Mechanical Vibrations

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Module - 1
Introduction

Lecture - 2
Harmonic and Periodic Motions, Vibration Terminology

In the previous class, we already introduced what is vibration and we have seen that, vibration is nothing but oscillatory motion or to and fro motion of any system. And any system – any dynamic system is generally executes to oscillatory motion when it has stiffness and inertia. And because of these two properties, the eddy dynamic system can have oscillatory motion. Also some of the classes of vibration we have seen; just introduced in the last class, there is the free vibration and forced vibration. Free vibration is nothing but if we allow the system to vibrate its own by giving initial disturbance to it like a pendulum or a spring mass system; if we just tap those spring mass system and allow it to vibrate, there is a free vibration. In forced vibration, generally in any machine occurs because of the shaking forces, which are there inherent into the machines like unbalanced force or one of the causes of forced vibration.

And, apart from this, then the last time, we introduced various kind of measuring instruments for measuring the vibration. And especially the applications – some of the applications we have seen are where the vibration can be dangerous or it can be advantageous to us like vibration… We already seen that, in most of the machinery they are present. And not only in the machinery, other structures also it is present including the… If you talk about the earth, that also vibrates. Even when we want to speak something, then also the vibration is helping us to speak our views and ideas. So, you can see that, vibration is present in not only in the machinery, also in the common usage like music systems. There also whatever the concepts of the vibration and acoustics or the sound is there; that is applicable. So, it is essential that we should study in great detail the behavior of these vibrations.

In the last class, I introduced the degree of freedom of a particular system. So, degree of freedom is nothing but a number of independent variable required to define the motion of a particular dynamic system. So, this particular definition, that is, today, we will explore more through some example, so that we understand what is the degree of freedom of a dynamic system?

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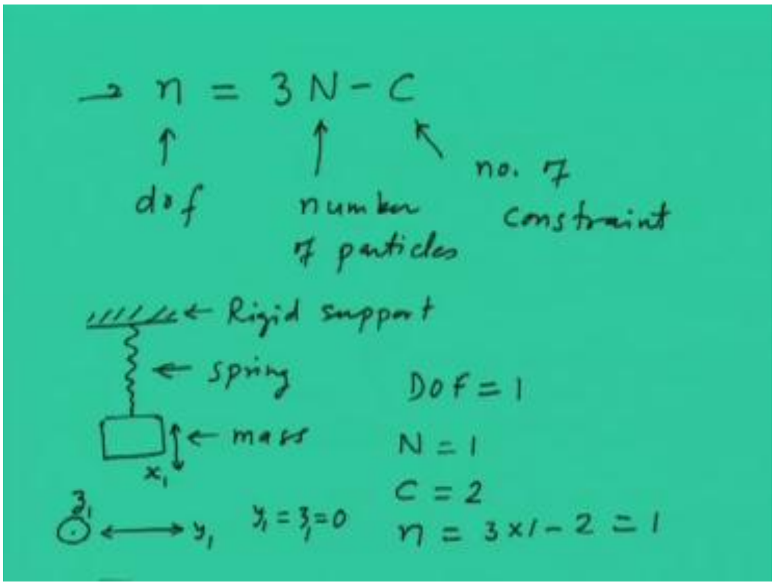

So, first, let us see what is the degree of freedom of a discrete system. So, degree of freedom of a discrete system can be given as like this. Here this is the degree of freedom. This is the number of particles in the system. This degree of freedom we are relating with the discrete system. So, number of particles is capital N and C is the number of constraints a particular system has. We will see what are these constraints. So, first, let us take one example of very simple case. A mass is attached with a spring, and a spring is attached to its rigid support. This is a rigid support; this is the spring; this is a mass. If we disturb this mass, such that we are allowing the motion of the mass in the vertical up and down motion. So, we have given a tap to this mass, so that it oscillates in only vertical direction.

Then, let us say that, motion is defined with a displacement x 1. So, in this particular case, the degree of freedom is… Directly, we can able to say this is 1; how we can able to arrive at this? Let us say use this formula in which N is 1, that is, number of particle, that is, the mass; that is, a single mass is there. So, N is equal to 1. Then, we have the constraints. How many constraints are there? In this, we know that, we are not allowing the motion of this particular mass in this direction; let us say this is y 1 direction;

horizontal direction we are not allowing. Also, perpendicular to the screen, we are not allowing; that is, let us say z direction; that is perpendicular to the screen. So, there are two constraints: y 1 equal to z 1; both are 0. So, these are the two constraints. So, C is 2. So, degree of freedom n will be 3 into 1 minus 2 is equal to 1. So, we can see that, using simple relation, we can able to get the degree of freedom of this system.

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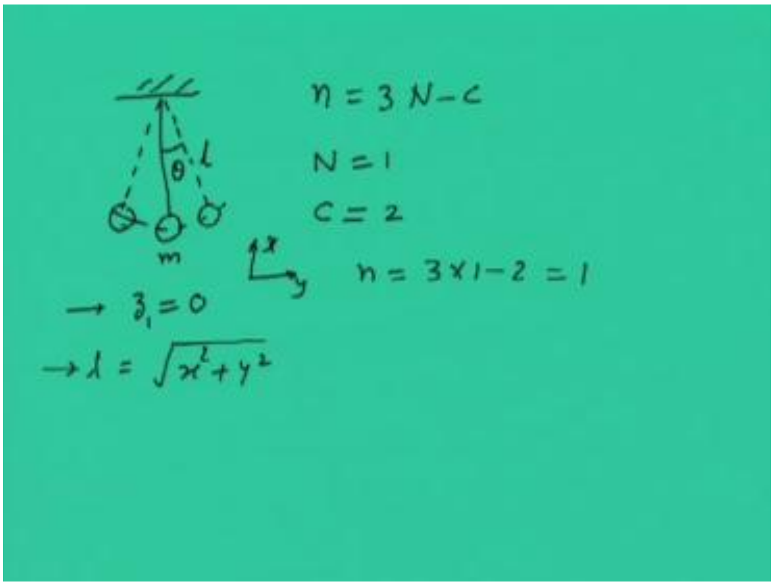

Let us see some more examples; like if there is a pendulum. So, this is a massless cord and there is a mass attached here m. If you are giving a disturbance to this particular pendulum like this; so it will oscillate about in one particular plane. So, we are assuming that, whatever the disturbance we are giving; because of that, this pendulum is oscillating in one plane. So, to define the location of the mass at any angular position, theta variable can be used. So, here if we use the same formulae as we had previously; so number of particle is 1; number of constraints here – again it will be 2. How it is 2? We can able to see that once we are seeing this mass is oscillating in this plane, then motion perpendicular to the screen is not there; so that means let us say z is 0; that z is the displacement perpendicular to the screen. Also, this particular mass is having motion in the… that is, two directions, that is, x and y directions. But, they are constraint motion; they are not independent motion. And how it is related let us say there l is the position of the ball here. So, l is related with the two coordinates like this. So, there is a definite relationship between the x and y and the radial position of the ball. So, we have two constraints in this case also. So, with this, we can able to get again the degree of freedom of the system as 1.

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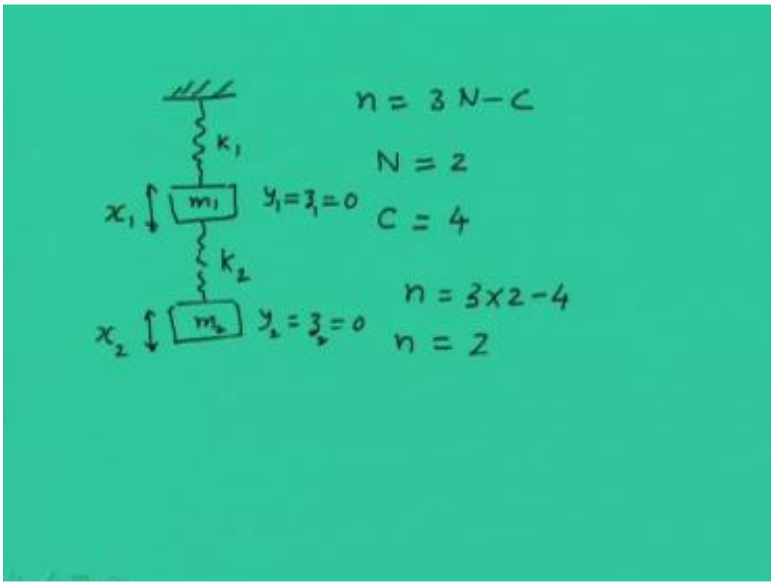

Or, take another example in which let us say we have two masses. So, one mass is attached with a spring having stiffness K 1; this is the mass m 1. Then, another mass is attached below that say mass m 2 and stiffness K 2. And if we are disturbing these masses such that it is having up and down motion; so let us say this is having x 1 displacement; this is having x 2 displacement; but, they are in the vertical direction only. So, here if we are using the degree… that is, number of particles are now two, that is, m 1 and m 2; number of constraints – in this particular case, we can able to see that, this m 1 mass is having no displacement in the horizontal direction and perpendicular to the screen. So, both are 0.

Similarly, this is having two constraints – is not moving in the horizontal direction, also perpendicular to the screen. So, total – 2 plus 2 – 4 constraints are there in the problem. So, the number of degree of freedom can be obtained as 3 into 2 minus 4. So, that will give us 2 degree of freedom. So, you can see that, to define the motion of mass m 1 and m 2, we require two independent variables: x 1 and x 2; and that is the degree of freedom of the system.

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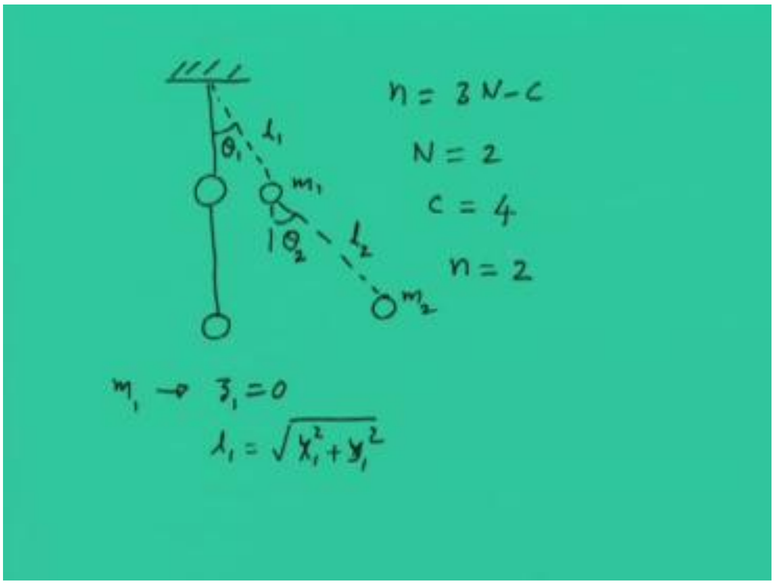

So, take another example to clear the concept very accurately. So, let us say there are two pendulum one below another. And if we are giving a disturbance let us say theta 1 to the upper one, so that the lower pendulum is getting another displacement of theta 2. Lengths of these cords are constants. They are l 1 and l 2. So, in this particular case, we can able to see that, we have number of particles as 2, that is, m 1 and m 2. And number of constraints here will be having – like for mass m 1, we know that, a motion perpendicular to the screen is not there; and the l 1 is related with the other two displacements: x 1 square and y 1 square. Similarly, m 2 is having similar two constraints. So, here you can see that, C is having… C is 4 constraints total in the system. So, we have n is equal to 2 again. So, with this simple example of one degree of freedom system and 2 degree of freedom system, we have shown how the degree of freedom can be obtained of a particular system. But, the similar concept can be extended for more number of degree of more number of mass system.

Now, let us see some of the vibration terminology especially when we measure the vibration; what to measure and… because these vibrations are sometime not perfectly sinusoidal or periodic; sometimes they are random. So, there are different terminologies of using how to measure these vibrations. Also, it has frequency components. So, how to measure the frequencies; and there are certain terminologies related to that.

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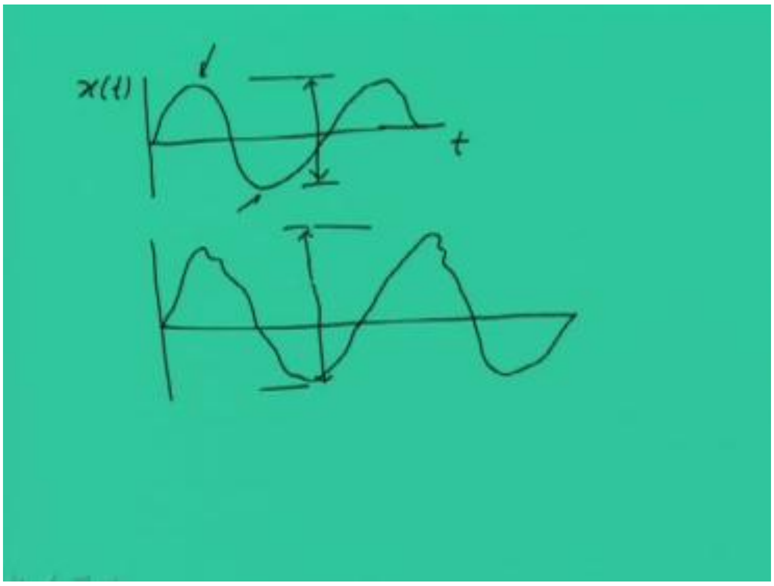

So, first, let us see when there is a signal, which is let us say a sinusoidal like this. So, obviously, in this case, we will be interested in the value of the displacement; that is, peak to peak value, because this is one peak; this is another one. So, what is the total displacement we will be interested? This is the time; this is x t. Then, if we have a signal, which is not… So, perfect; maybe it is something like this and which repeats after certain duration. So, in this case, because one way is to get the peak to peak… Maybe this is one peak; this is another peak. So, this is the total displacement, because this peak to peak value gives… These are the displacement of the machine surface or machine structure. So; obviously, they are related with the stress, which they are undergoing with respect to time. So, they are reflecting in direct way that, they are the stresses. So, these are very important. Another term, which we use during the measurement, is the average value of the vibration. And let us see what is the average value.

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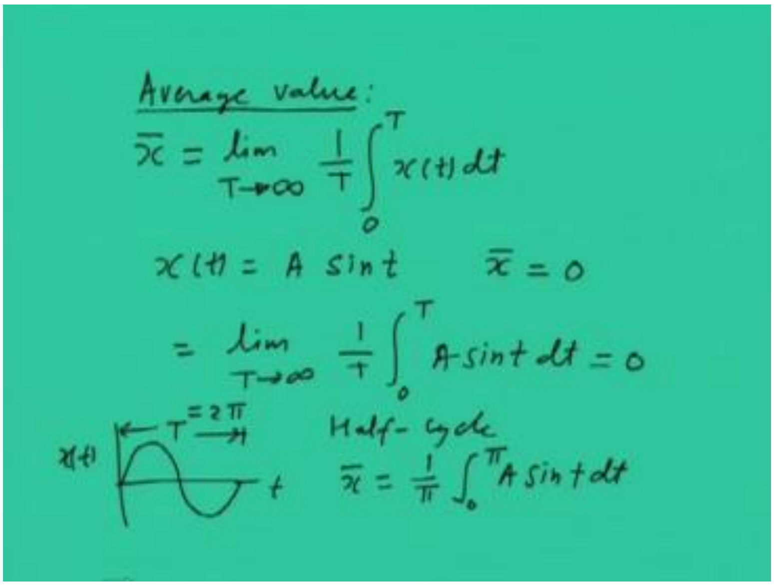

Mathematically, we can able to define the average value of the displacement if we have the… Let us say especially when we have some kind of random signal, then we take the average displacement. And this can be defined as when time is theoretically infinite of the measurement, which we have taken… So, thus is the displacement; this is the average value of the displacement, which we are giving, we are measuring. And we can see that, if let us say we have displacement, which is A sin t and if we want to obtain the average value of this; obviously, through figure, we can able to guess that, it will be – average value will be 0. And even if we substitute this in the formula, we can get this. This is… So, over the period, we know that, the integration of this particular term becomes 0.

Or, like there is a particular vibration – sinusoidal curve; obviously… because this is the total one period of the cycle. And when we are talking about one period, this value of the displacement is positive and equally this side is negative. So, if we take the average; obviously, will come 0. So, sometimes we do the averaging of this kind of signal for half cycle; that is, x for pi, because we know that, this particular sinusoidal signal is having time period as 2 pi. In one rotation, that is the period of that cycle. So, we can able to integrate this quantity over the half cycle. And then from here you can able to see that, we get…

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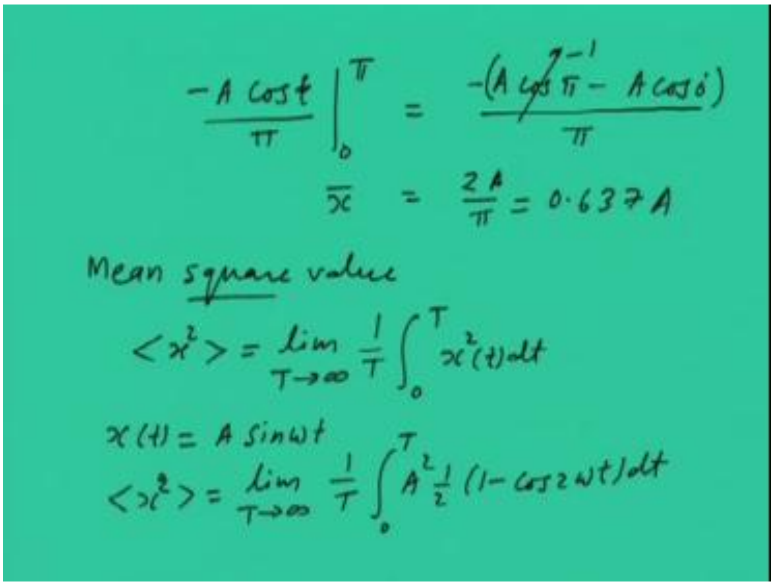

We can go to the next slide, that is, A minus cos t by pi – 0 to pi. And that is nothing but… Now, we will get minus A cos pi plus A cos 0. Or, I should write like this. So, you can see that, this becomes minus 1. So, this will be 2A by pi, which is 0.637 of A. So, this is the average value of a sinusoidal or signature or the signal for half cycle. Another term, which we use the mean square value of the signal. So, mean square is defined as… This is the mean square when time period is in limit of infinity 1 by T 0 to T. There is square. As the name implies, there is a mean square. So, square of the signal we are integrating over the domain. And if let us say we have the signal as A sin omega t, we can get the mean square as 1 by T – 0 to T A square; sin square can be written as half 1 minus cos 2 omega t dt. And now, we can able to integrate this.

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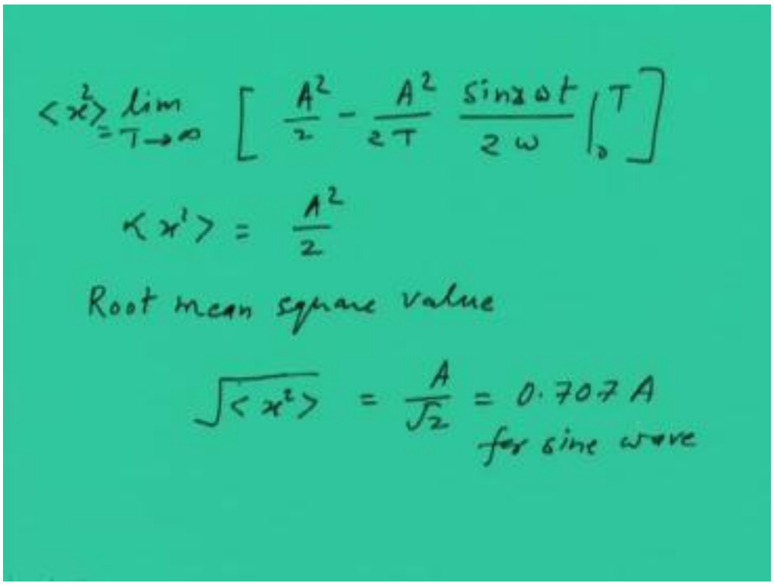

So, after integration, we will be getting limit T tends to infinity; that is, mean square is equal to… So, first term will give A square by 2 minus A square by 2 T sin 2 omega t, that is, of the second term – 2 omega – 0 to T. So, you can see that, this term becomes 0 because when we put the time period T here, it becomes 0; also, for 0 value also, it becomes 0. So, the mean square value is now A square by 2. And there is another term that is called root mean square value. So, that is the square root of the mean square. So, it will be A by root 2. And that in fractional form, we can write as 0.707 A. This is for the sine wave. Generally, mean square value we use because we know that, the square of the displacement is related with the power of the system, because any kinetic energy or potential energy – that is the square of the displacement or velocity. So, that is why we use the mean square value. There is another unit of this vibration signature we use; that is called decibel. This is nothing but the relative displacement of the measured quantity. And this decibel is… This is not absolute displacement; this is a relative displacement; or, sometimes velocity and acceleration.

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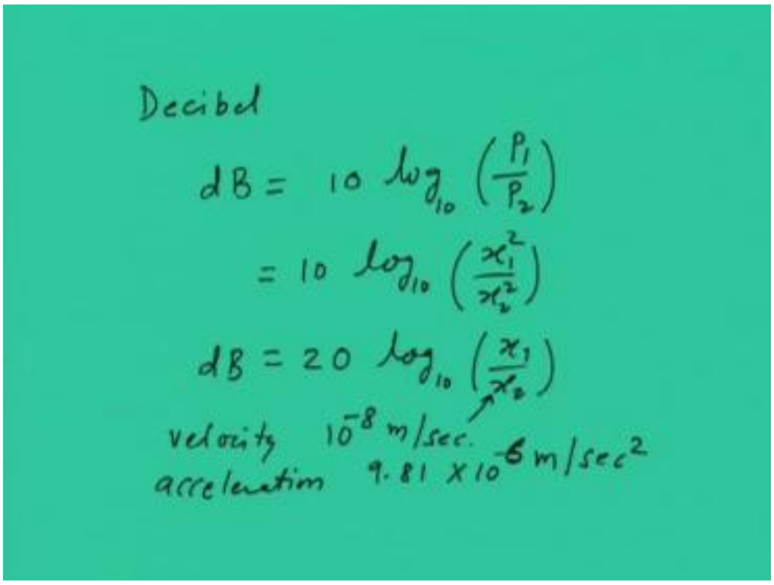

And, it is defined like this. So, decibel is defined as – it is called small dB – here 20… Or, let us write this as 10 log 10 P 1 by P 2. Actually this decibel we define in terms of the power ratio. And this power ratio as we have already seen, this power is proportional to the square of the displacement. So, this can be written in terms of the displacement, that is, this square of the displacements, because this can come outside to 20 log 10 x 1 by x 2. So, this is the definition of the decibel unit. You can see this is the ratio. And this x can be displacement, velocity or acceleration. And especially this denominator quantity is reference value. And for velocity, we use this reference value as 10 raised to minus 8 meters per second. And for acceleration, when we are measuring the acceleration, we use 9.81 – 10 raise to minus 6 meters per second square.

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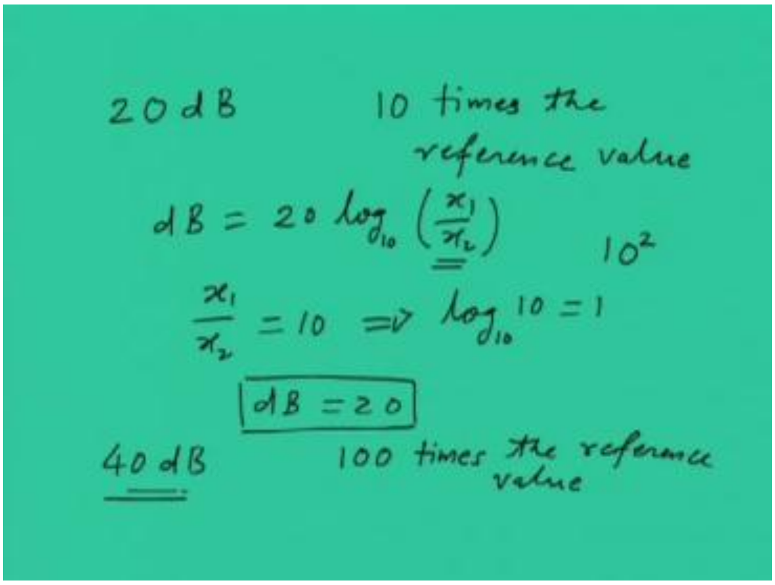

And, this particular dB – let us try to see what it represents. If we are saying 20 dB; 20 dB is nothing but that is the displacement is – the measured displacement is 10 times the reference value. How it is? Let us see the definition of the dB. Then, it will be more clear. If x 1 by x 2 is 10, then we will be having log 10 as 1. So, dB will be equal to 20. So, you can see that, when this ratio is 10, the actual displacement is 10 times the reference value. Then, we have… That measurement is called as 20. So, this is a relative displacement, not the absolute displacement.

Similarly, if we take another example, let us say, 40 dB; 40 dB represent that, we have the measured signal as 100 times the reference value. This also can be seen that, when we put hundred here; that is nothing but something like 10 raise to 2. So, because this is log 10. So, 2 will go in front. So, that will become 40. And log 10 will become 1. So, we will get 40 dB. There is another unit especially on the frequency; that is, we call it octave. Octave is also a relative magnitude of the frequency. If the upper frequency limit is twice the lower frequency limit, then we call that as octave one. Like if we have 200 hertz as upper limit and 100 hertz is lower limit, then we will call this as 1 octave.

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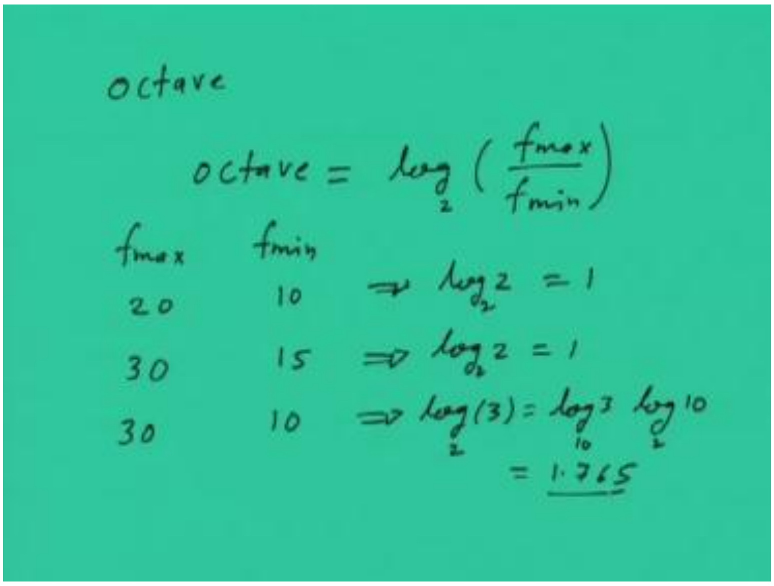

Let us see more definition of this octave. So, octave is defined as in expression log to the base 2 f max – the frequency max by frequency mean. So, if we have f max let us say as 20 and f mean as 10; then, we will be getting log 2; or, this ratio is 2 now. So, this will be 1, because base 2 – log base 2 of 2 is 1. If we have this is 30 and this is 15; then also, it gives the same octave number – 1. Or if we have this 30 and this is 10, then we will be having some different value. Or this will be now 3. So, this can be split as log of 10 3 and log of 2 10. And then, we can able to get the values of individual – these terms. And if we multiply, I will get the octave number as this. Regarding vibration when we define, we said this is nothing but oscillatory motion. But, what is the oscillatory motion? Oscillatory motion is – can be a periodic motion or it can be a random motion. And periodic motion – as we already defined earlier, it repeats after certain time interval. So… And most of the vibrations, which we have from the machinery – they are periodic in nature, because especially they are periodic in terms of their rotational speed.

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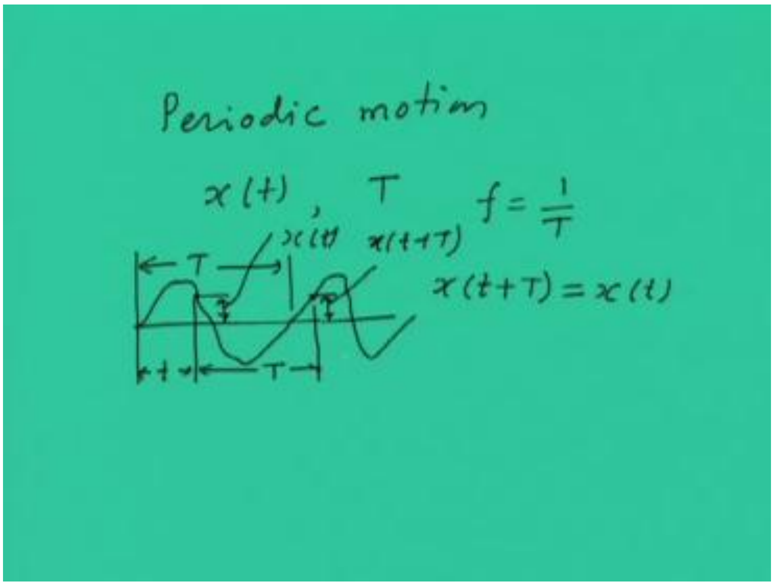

Let us again see how mathematically we can able to define the periodic motion. So, if x t is a particular signal and the time period of that is T; time period is nothing but the time in seconds after which this particular signal repeats. So, if we see a particular signal, it is periodic in this. So, it is repeating after this time. So, there is a period of the signal. And frequency of the signal in cycle per second can be given by inverse of the period. And from here we can able to see that, the condition for the periodicity is this. So, you take signal at any time. This is let us say at time t. Now, if you add to this capital T; this much from here to here you will get another point. So, you can see that, this particular displacement is equal to this particular displacement. So, this is x t and this is x t plus T. So, it is repeating after its period. Or, is valid for all – each and every point.

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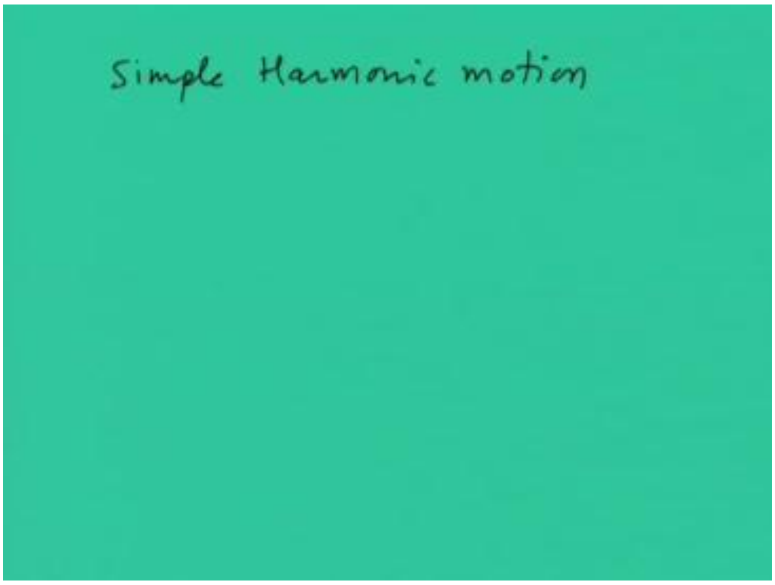

Now, once we are calling a periodic signal, there is a simplest – more simple signal, which is period is the simple harmonic signal; that is, the sine waves and cosine waves – they are the most simple periodic motion. And that is why it is called simple harmonic signals. And let us their characteristics. So, simple harmonic motion. How we define the simple harmonic motion? Simple harmonic motion will define… We take a projection of a point, which is moving in a circle at uniform velocity. So, motion of that projection point is defined as this harmonic motion. Let us see this particular thing through one simulation.

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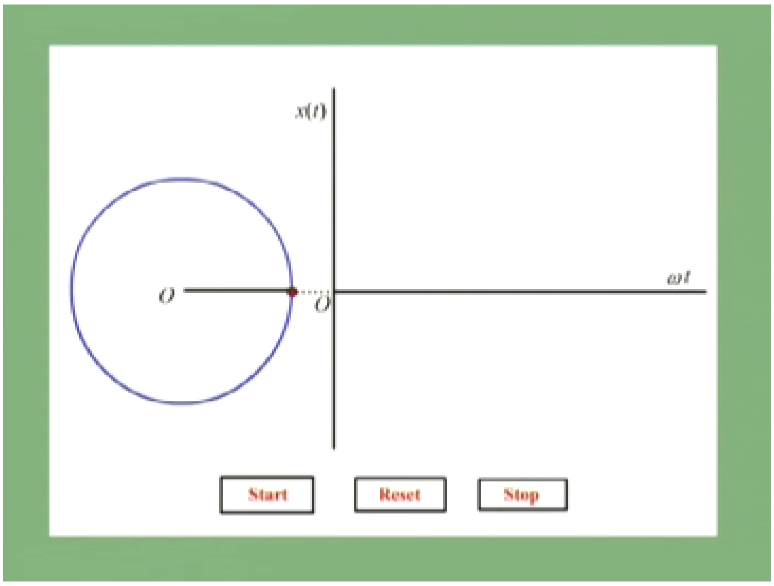

So, you can see that, I have drawn here one circle and this is a point, which will be rotating about the circle at uniform velocity. And we will be taking the projection of that point on this vertical line or… And that vertical line especially with respect to time… Even because you can see here omega… This is omega t. So, as this point is moving here, that particular angle will also will be moving here. So, we will try to track the projection of this point on this line and the angle. And we will try to draw how this particular motion is taking place. So, let us see how this motion takes place when this point rotates about this particular circle.

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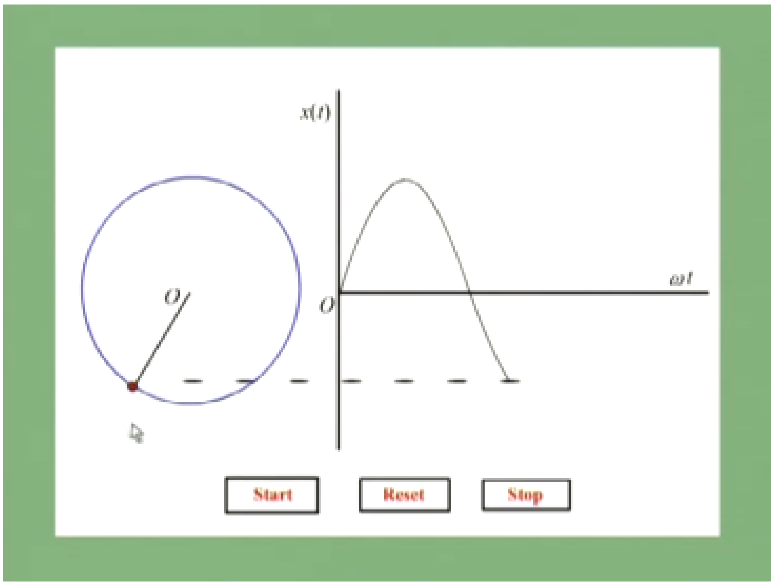

So, you can see that, as it is moving, we are doing the projection.

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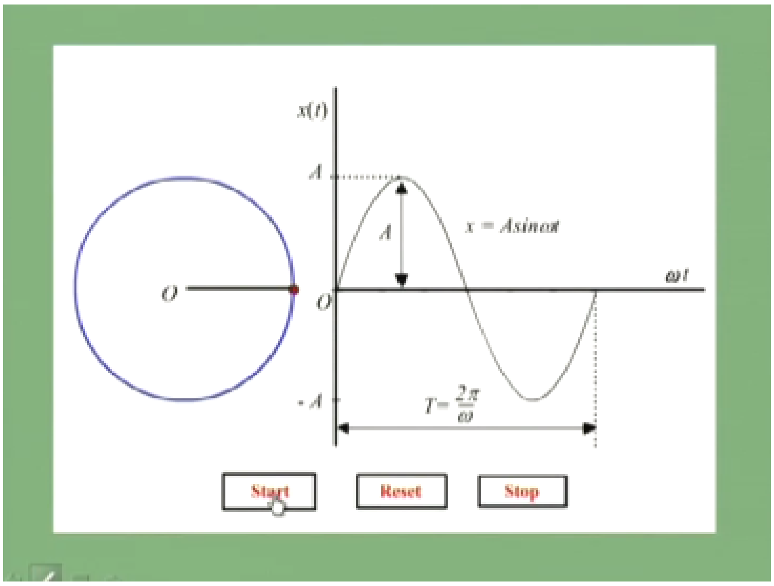

And, corresponding angle also we tracked. So, finally, we got this particular graph. This is a simple harmonic graph. That is nothing but we can able to express that as a… If x is the displacement in this direction, A sin omega t; A is the amplitude of this particular signal. So, x omega t is the… x is nothing but displacement at any one point. So, this particular animation… Again I will show how this point is moving along this circle; and that particular point we are projecting on this direction. And the angle, which is angle of this line with respect to horizontal – we are representing on this horizontal line. So, let us see again once this simulation.

So, this is simple harmonic motion, which is sinusoidal in nature. And you can see here the period of this cycle is 2 pi by omega; omega is the speed at which this particular radius is rotating about the circle; that is, a uniform angular velocity. So, we have seen how a simple harmonic motion is defined. I will show some more examples especially of a pendulum if we give a small displacement to that, how the motion take place; or, if there is a spring mass system; if we disturb the mass, how the motion takes place; and how we can able to plot those vibrations with respect to time.

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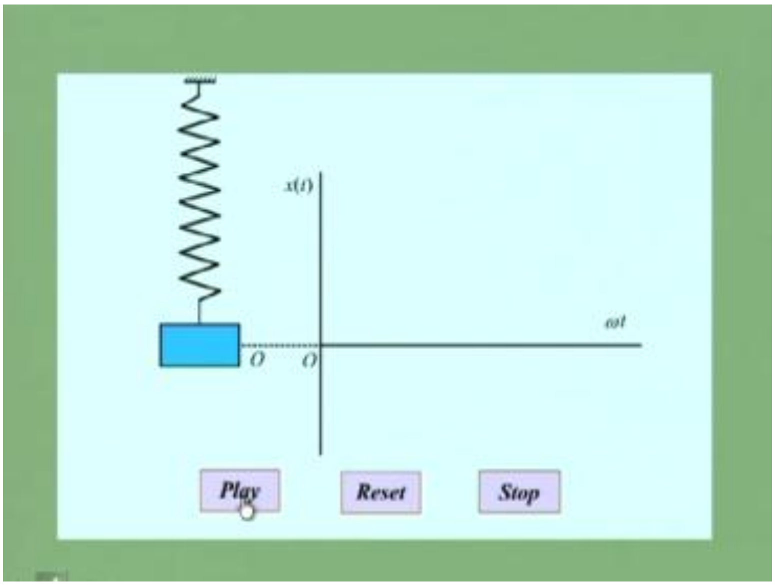

This is a spring mass system. The mass is… It is equilibrium position – static equilibrium position. And now we are giving a disturbance to this mass and we will track the displacement of this with respect to this time; this is time.

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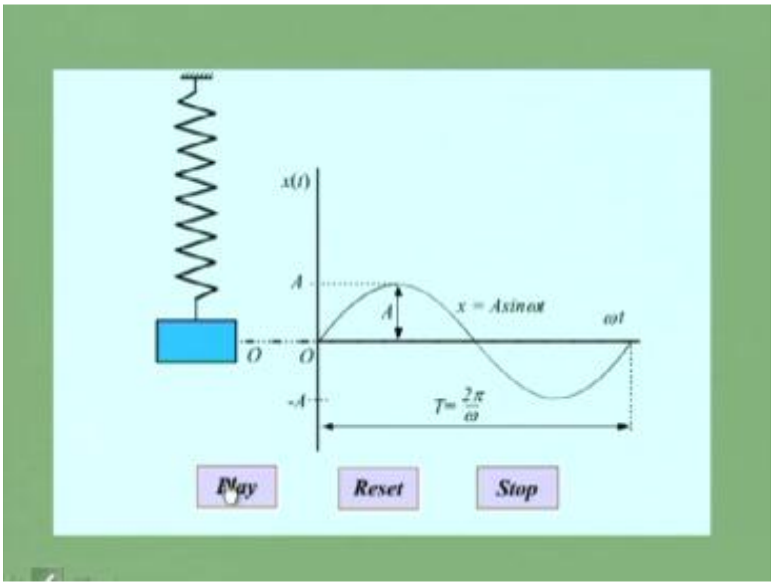

So, this is the… You can see it is identical to the previous one. Once we can able to see… So, when it is reaching at the mean position; mean position is occurring when it is reaching maximum position – maximum displacement; it is maximum displacement is occurring. Again, this is the mean position at which it got stopped.

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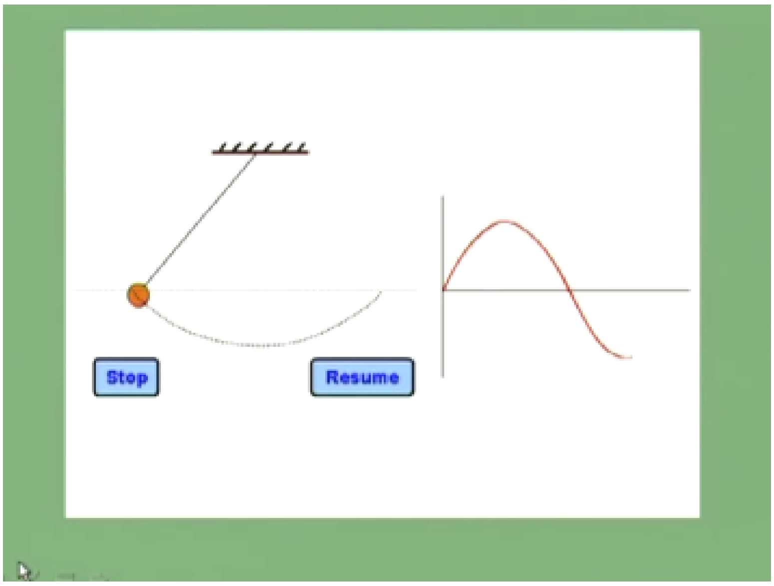

There is another example of the pendulum, which is shown here.

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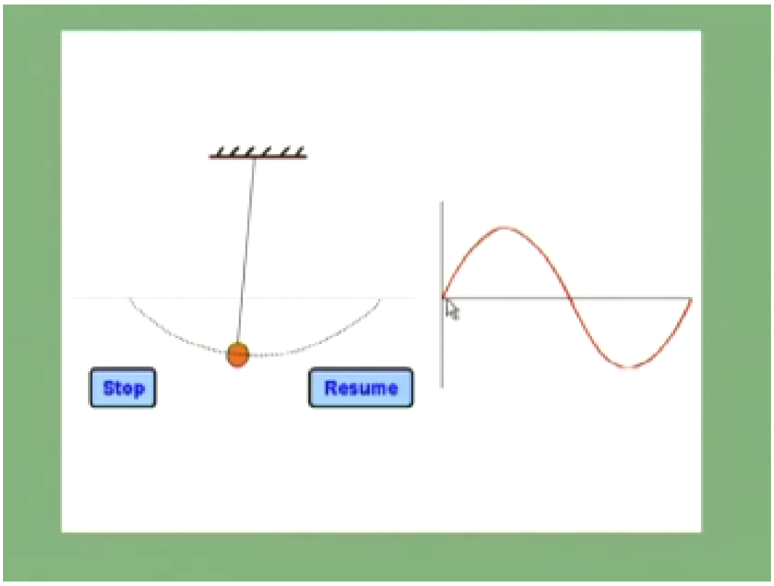

You can see as it is oscillating. This is the mean position of the pendulum. And this is the mean position of the pendulum. As this is the extreme position of the pendulum; so there is extreme position corresponding to that. So, it is also… In this, the displacement angle we have shown is large. But, if we are talking about simple harmonic motion, then we need to have this displacement as very small. So, this gives us some idea about how the motion, which is taking place of a particular object we can able to trace on a plot.

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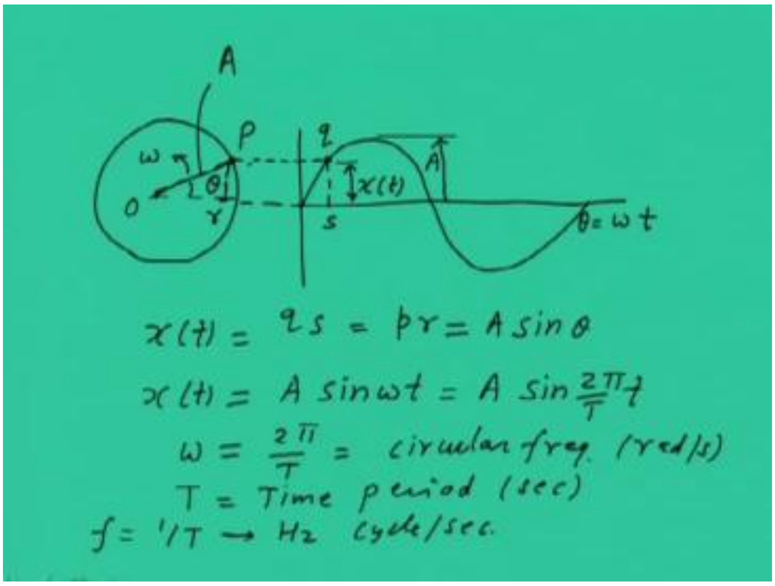

So, I am… Just for sake of completeness, I am drawing the simple harmonic motion. To show, at some intermediate position, there is theta. A point is present at some intermediate position, which is rotating with omega rpm at constant speed. And the plot of that – as we have drawn through simulation also, it is this. This is theta is equal to omega t. Now, at this particular position, if we project the point on this curve here. So, this point is let us say q; this is s. And if we drop a perpendicular on this, this point is r. So, this particular distance is x t at particular time. x t is qs – from q to s. And that is also equal to pr. And pr – if we know the radius of this; which is nothing but if we define the maximum displacement as A, when this radius comes at the top; that is nothing but A. So, this length of the radius is A. So, this can be written as… pr can be written as A sin theta. From triangle opr, we can able to write this. So, you can see that, x t, which is displacement at some point can be written as A sin… Theta is nothing but omega t.

And, here omega also we can able to express as 2 pi by the time period. So, this takes the form A sin 2 pi by T and this is the small t at particular time instant. This particular frequency is called circular frequency. And unit of this is radian per second. The time period T is the time period – this is in second. And inverse of time period is called frequency; the unit of which is hertz or cycles per second. We have seen that, how a displacement in a simple harmonic motion becomes basically sine function. So, once we have the displacement in some functional form, then we can able to get from displacement, the velocity and acceleration.

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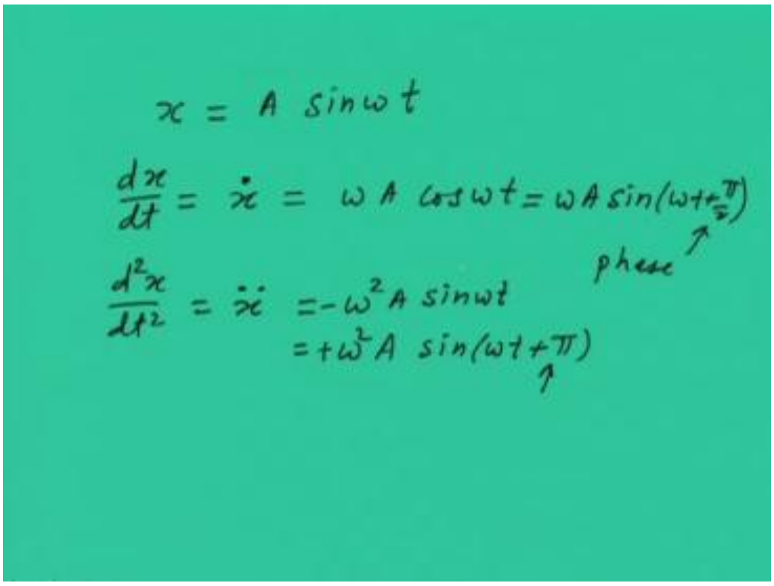

And, we can able to see how they are related through x is equal to A sin omega t. And velocity can be obtained by differentiating displacement with respect to T, which we represent as x dot; dot represents the derivative with respect to time. So, this will be omega A cos omega t. And if we want the acceleration, then we have to differentiate this once more. So, that we will be representing by x double dot. And that will give as omega square A sin omega t. And if we want to convert this in the sin function form, we can write this as omega A sin omega t plus pi by 2. So, that is equivalent to cos omega t. And similarly, this can be written as omega square A sin… Or, if you want to make it positive similar to this, then it will be omega t by pi. So, this particular quantity, which is coming… Or, they are representing phase. So, you can see that, the velocity term is having phase difference of pi by 2 or 90 degree with respect to the displacement. So, here the this velocity is leading by pi by 2 with respect to the displacement. Similarly, this acceleration is leading by 180 degree or pi radiance with respect to the displacement. And this particular thing can be shown in graphical form.

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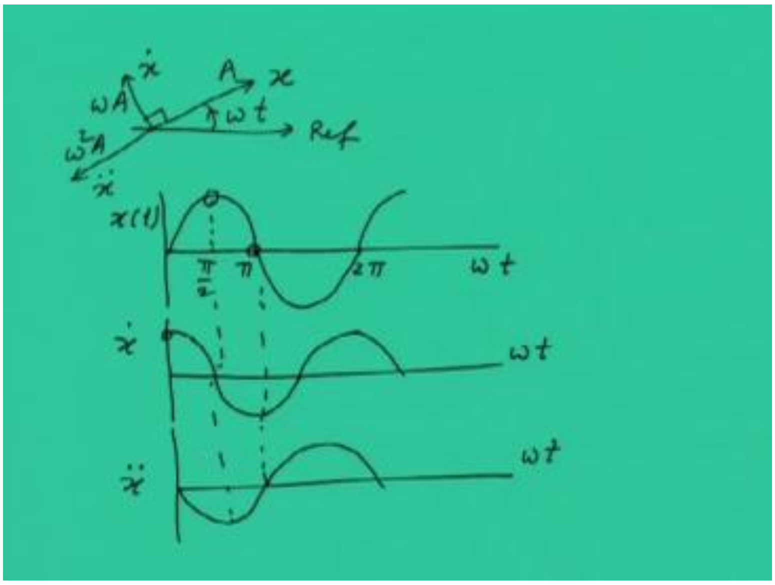

If we have let us say this is the reference line; this is the displacement, which is having angle omega t; then, velocity will be perpendicular to this. And we will be having a 90 degree lead because this is the positive direction. So, velocity will be represented here. And acceleration will be then just opposite to the displacement – 180 degree phase. This will be the acceleration. And the amplitude of displacement from the previous expression we know is A; velocity will be omega A; and acceleration amplitude will be omega square A. These are the terms you can see, are present here. This is the amplitude.

In graphical form, if we want to compare these – displacement, velocity and acceleration, we can able to compare at this. That will give us a better area how these signals are. So, this is a displacement signal; below this if we want to draw the velocity signal, this we have to start from here, because this is leading by 90 degree. Here if we want to express this; this is pi; this is 2pi radiance; this is corresponding to the pi by 2. So, velocity signal will start from here like this. So, you can see whenever it is having maximum; it will be having minimum. And wherever it is having minimum, it will be having maximum. So, you can see that, they have now phase difference of 90 degree, because now it is starting from this point directly. So, this is the velocity. If you want to draw the acceleration; then, because it leads by pi degree; so pi is somewhere here. So, we have to start the acceleration diagram from this point; that is, it will come like this. So, wherever minimum is there, maximum will come; wherever maximum is there, minimum will come. So, you can see the… Now, it is having pi phase difference. Through this illustration, we have seen that the velocity and acceleration – they lead displacement by 90 degree and 180 degree respectively.

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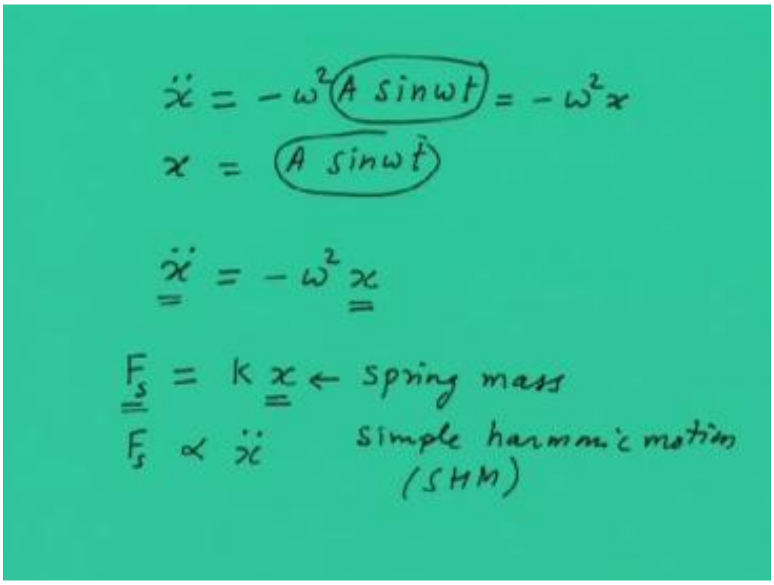

So, in this particular case, if you see the acceleration, which we expressed is this; and the displacement was A sin omega t. So, if we combine these two expressions… because you can see this term is present here. So, we can able to write this as minus omega square x. So, x double dot – acceleration is minus of omega square x. So, you can see that, acceleration is directly proportional to the displacement, but it is acting in the opposite direction. So, this is the definition of the harmonic motion in which the acceleration is proportional to the displacement, but it acts in the opposite direction to the displacement direction. So, we will see that, how this can be useful when we analyze the vibration of mechanical system, how we can able to seek the solution in the form of sinusoidal functions when we have the acceleration proportional to the displacement.

In the case of a simple spring, we know that, spring force is equal to stiffness into the displacement. And from Newton's law, we know that, the force, which we apply to the system is proportional to the acceleration. So, indirectly, here we can say that, acceleration is proportional to the displacement; that means in the case of spring mass system, when we take this particular kind of spring – linear spring in which spring force is proportional to the displacement, then it must execute a simple harmonic motion. Or, sometimes we call it as SHM – simple harmonic motion, because they satisfy the simple harmonic motion condition that, acceleration is proportional to the displacement; and which acts opposite to the motion.

Sometimes it is advantageous to represent the harmonic motion in the form of a vector, which is rotating about a point. Especially in this particular case, when we express the vector in the exponential form, then we get the mathematical advantage; especially the expressions, which we will be handling in analysis of the vibration – those will be simpler. And even the mathematical operations of the exponential form of the terms are simpler. So, let us see how we can able to express the harmonic motion in a vector form.

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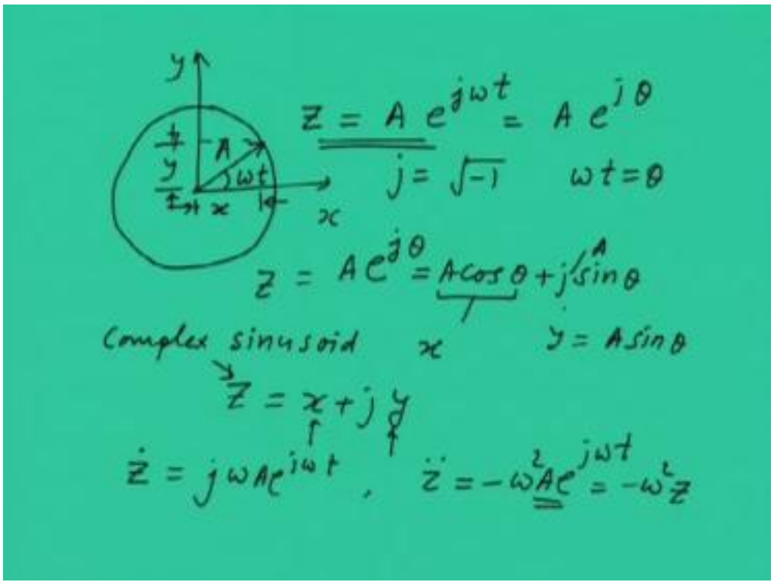

So, in this particular case, we express the harmonic motion in a vector form. Let us say this is a circle with these axes. And this is a vector having amplitude A, and which is making an angle omega t with reference axis x. So, we are representing a vector z as A exponential j omega t; j is nothing but root of minus 1; omega is the speed at which this particular z vector is rotating in anticlockwise direction inside the circle; and A is the amplitude of this particular signal. So, we express like this. Now, the advantage of this is that, even we can able to write this as in terms of the angle, because omega t is nothing but theta; omega t is nothing but theta.

As we already know, we can able to express this using Euler equation as cos theta plus j sin theta. And if we have amplitude of this – here amplitude; so this from figure, we can able to see that, it gives the x component. If we project this vector on horizontal axis, x is given as A cos theta. And if we project that in the vertical axis, this gives us the y. So, y is nothing but A sin theta. So, we can able to write this is nothing but z. So, z can be written; which is a vector as x plus jy. So, this we call it as complex sinusoidal. And in this, the real component of this; and this is the imaginary part of that. The advantage of this is we can have a time derivative of this. You can see omega t j omega t. This we are doing the time derivative of this – first derivative. And second derivatives – similarly, minus omega square j omega t. And that we can able to write it as… A's are there. And this quantity we know – omega square z itself; this is z.

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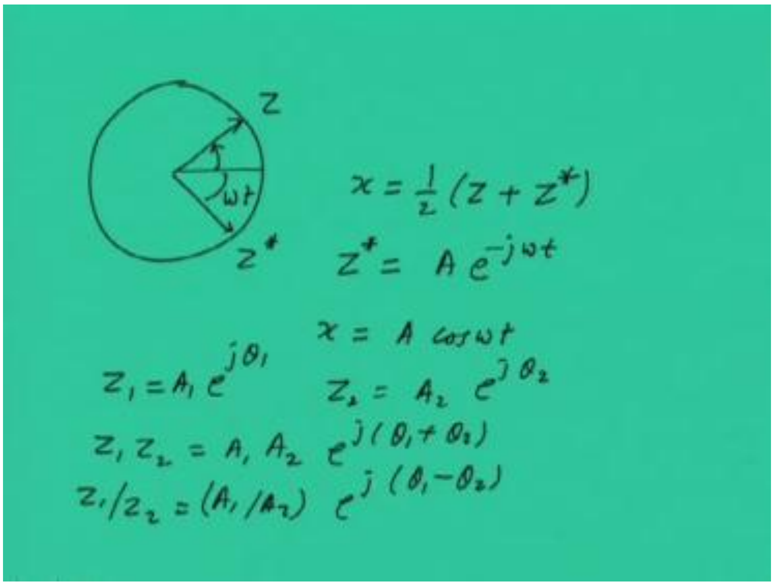

Now, if we have two vectors: one – z, which is rotating counter clockwise direction; another – z star, which is rotating in the clockwise direction. So, the projection of this on horizontal axis will give as x, that is… So, z star is nothing but a complex conjugate of z. And complex conjugate means in this particular case, we will be having A minus j omega t. So, if you substitute this here, you can see that, x becomes A cos omega t; if you substitute z and z star both here, you will get this quantity. This is the real part of the z. Some more advantage we can able to see if we have let us say z 1 as A 1 e raise to j theta 1 and z 2 as A 2 e raise to j theta 2. So, some simple operations like multiplication of these two vectors will be given as multiplication of this and summation of the angle. Or, division of that vector will be given as A 1 divided by A 2 e raise to j theta 1 minus theta 2. These are the simple operations we can able to do with this.

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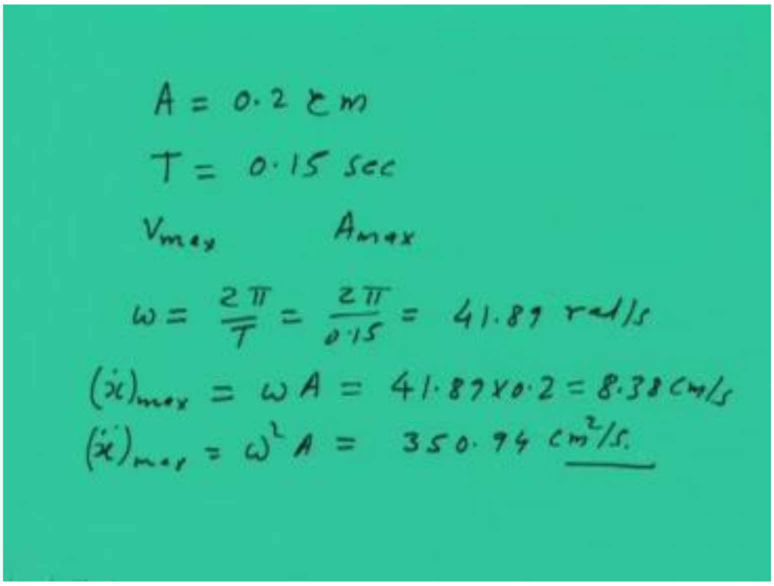

Let us see one simple example in which we need to obtain the velocity – maximum velocity and maximum acceleration of a sinusoidal signal. So, in this particular case, we have one harmonic motion; magnitude of that is let us say 0.2 centimeter. And the period of that particular harmonic motion is 0.15 second. And we have to obtain the maximum velocity and maximum acceleration of that motion. So, we know that, once we know the period, we can able to get the frequency, which is given like this. So, 2 pi by 0.15; that will give us 41.9 radian per second as frequency. The velocity max is nothing but the amplitude of the velocity; or, the sine terms will be 0; sine terms will be 1. So, here we can get this; that is, 8.38 centimeter per second. Similarly, we can get the acceleration maximum as omega square A. If you substitute on this, you will get 350.94 centimeter square. So, these are the velocity maximum and acceleration.

Today, we have seen the definition of the oscillatory motion, some simple terminologies used especially in the measurement of the vibration, amplitude; and especially in the frequencies also, how we can able to get the relative frequency measure of a particular signal. We have seen how the simple harmonic motion has been defined. And with the help of this simple harmonic motion, we have already seen that, how the velocity and acceleration have their phase difference. Finally, we have already seen that, all the exponential form of the definition of a particular motion help us in especially when we have some kind of a mathematical complexity while analyzing the… When solving the terms related to this vibration problem. In future, we will be using this in more detail.

Then, the advantage of this will be clear. So, with this background, now, from the subsequent classes, we will go into much deeper mathematical analysis of the vibration. So, in the next class we will be studying the free vibration analysis especially for the undamped case.