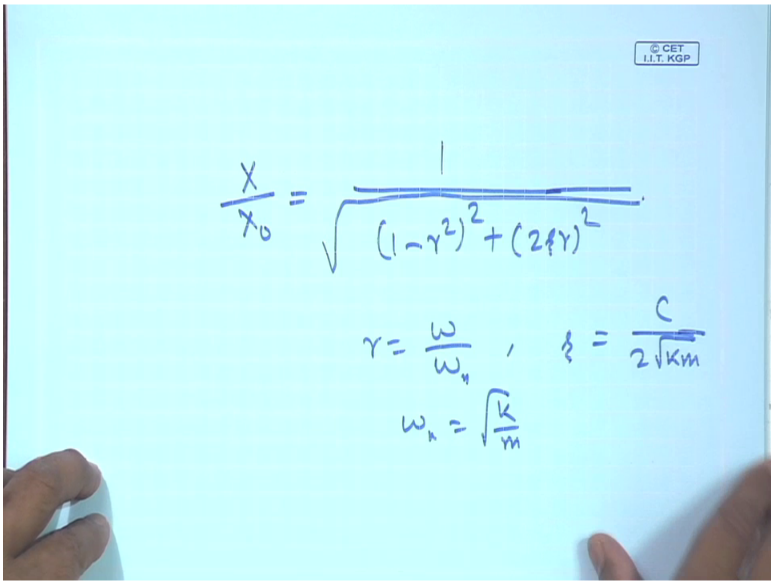

So, this response which will see, yeah you will see this is the dynamic magnification factor as a function of damping and frequency response.

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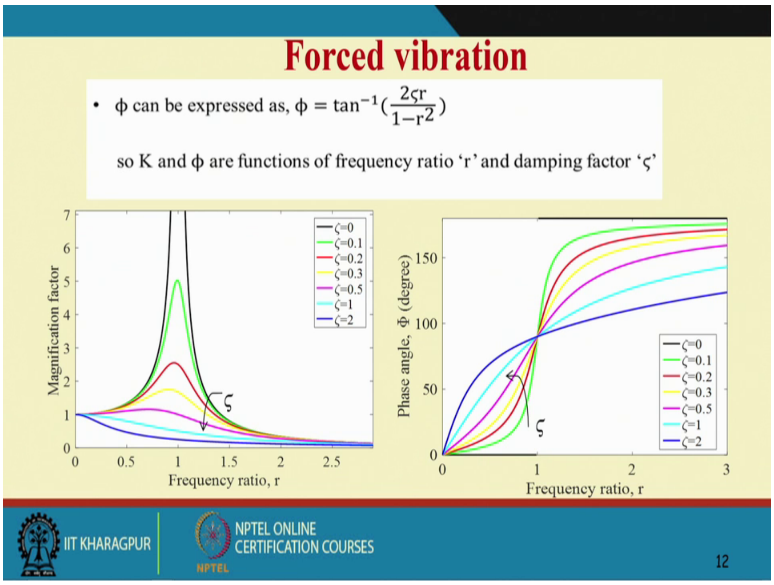

When we have frequency ratio r as 1 that is omega by omega n add for the case of very less damping no damping this almost peaks to an infinite, but with damping the peaks reduce. So, we will see that the vibration response at resonance can be controlled by increasing damping and this is one take a way we have from the slide. And you will see for the case of no damping the phase angle changes by 90 degrees here and this is a function of the increasing damping. So, change in the phase angle between the response and the force and the maximum value of the response as frequency ration 1 a r indicators by which we can find out the occurrence of a natural frequency and so on.

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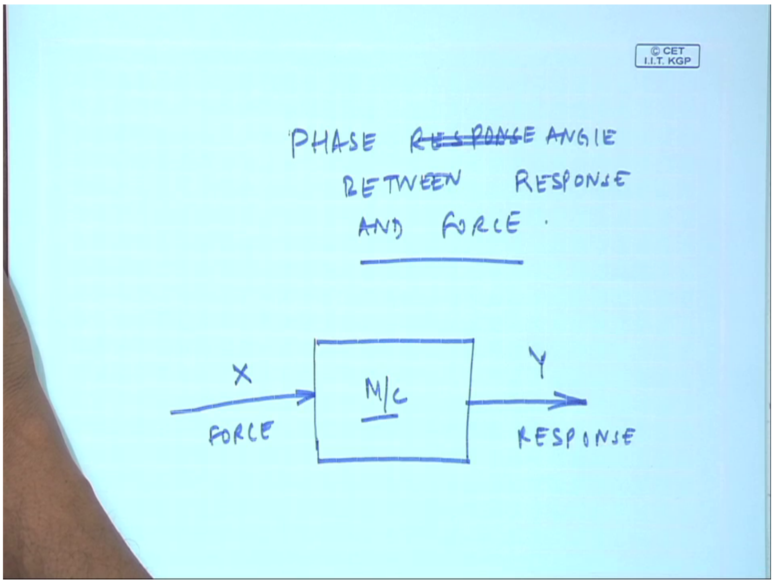

So, many systems we need to find out the natural frequency of systems. So, looking at the phase response between or phase angle between response and phase and force we can find out the natural frequency.

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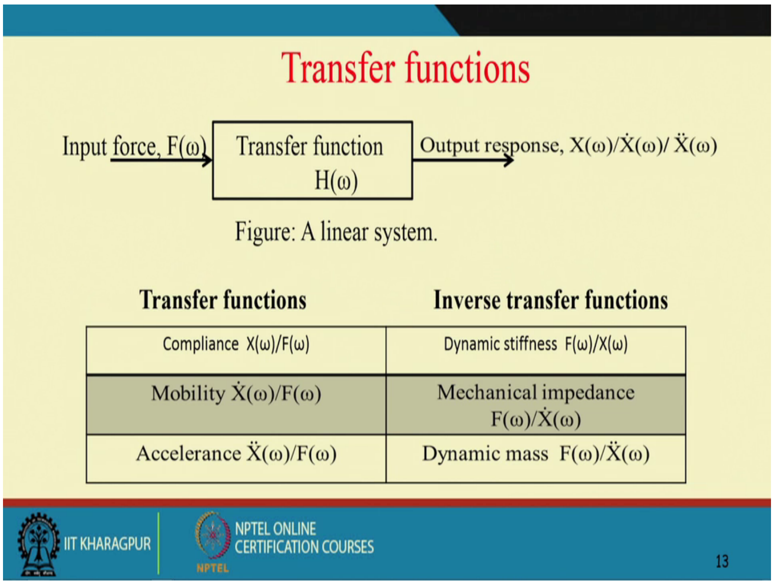

Now, we have seen this was for a single system, but many systems you will see that there is an input and there is an output this could have been force and this could have been response and this could have been my machine or a system excuse me.

So, there are certain names given to these ratios. The ratio could be for in the form of X omega which is nothing, but displacement or X dot omega which is nothing, but velocity or X double dot omega which is nothing, but acceleration and this is an input force X. So, there are certain in the linear system certain names given to these ratios which are known as transfer function the frequency domain, compliance is nothing, but the displacement by the force and inverse of this is the dynamic stiffness.

Similarly, mobility is nothing, but the velocity by the force and inverse of that is the mechanical impedance and acceleration is nothing but the acceleration by force and the inverses either the dynamic mass or the apparent mass. So, this transfer functions helps us characterize the system and there is a; and we can find out the mechanical impedance of many different elements like spring, damper or mass and you can see the corresponding phase.

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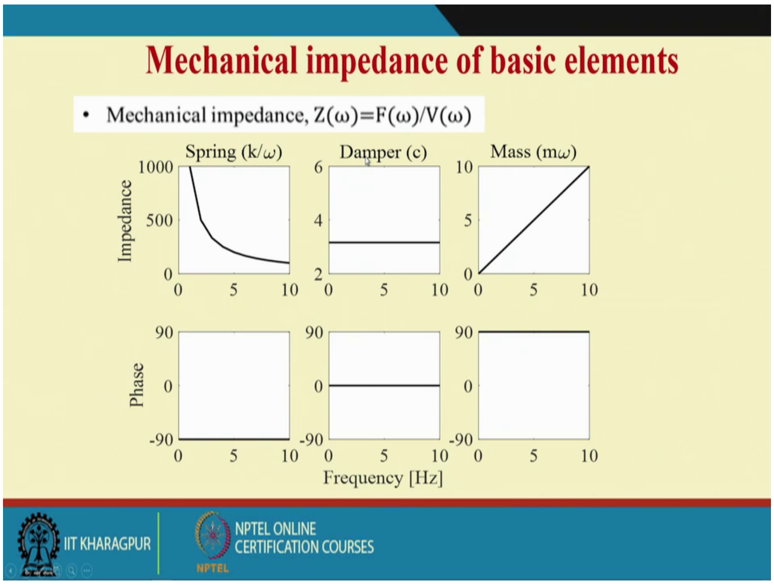

So, this is like an homework for all of you to find out the impedances of few mechanical systems like a spring damper and mass and I just show you what this impedance value is. So, you can given force, harmonic force find out the displacement, find out the velocity and find out take the ratio to find out the impedance.

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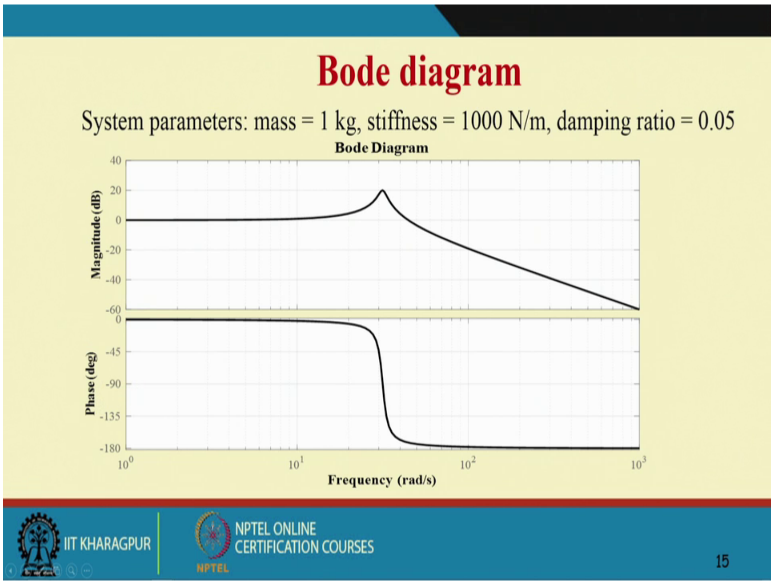

Now, sometimes in vibrations the magnitude and phase are product together of the function of frequency and such is known as the bode plot. Now, when I say here magnitude db basically this is a log scale. So, if it is logarithm of any number when it is 1 to any base is actually 0.

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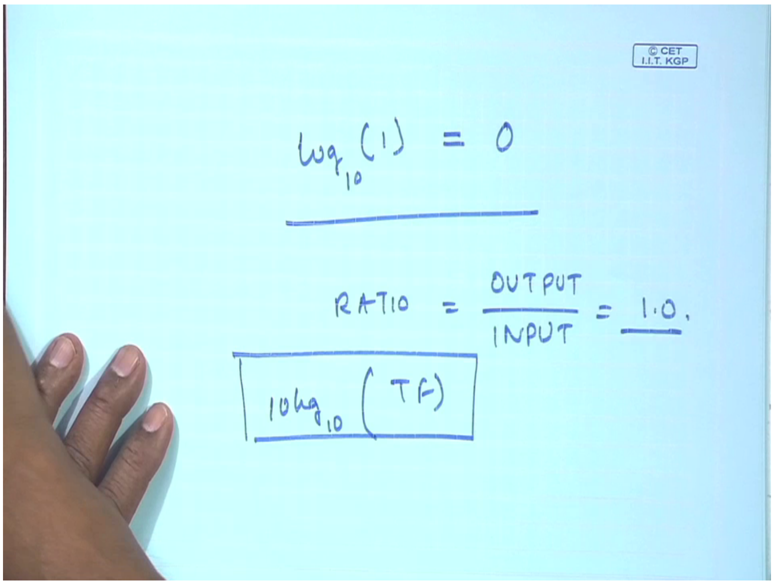

So, when this ratio output by input becomes 1 when output is equal to input this is what is represented by 0 decibels. So, when I say magnitude here it is 10 log 10 of the transfer function. So, bode plot is used to describe the systems response. So, I can see here that this is a resonance phase are angle has undergone a change and there is a peak at a particular frequency ratio. So, I can all are frequency and so I can find out what is the natural frequency of the system. So, this is what is known as a bode plot and we will be using this to find out the natural frequency of the system.

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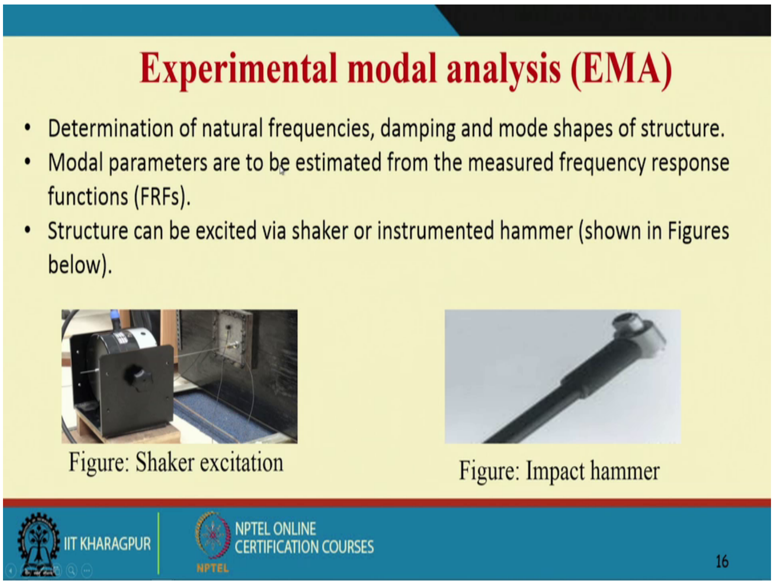

Of course when I shown you impedance and mobility. Sometimes to know more about the systems is a technique called experimental modal analysis will be discussing this later towards the end of this course, but just to give an example here we have a plate and or transducer is put measure is response this is an exciter or I could have an impact hammer or the force transducer. So, simultaneously I can know what is the force being applied to the system and the response generated. So, then I can find out the impedance of the system or the mobility of the system and plotted as bode plot to find out the natural frequency.

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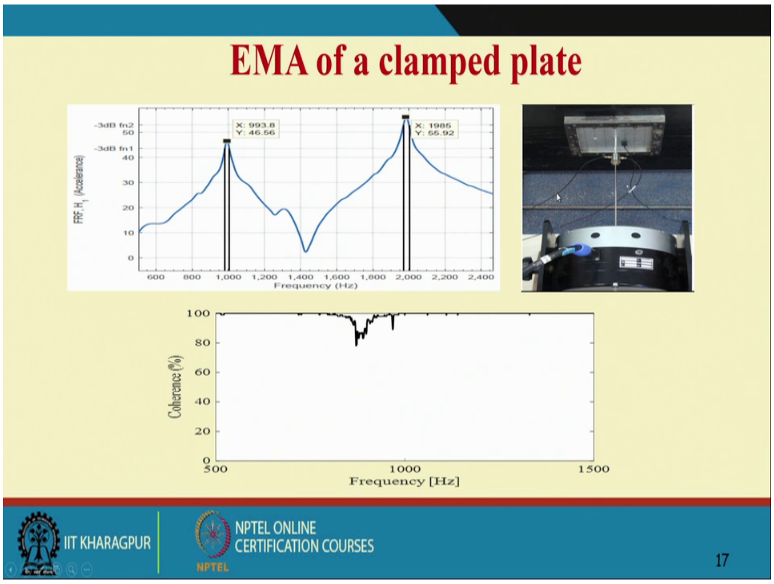

So in fact, if you look at the system this system has many degrees of freedom and right now we have just shown you the two natural frequencies of a clamp plate and there is a coherence which I will describe you later on as the causality between the input and the output. And this means the force is only producing the response and so on at almost all the frequencies.

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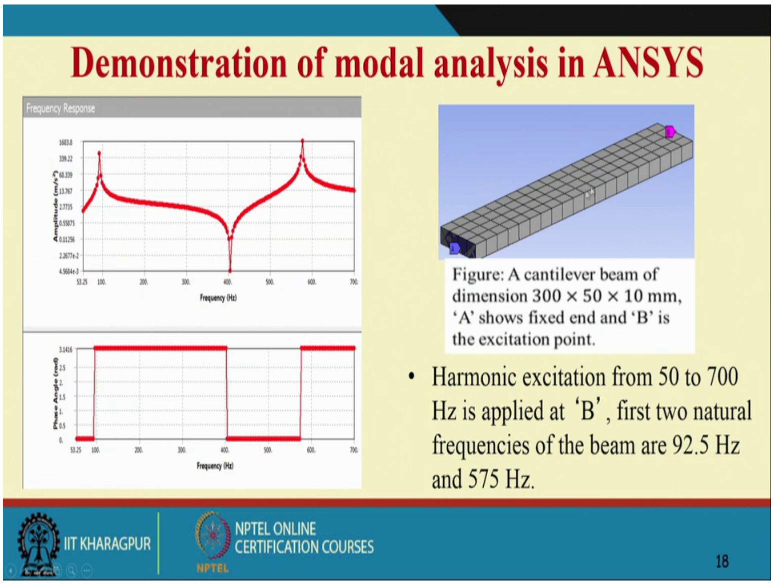

Through finite elements studies in a people have done this in the sense we have divided a plate into many bodies and then final element study to find out the natural frequencies of this cantilever plate or beam.

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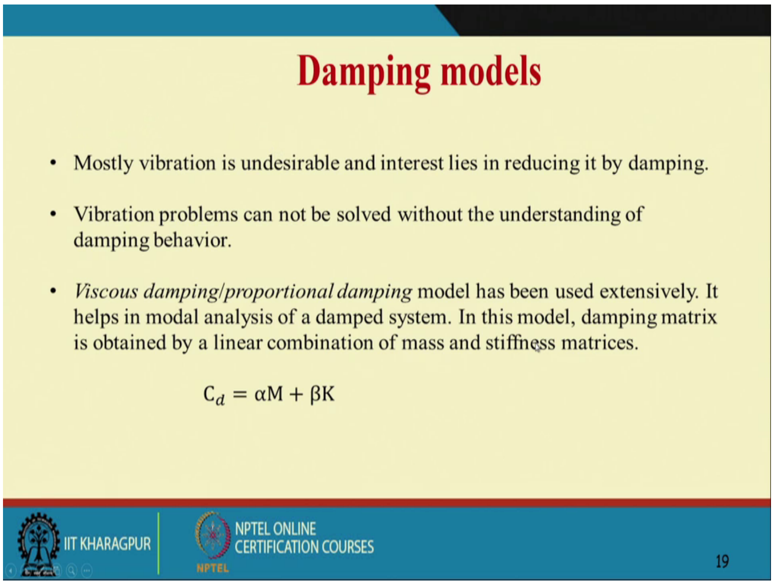

Now, we have some idea regarding stiffness mass of a system, but then as you would have seen this damping controls they responds vibration response of many of the systems.

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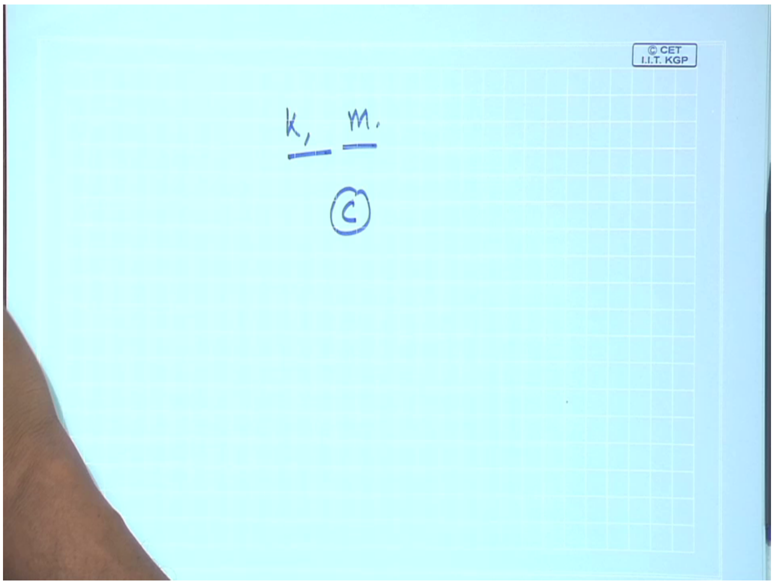

So, mostly vibration is undesirable and interest lies in reducing it by damping you would have seen the case of the natural, the dynamic magnification factor thereby reducing the damping we could play around. But then there are many models of damping one is the viscous damping where it is a linear combination of mass and stiffness matrix we have hysteretic damping usually in a structures or the dry friction or coulomb damping given by this expression.

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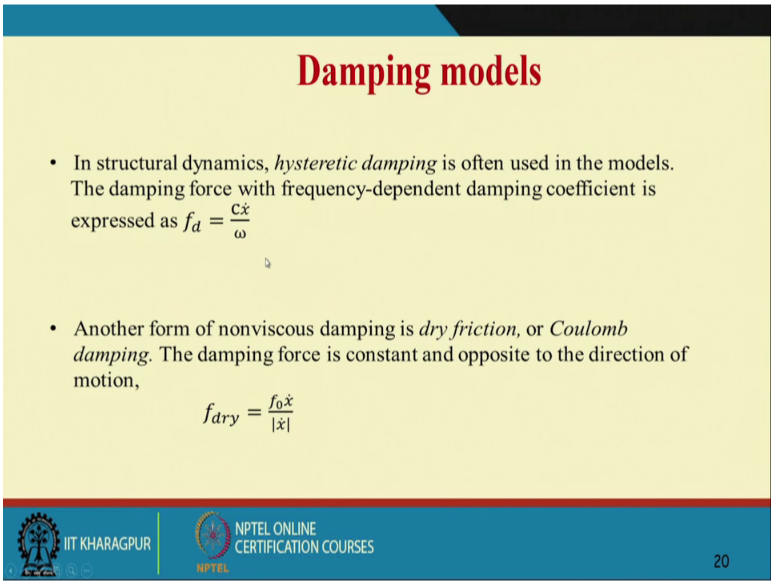

So, different models of damping can be used to describe your model.

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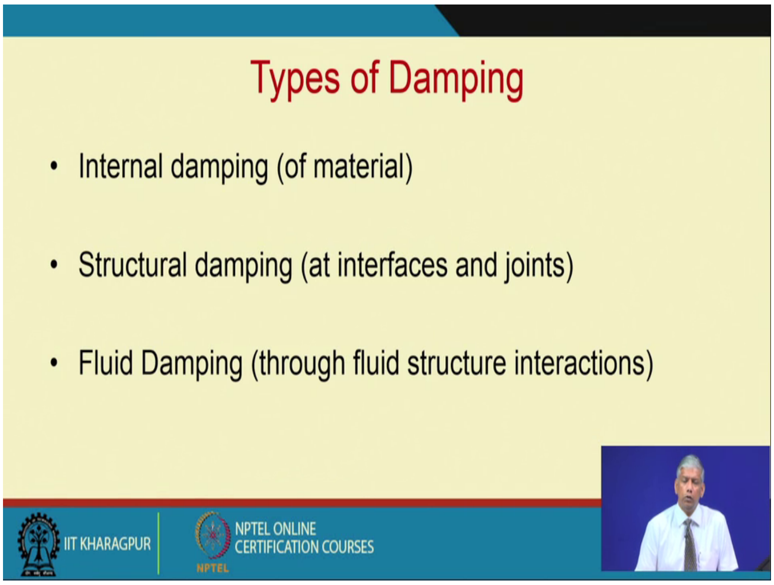

And many a times in materials this is all internal damping, structural damping at interfaces and joints, and fluid damping through fluid structures and interactions. So, this dampings control the response and we must have a good idea of estimation of the dampings in the system.

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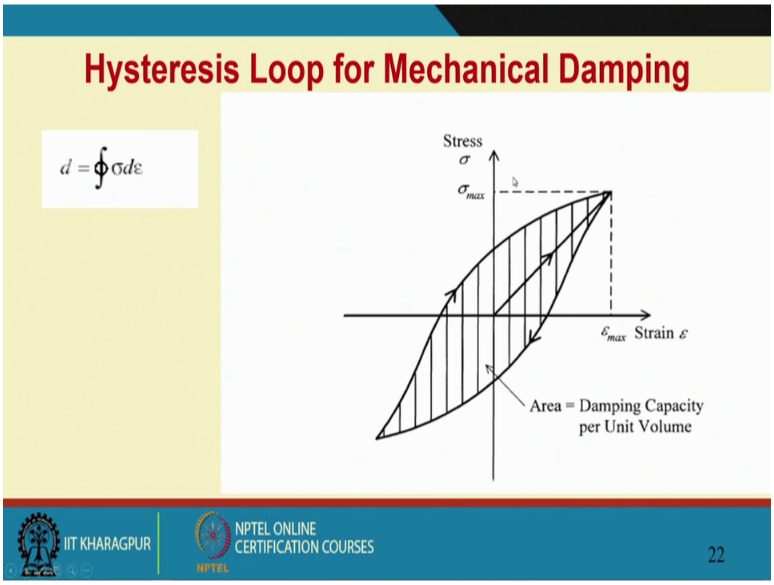

The statically loop because of mechanical damping. So, metallurgists are developing materials with high damping capacity so that the vibrations could be reduced like the cylinder block of an engine having materials, having high damping and so on.

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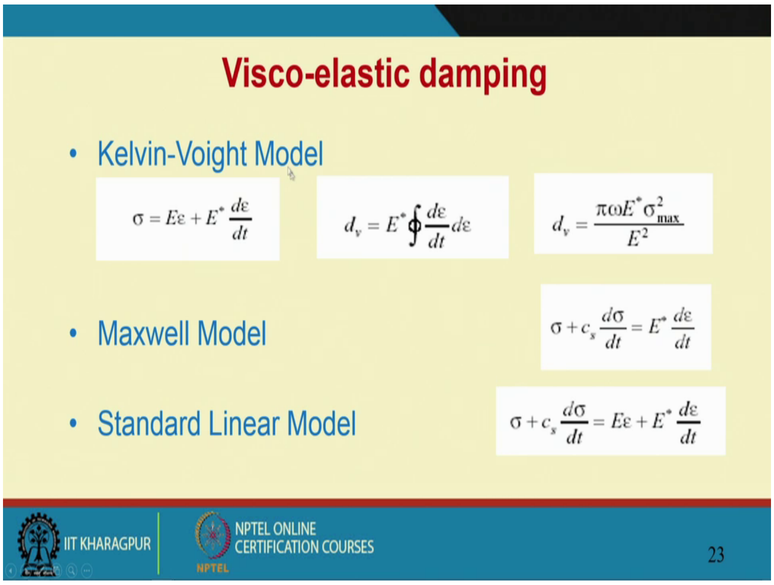

And then for viscous elastic damping there are different models which you will refer to in any book advanced books on damping and so on.

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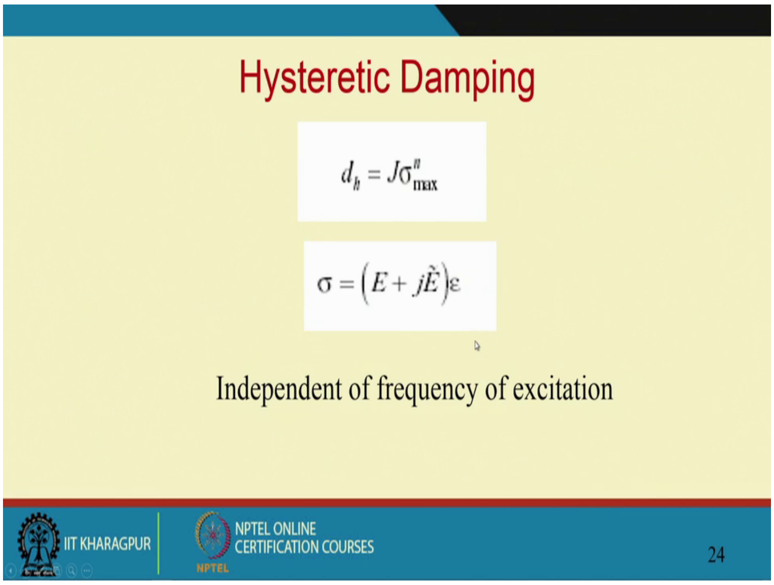

Damping can be measured either through time response measurements or through frequency response measurements.

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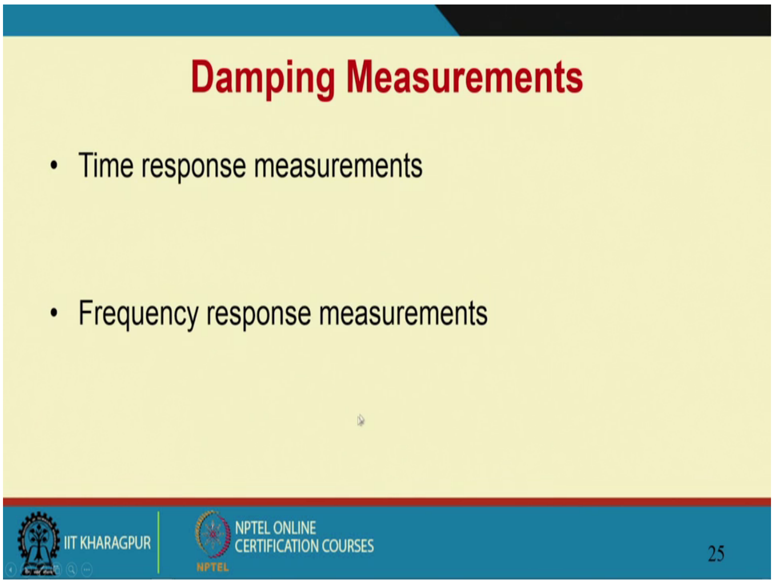

And this is the log decrement method if you recall in the case of the underdamped case because of damping presence this oscillations will die out with time. So, by measuring the success of amplitude ratios one can get the estimate of the damping present in a system and that is usually used by many experimenters to find out the damping in systems.

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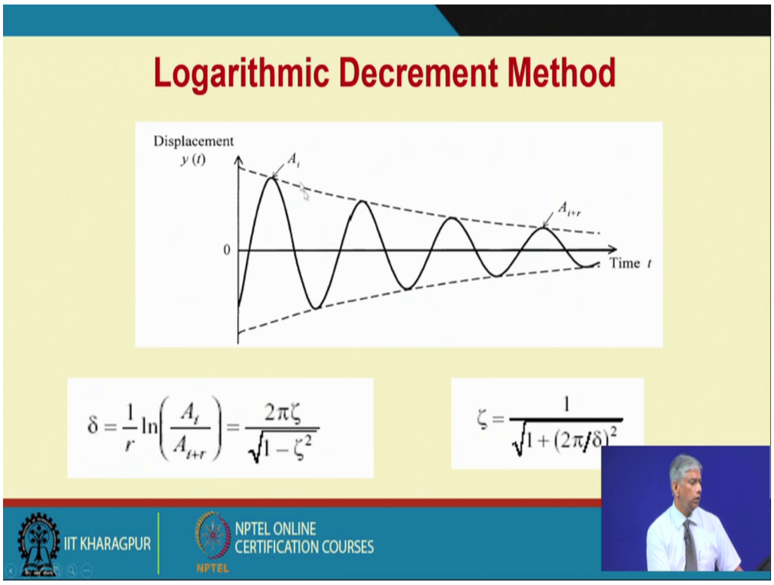

There is another method which is known as the Half power method in the frequency domain looking at resonance if the peakness or the sharpness of this peak depends on the damping present in the system and this is calculated by what is known as the loss factor of the system and omega 1, omega 2 or points where this amplitude has reduced by root 2 or this is 0.707 Q. So, we can find out this two resonances points omega 2 omega where delta omega is omega 2 minus omega 1 and omega r is the resonance frequency and at every natural frequency we can find out the damping in a system.

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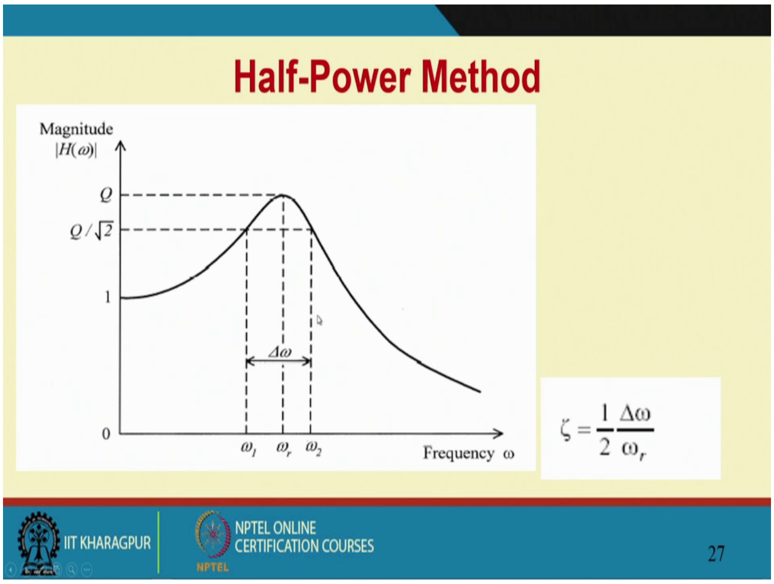

This there is an ASTM standard to measure damping and with this could be put in a chamber with an excited under response and there are equipment like dynamic mechanical analyzer wherein you can find out damping in the material for different temperatures.

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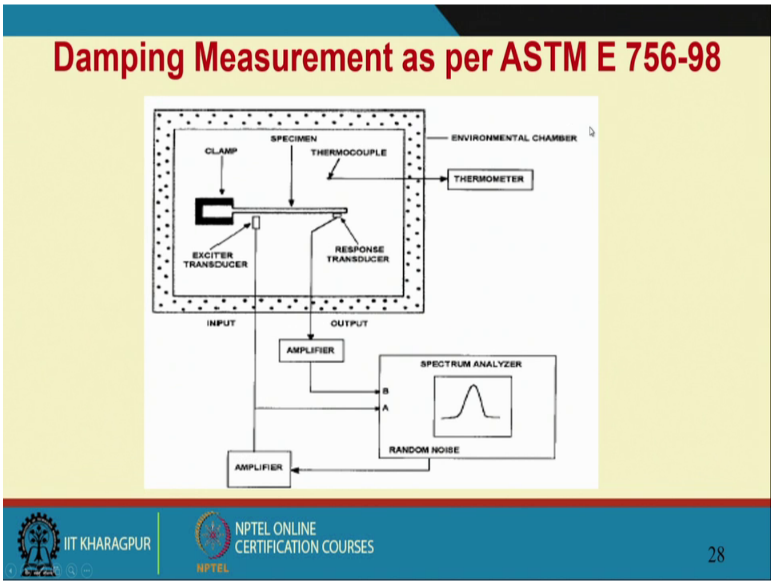

And this is an experiment in the lab wherein we are exciting and we have in response to find out the damping in a cantilever beam.

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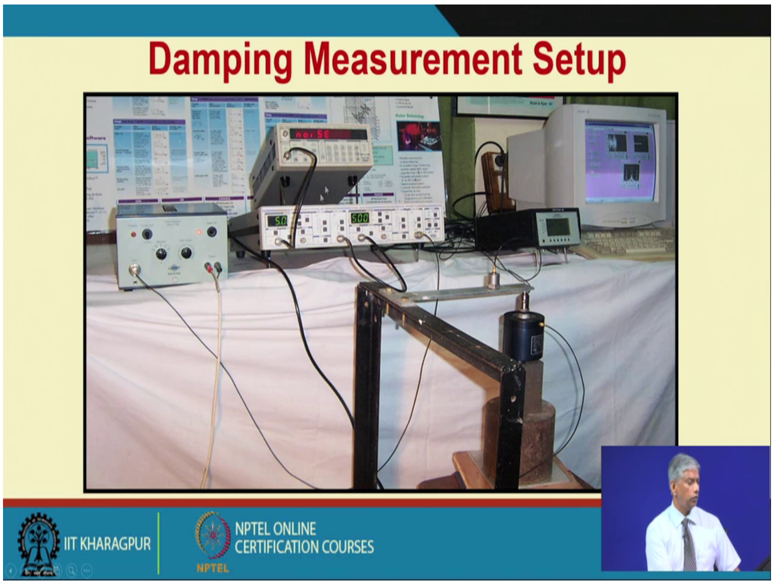

Certain parameters are used you will see in the literature we have used this as damping ratio somebody calls them 2 eta has lost factor quality factors 1 by eta 2 zeta and 1 by eta and damping capacity is quality factor by pi and so on.

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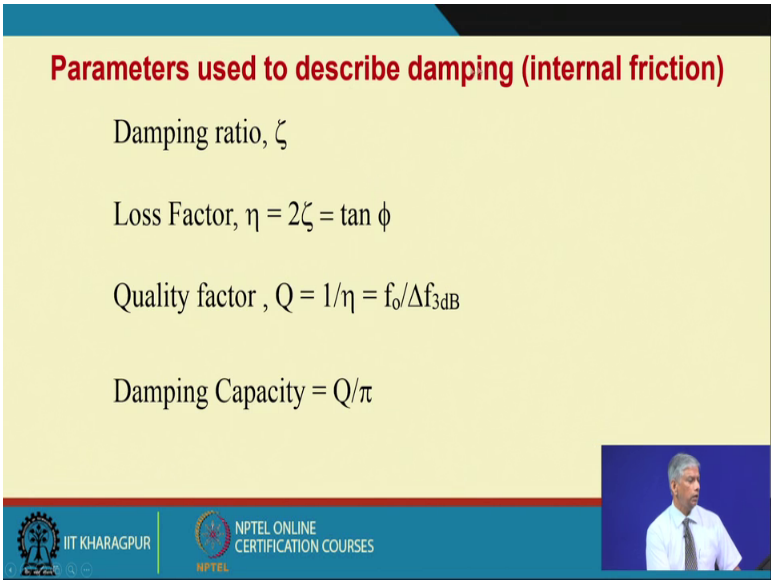

So, these are all related terms which you will find in the literature.

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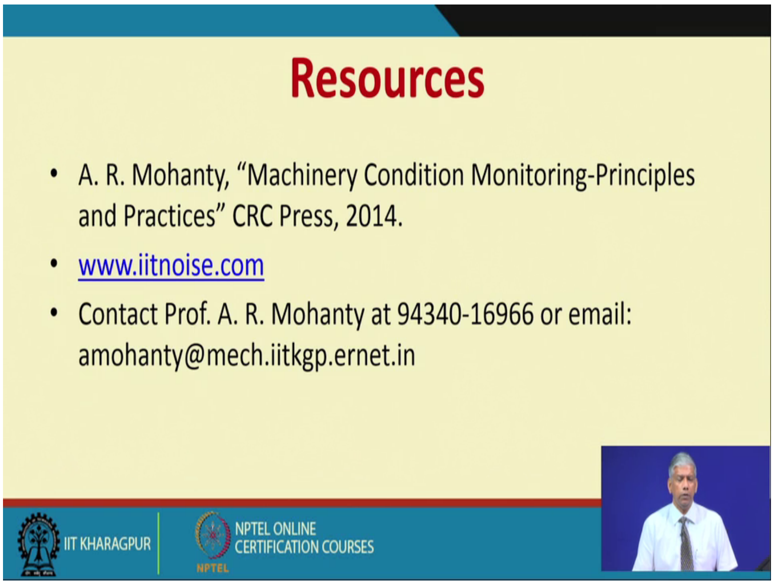

More examples and applications you will find in my resources.

Thank you.