Machinery Fault Diagnosis and Signal Processing
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Lecture -13
Envelope Analysis

So, far you know we have studied about modulation and signal beating. But the question to us is you know how do, I find out this modulated signal which has been carried by a carrier signal. We talk about amplitude modulated signal how carrier frequency carries their modulated frequency. The information from the machinery to us is actually the modulated signal.

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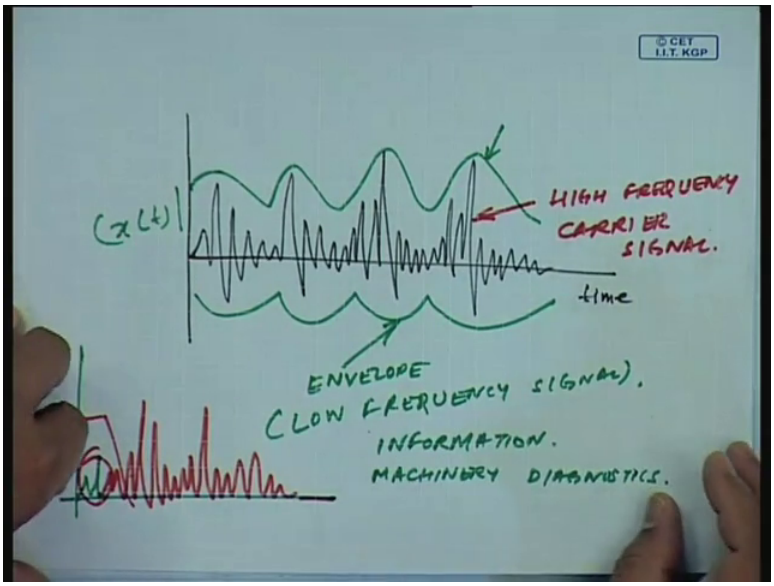

So, when you look at the amplitude modulated signal in time domain. We had a signal of this nature where in this is the high frequency carrier signal; this may not be of interest to us. But it is this envelope which is a low frequency signal. As you can see from the time period is actually the signal which contains information which will be useful for machinery diagnostics.

The question before us is you know if we go to a real machinery we will be having such signals on top of it there will be a lot of noise. So, question is once I do an FFT of such a signal which has the high frequency signal which has the noise etcetera. In the frequency spectrum the significance of this green signal in our case will be lost. It will be kind of buried in a high frequency noise.

A lot of high frequency noise and then how do I identify this, well intuitively you can write ever say now why do not we filter it, will filter it, filter the high frequency signals. So, that the green signals in the low frequency green signals are available that is fine. It is people can do it that way and people also do that without putting a highpass filter.

Where they when sorry rather a low pass filter wherein they will remove certain high frequency components and look into the low frequency signal. But sometimes it happens that even in these low frequencies there is lot of noise or other phenomena happening, which kind of obscures this green signal. So, we have to find out ways to find out this low frequency envelope.

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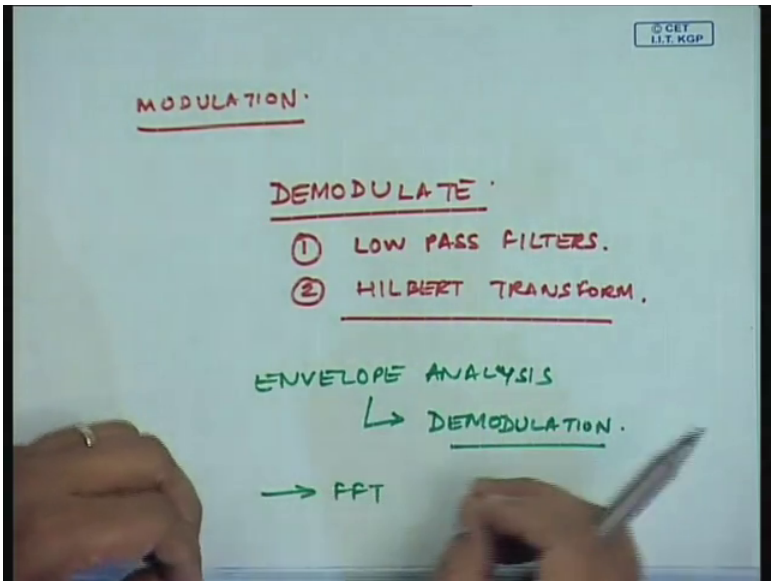

So, this big happens because of signal modulation, so at the receiver at the generation point of the signal there is a modulation effort happening because of the frequency. One is being related to other or one being caused by the other. Like the case of the rotating fans which I was telling you about. So, a signal has got modulated it has come to us as a modulated signal. So, our objective on how is demodulate the signal.

So, this demodulation has to be done by one is, I can put a set of low pass filters and then there are another technique which you will be covering mostly today is this Hilbert transform. But the problem with low pass filter as you will realize is, we do not know the frequency content of the

signal. So, what will be my cutoff frequency of the low pass filter is a very difficult thing to establish.

But you know diagnosticians or unless to dilute certain signals they play around with the low pass frequency and the cutoff frequency of the low pass filter and see whether any meaningful information is being obtained in the low pass low side of the frequency spectrum. That is one way wherein just by analog filtering we can do some sort of a demodulation. But now there are well established digital signal processing techniques using Hilbert transform.

Which will demodulated demodulate the signal to find out its envelope. So, envelope which we call as envelope analysis is nothing but it is also signal demodulation. Because I need to find out the low frequency signal which is coming as an angle, I can demodulate it the modulate the measured signal and then I can get the information about the signal.

Once this signal has been demodulated or envelope analyzed I can then do my traditional FFT to find out its frequency content okay. So, demodulation itself is in time domain or the low pass filters, you know we set it in all the signals from this filters are again in time domain after the Hilbert transform also the signals are in time domain.

So after we have got this time domain signal and that was that green envelope signal which I talked about. We can do further signal processing like an FFT analysis okay. Now I will before I go to the process of doing demodulation our envelope analysis. Let me give you one example as to how this demodulation of this modulation occurs in a real machinery and then how we can demodulate it to find out the defect frequencies of that machinery.

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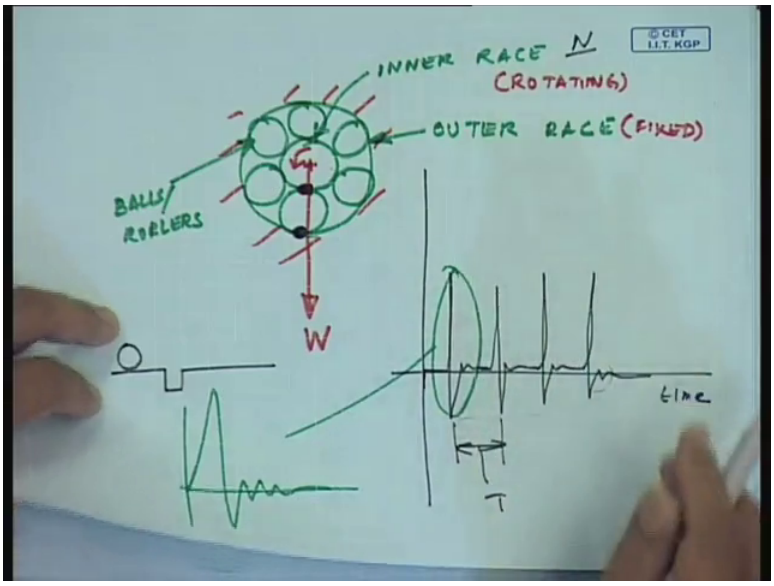

Let us take the case of a simple ball bearing ok. So, ball bearing actually has you know many elements this is known as the outer race which is usually stationary and this is the inner race and these are the rolling elements and these are the balls or rollers ok. Now there are possible scenarios this is rotating and this is easily fixed.

The outer race is fixed in our case and this is rotating. Now there could be a few possible cases that I have a defect located here in the outer race. In this case if we will imagine if you look at the time signal and each time this balls move, basically this balls will spin and rotate around the inner race and outer race and they have these rotating frequencies that can be calculated from the dimensions which we will come to later on.

There are different because if the shaft is rotating at N RPM all this will be relative to N RPM you know some will be little higher some will be little lower and so on. No matter what each time this rolling element or the ball passes over the outer race defect it is as if you are going over a pit each time and if you measure the vibration created because of a ball hitting a pit each time I will get an impact.

And then I will get another impact, another impact as many times the balls hit this defect I will be getting a continuous pulse of impacts okay. Now this impact the frequency of the impact is actually, inverse of this time period and that relates to the speed at which the balls are going over.

The defect okay but the phenomena is actually inside this impact if you magnify one of one such impacts maybe he will get a ringing signal like this.

The frequency which is there or which is characteristic of this defect is actually inside this. This is one way of getting a uniform signal out of this bearing because their defect in the out race. On the other hand suppose the defect was there in the inner race, let me put it here and because the shaft carrier load and load is always acting downward, some load W ok.

So, each time the defect comes under the load axis there is a great amount of force on this defect here and the outer inner race and then once the inner race moves away this force will decrease and so on. So, the intensity of the vibration will be modulated as the as a function of the rotational speed.

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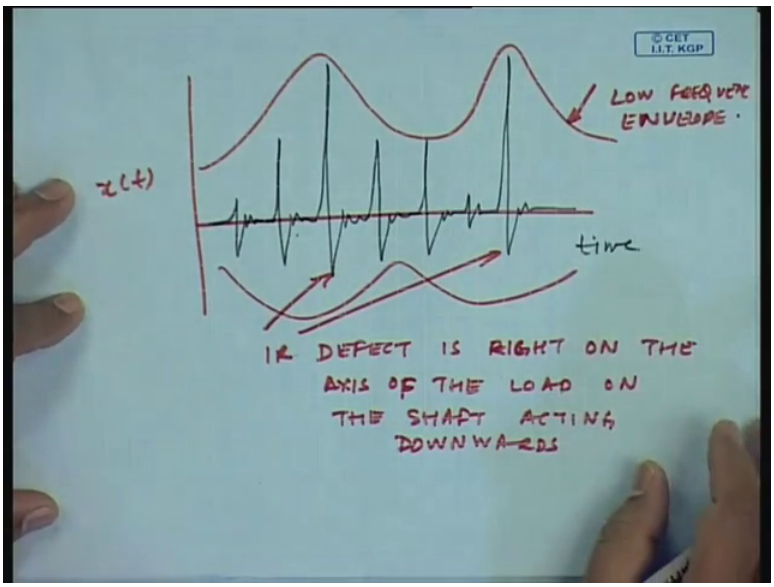

And I was to draw it here; I will have one defect in time domain, this high peaks means the IR defect is right on the axis of the load on the shaft acting downwards and of course this is the vibrations signal. So, you will see that there is again a effect of modulation occurring here. So, this is how physically a modulation also occurs okay.

Now if I am talking about a gearbox with intermediate shafts he can imagine there are about six to seven bearings. And you see because if I put just one transducer on the machine and this transducer.

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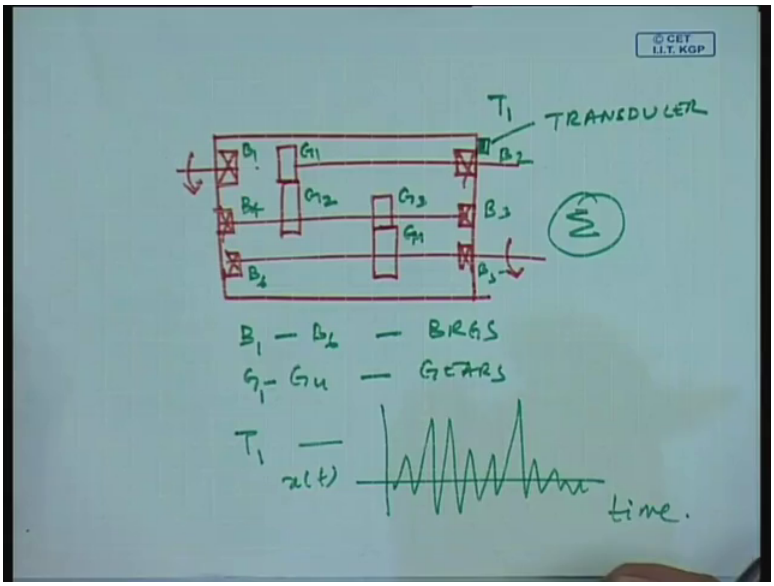

Suppose it is to measure, now I am going to explain to you the severity and the magnitude of the vibrations in levels and what kind of contamination a transducer may be having. Suppose this is my shaft this my gearbox okay there are bearings here, the bearings here, bearings in the holding the intermediate shaft and there could be gears.

But this is my input shaft, output shaft if I just put one transducer somewhere here and these are all the gears bearing B1, B2, B3, B4, B5, B6 a simple gearbox has an B1 to B6 could be six bearings G1 to G4, gears and I have one processors the T1. So, the signal measured but the transducer T1 could have everything okay. The problem before me is to identify from signal processing which bearing is defective and this is what in reality we face the problem.

So, the effects of supposing there are few bearings which are moderate which are having defect there are a couple of gears which are having defect so everything is a composite signal is what we get a some effect of all problems are there in one signal. So, the problem before us is in how do, I find out which bearing is defective.

So, we have to know the characteristic frequencies of each of these gears and bearings and if specifically if I come to one bearing. One bearing itself the inner race there could be a defect, outer race there could be a defect. In the rolling elements there could be a defect. So, all these defects will have characteristic frequencies and these frequencies we will tell later and how they can be calculated once you know the rotational speed and the dimensions and the number of rolling elements.

So, if these frequencies are known to us beforehand I am sure that in this signal these frequencies are buried, they are there but then we have to have a right kind of eye or magnifying glass if you may say so, to look into them and find out what these frequencies are. So, the envelope analysis is one such technique or signal demodulation is one such technique by which I can find out these characteristic frequencies.

So, nowadays in the FFT analyzers which are available there is an option of doing FFT after envelop analysis. We do the fast Fourier transform not of the total signal but only of the signal which is carrying the information. I am not interested to know about the carrier frequency okay. I am not interested to know the rotational speed.

I am interested to know whether my defects which are showing as modulated signals which are showing us that envelop can be detected in this signal. So, envelope analysis is that way a very, very powerful technique for signal processing. Now as I was telling you filtering is one method of finding out the envelope in a signal but another method is this technique known as the Hilbert transform.

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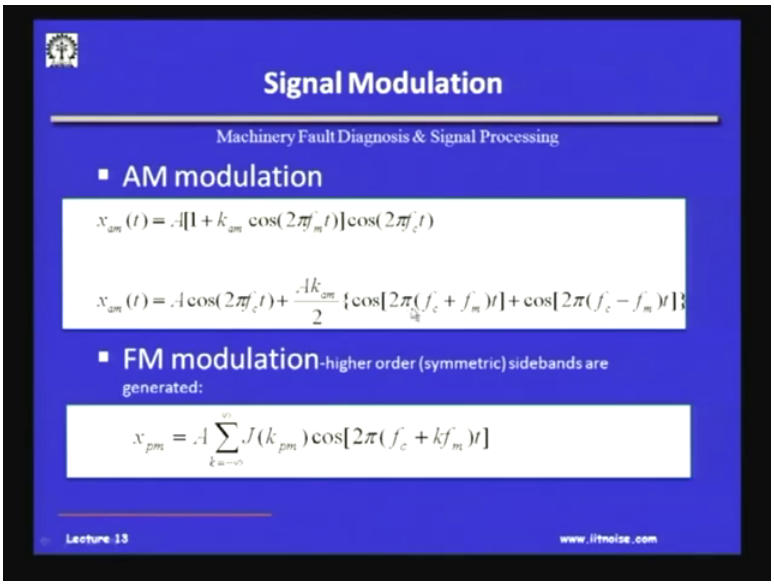

So, before I go into a Hilbert transform I just wanted to briefly tell you about this signals which are; one is an amplitude modulated case if I have this amplitude as a function of cosine or a sine series this is the frequency of modulation and then this is the carrier frequency you will see that the amplitude the modulated signal can be represented as this equation.

And you will see the sum and difference signals also show up and that is what we did by what is known as the sidebands occur because of a modulated signal okay and apart from the carrier frequency. But the just to recall if the signals were beating you will not see an individual frequency you will only see the sum and difference frequencies.

But once they are moderating you will see an individual carrier frequency and the side bands around the carrier frequency as fc + fm and fc - fm and then once you have the frequency modulated you will see a lot of symmetrical sidebands okay and given by this number k here. So, fc + k, k could be 1, 2, 3. So, there are a lot of symmetrical sidebands our locker and this particularly occurs in a gear box.

We will see practical examples later on. But the question is we know how to detect side bands because of signal modulation okay but question is if I am just interested to know fm it becomes a problem for me. Because the fm could be a very, very low frequency signal. How do I find out that fm from signal analysis okay so, that is the problem we have in front of us.

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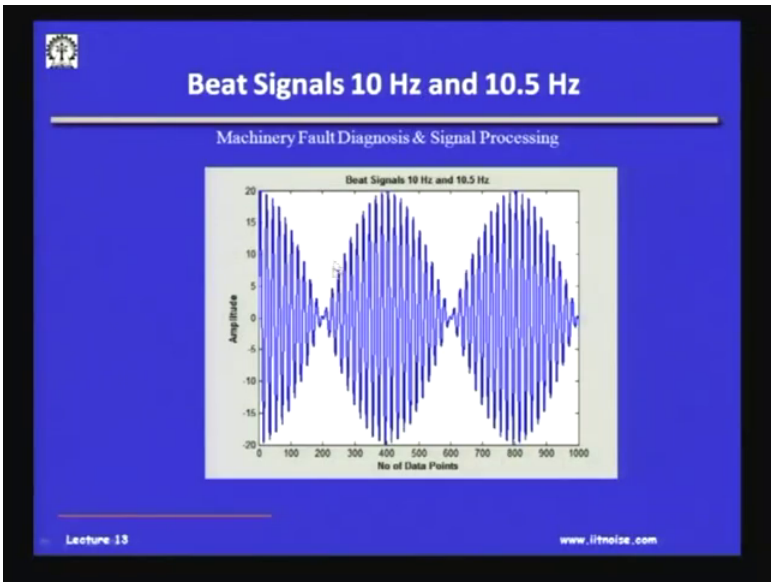

So, there is one mathematical technique which we do for example if the two signals are beating, I will get this kind of waveform. An amplitude modulated signal would also look like this as you would have seen. So, these signals here are actually a high frequency carrier signals. Because this number of data points are 1000 here. And that the time period here could be dependent on the sampling frequency whatever sampling frequency is taken here. So, number of data points times delta t.

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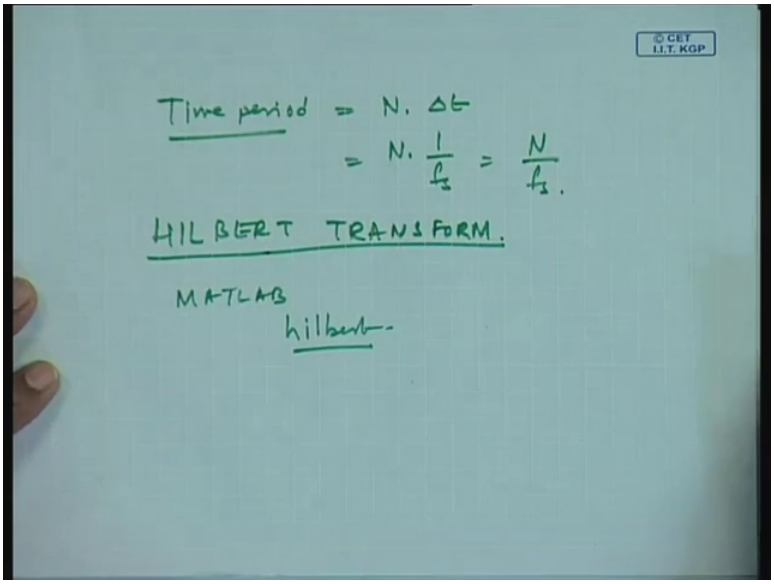

So, delta t will be total time period will be just to recollect total time period is nothing but N times delta t which is nothing but N times 1 by fs and N by fs. So, total time period of a block if N =1000, fs is whatever you will get that many seconds here. Now the question is I am interested to find out the, this envelop here ok, how do I do that.

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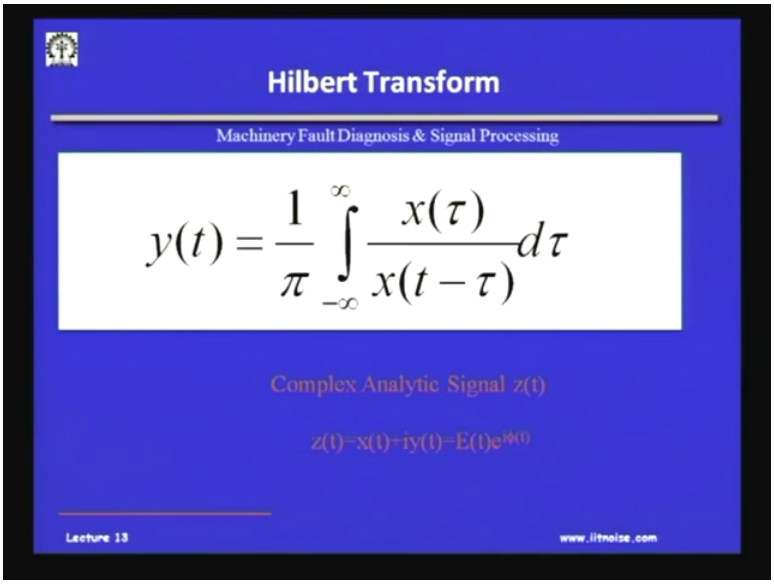

There is a technique which is very widely used in the transform in this, what happens is this is a mathematical expression of the Hilbert transform okay. We generate on an electrical signal zt here which is the original signal xt plus the imaginary part is the Hilbert transform of this signal xt okay, so, this analytical signal actually if you do the FFT of the analog signal.

We will get what is known as, I mean sorry the analytical signal itself is going to give you the envelope of the signal and this can be done in the software MATLAB. You use the function Hilbert on an amplitude modulated signal we will get the envelop.

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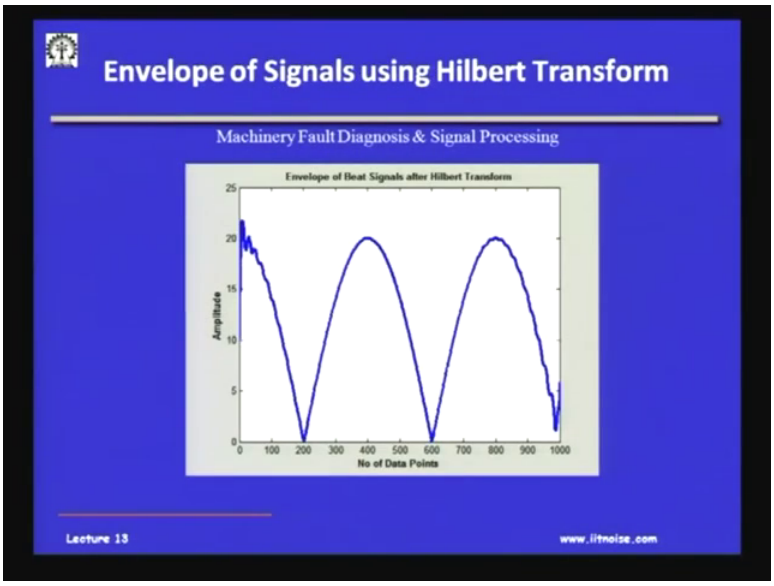

Now if you look here this is the envelope which was of the beating signal which has been obtained by just doing Hilbert transform of that beating signal and this you all can do in software like MATLAB etcetera very easily. So, no matter what because this is the low frequency signal which has been carried by my high frequency carriers.

If you look at the high frequency carrier here ok, this high frequency carrier has is carrying this modulated signal and I am interested to know this envelope and I will not go into the mathematical details of this transformation but it suffice to say by just by doing Hilbert transform the signal if you get an analytical signal wherein you can get the instantaneous frequency of the signal you can get the phase angle of the signal.

I will not go into details of this right now and then we will very easily and this envelope can be you can do the frequency analysis of this envelope signal. So, that you can find out the properties of the signal frequency content of the signal, so, envelope and an analysis of the barring signals can be done and then we can get the low frequency bearing defect signals.

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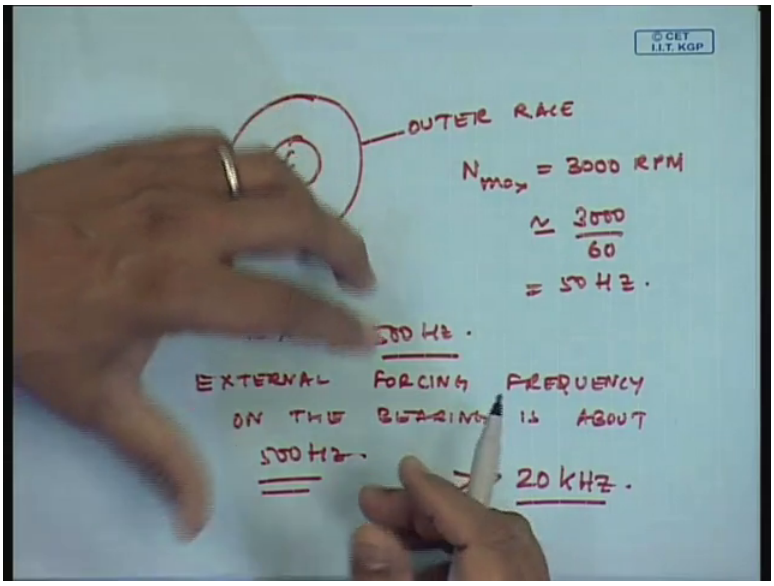

Because if you will recollect these bearings, bearings are elastic members say let me take the case of an outer race is just an outer race say a bearing is used in and machinery where in the maximum RPM is 3000 RPM and that boils down to 3000 by 60 that is 50 Hertz. So, any operation in this bearing is going to produce 50 Hertz excitation frequency right or few multiples of it at the most maybe if it is 10 times the fundamental rate this could be 500 Hertz.

So, the external forcing function external forcing frequency on the bearing is about 500 Hertz imagine because this is an elastic material it has its mass, it has its density, it is its stiffness etcetera okay. So, these rings also have their natural frequency we can model them in some equivalent stiffness and mass.

Obviously a bearing designer is not going to design a bearing whose natural frequencies are in this range otherwise in every time the bearing is in order operation it will get excited at its resonance. So, no designer will do that easily as a thumb rule. The natural frequencies of the structural elements of the bearings are much, much higher and above 20 kilo Hertz okay.

So, that during the operation of a bearing these does not get excited the bearing does not have large motions because efforts resonating conditions.

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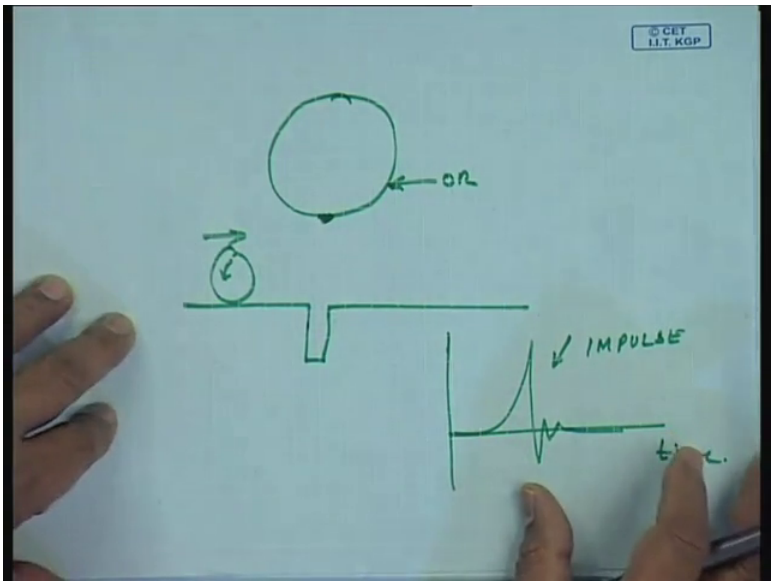

But you can think of it another way suppose now this outer race there is a defect as a pit as if you are going on the road okay and suddenly there is a pit. So, if these balls are traveling spinning and traveling on this outer race what is going to happen that if I come across this pit on the outer race I am going to have an impulse this will be an impulse excitation.

As if something has hit the outer race, as if you have banged on it like you go on a bump or a pothole on the road. You feel that impulse so this bearing has got excited by an impulse read.

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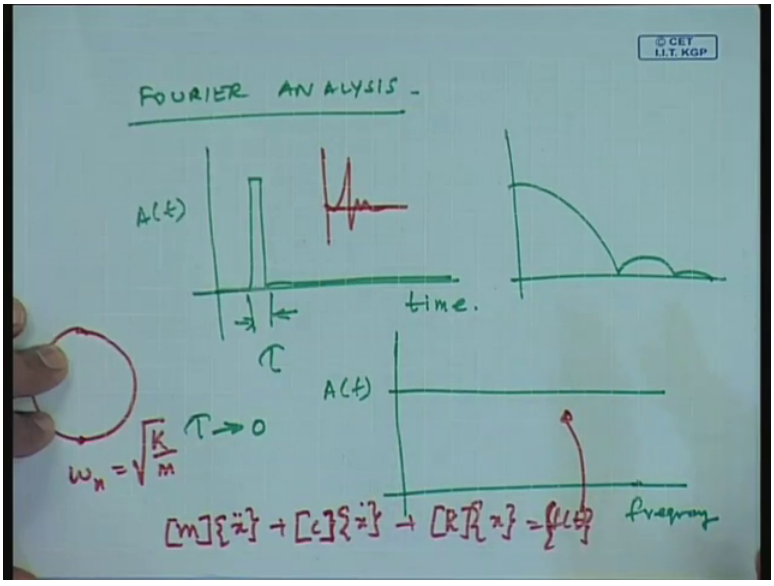

Now I will draw your attention to your earlier theories on Fourier analysis any time domain signal At. Suppose this is a very small signal of dimension Tau, Tau becomes very, very small its

response and the frequency domain will be very, very large and you perhaps would have done this at the homework I believe and so on okay or if this is this Tau tends to 0.

I will have the frequency response of a similar to a broadband excitation that means here, because of an impulse where time period is very small. The frequency response is very, very large when time and frequency are inversely related. So, now if I go back to the example of my rolling element bearing, the bearing is getting excited by a frequency because of a small defect which looks something like this or something like this okay.

Almost close to an excitation where all frequencies are present okay. So, if this mechanical system which has a stiffness which has a natural frequency Omega and k by m is getting excited by a forcing functions wherein all the frequencies are getting excited. Obviously its natural frequency will get excited, if I was to pose the problem another way.

Suppose I can model the bearing by this set of equation by a forcing vector in there our left hand side. So, this force is actually this in the frequency in the in this in time domain. But in the frequency domain this would look like this that means what the system in this case the bearing has got excited at all the frequencies and it has got excited at its resonant frequencies.

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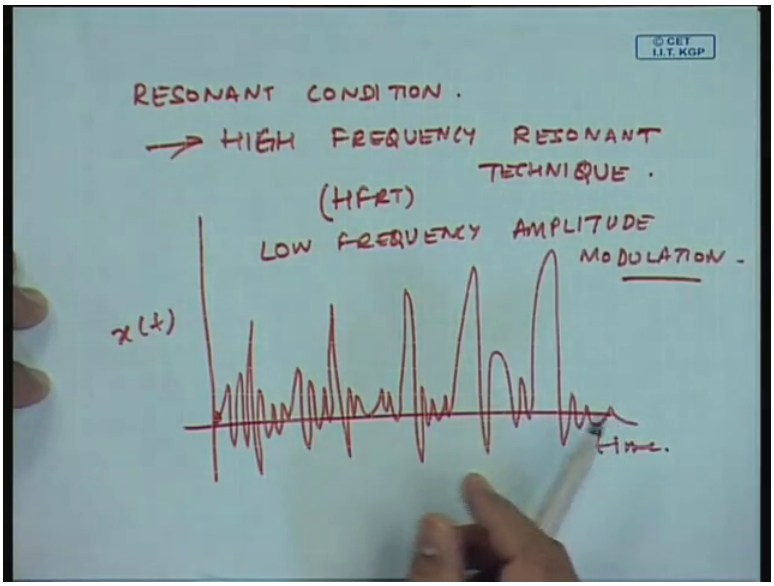

So, I am going to have a resonant condition or it is known as the high frequency resonant technique HFRT. So, in this case what happens if I go to the bearing signal, on top of the amplitude modulated signal I will have; just to draw them visually, on top of it I will have also large motion. So, I have a high frequency resonant technique a resonance phenomena occurring. On top of it I have the low frequency amplitude modulation.

And my transducer is not a mathematician, transducer cannot understand how this, transducer will faithfully represent my mechanical vibrations as an electrical signal and it will only give me this. So, it is we through our technique we have to understand where there are rather than taking a resonant has a resonance has occurred or whether a modulation is occurring.

Because in such large motions very, very low frequencies small amplitude, amplitude modulation will be obscured on top of it there will be so much of signal noise okay. So, we have to again find out by what method I can be sure that defect in the bearing has occurred.

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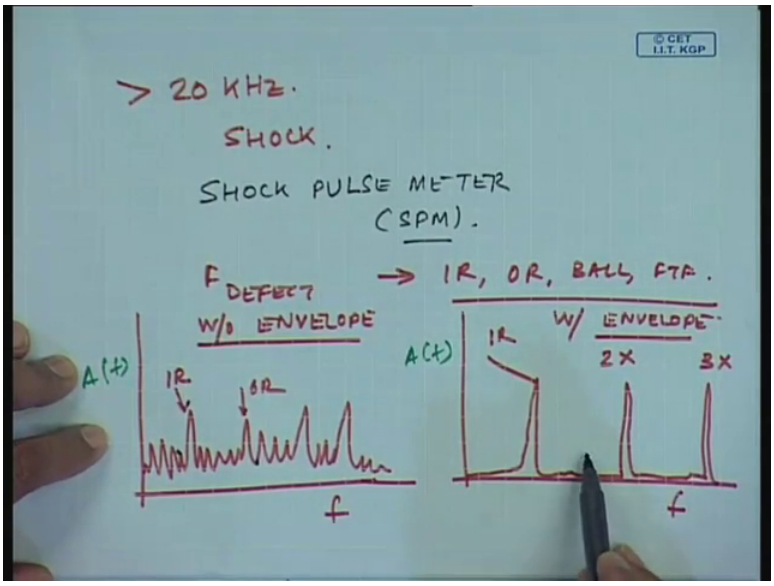

So, one way is to monitor the high frequency vibrations anything greater than 20 kilohertz, so, because of an impact or because if you say because of a shock this is considered as a shock because of a shock large motions occur and they occur at high frequencies. So, traditionally or conventionally there are many products, one such is the shock pulse meter or SPM.

This essentially means to measure the bearings response at frequencies beyond 20 kilohertz. To check whether the bearings resonance has been excited or not, well whose exciting the bearings resonance? It is not the normal operating functional of a bearing but it is, if there is a defect like a pit, like defect in a inner race and outer race.

Because of this pit I am getting an impulse and these impulses frequency responses a wideband response which has excited the right hand side of the equation so I am getting large motions at the resonant frequencies of this bearing. And as the bearing designer they would, they always make sure that the bearings natural frequency are not in the operating frequencies of the bearing and they are the frequencies much, much higher than the operating zone.

And usually of the order of 20 kilohertz, so in fact a vibration measurement at high frequencies is a sure indicator that a defect has occurred. So, in fact a shock pulse meter is nothing but a high frequency vibration meter so then we can say for sure that the defect has occurred. But we have a little more diagnostic problem in the sense here; well this defect is because of what? Is it because of an inner race, is it because of a ball is it because of an outer race.

So, from the geometry if I can calculate the defects frequencies okay this could be because of the inner race, outer race, ball on the fundamental trend frequency. And I will tell you later on how these frequencies can be calculated. Once these frequencies are calculated we can then use the envelope analysis or signal demodulation to identify in the frequency spectrum whether these frequencies show up okay.

And then I will when we talked about the fault diagnostics and bearings I will give you certain actual measured values measured spectrums of the inner race frequency or total frequency after the modulation. Because if you will see and just will give you two frequency spectrum, one without envelope analysis, one without envelope analysis, one without envelope analysis okay where this could be the defect frequency.

But if I do it with the envelop analysis, so this could be the IR different this is 2 times X, 3 times X and so on. And these are IR, this could be OR and this is what without envelope, this is with

envelope. These are the vibrations signals in fact the signals which I have drawn here, they are even much, much; I would say dirtier or noisier than this spectrum shown here.

So, it becomes sometimes very, very difficult to know whether it is an IR signal or noise signal. But once we do an FFT and I am sorry envelope and then do an FFT all this modulated frequencies will very nicely show up. But this is not to be confused with the shock pulse meter because shock pulse meter is a very, very high frequency vibration.

And other elements which will only tell you about the level but with this envelope analysis I can find out the individual defect frequencies okay.

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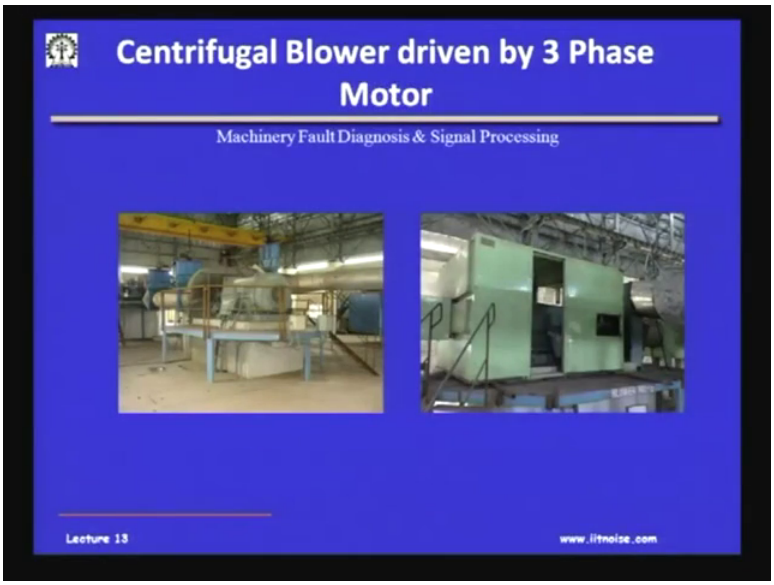

Now I will give you another example here, as to you must have all realized this is this is from a plant very close to Kharagpur, wherein this is a electrical motor it is a three phase electrical motor and then there is a blower. Basically they take in air and from the atmosphere and there are men there are series of blowers in this blower house.

There are about five such blowers and each one operating at close to 28, 29100 RPM and then you will see all of this there are a lot of valves here because these five blowers are in series and eventually they will take in the air and feed to the feed to the blast furnace okay. Now in this

single room because there are five blowers what happens if one of them is having running at as frequency or speed little less than even you know 1 RPM or a few RPM's.

The frequency of these machines will be different and because they are close by, you will happen they happen and the phenomenon of beating is going to occur. And if you enter such a place you will hear this kind of a loud no decreasing, increasing sound. If you go to any plant wherein many machines are operating supposed to operate at the same speeds.

Because of some reason or the other if some machine is running a little lower speed than the other you will hear this kind of wow, wow, this kind of veining waning noise which happens even in the ship engine rooms also I believe. Because there will be machines which will be running not exactly at the same frequencies. And this happens in the blower's also of course you know.

Now the reason I wanted to show you this is this sometimes should not be confused as more modulation okay. Because if you look at the response of a beating signal and a modulated signal they all look over is similar in the time domain. But if you look at the frequency contents of these rooms, now this signals they are quite different. In the amplitude modulated signals, I will see sidebands fm, fc - fm and also if I am interested to know fm.

I can do the signal demodulation or do the envelop analysis. But if I want to do find out the two frequencies which are responsible for greeting I can simply do a fast Fourier transform wherein how to be sure that the Delta f is very fine excuse me very fine okay.

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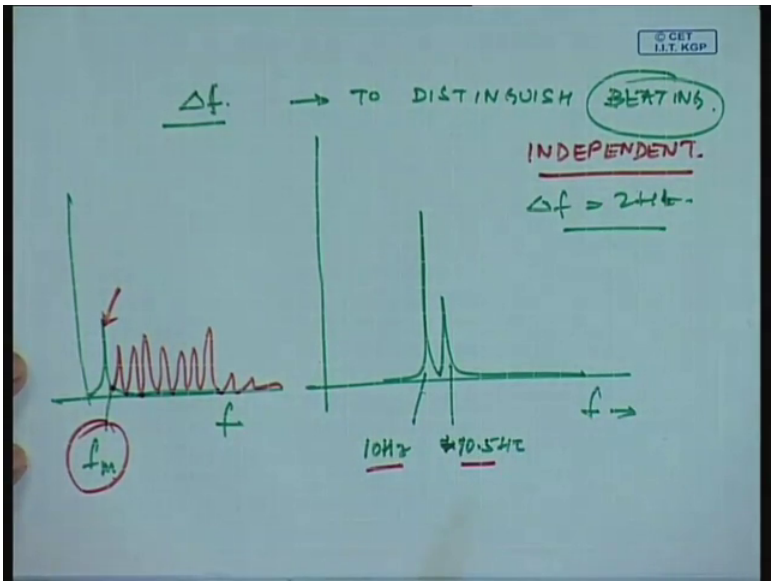

To distinguished beating I need to have a frequency resolution where Delta fs is very, very fine. Suppose I have one signal at, so this is a 10 Hertz and this is 10.5 Hertz, if my Delta f is 2 Hertz I am never able to distinguish between these two signals is not it but this signals would have created beating. So, in my frequency demand I can very easily mess this if Delta f is kept at 2 Hertz, if Delta f was equal to or less than 0.5 Hertz, I will be able to distinguish them.

So, that is the problem while doing frequency analysis to identify beating. Otherwise I will just mess this and beating is because of in demand independent frequencies. Because in this example this two blowers or two motors may not be having the same speed okay and they are independent. One is not related to the other okay but then this will give rise to a beating phenomenon.

As opposed to the case of the ball bearing wherein they defects and the frequencies which are related because if I have the inner race rotating at one speed, the outer race the balls their frequencies are all related to the inner race frequencies okay. And thus they modulate, modulate because of the load, modulate because of the speed and so on. So, amplitude modulation can be very nicely because you know if I if I have an FFT of a signal.

Where in there is a modulated frequency of a very low frequency fm this will be as I am telling very easily obscured in other noises. So, envelope analysis is a excellent method to find out fm

okay. But there may not be any other frequencies next to fm, if I have finite resolution so I can check that. But if I see other two frequencies 10.5 and 10 who are not related to each other then I can say the signals are independent and they are responsible for beating of the signal okay.

Now in a plant like this when I should just mention it to you that in fact we at IIT Kharagpur we designed it for them just to kill this noise which was generated because of the beating. Because again if you see if I have one machine generating 100 decibel of noise and we are machine of course another 110, 100, 100 decibel of noise there is some effect will be 106 decibels but because of beating at some frequencies there will be a large amplitude and that amplitude will be very, very loud.

So, to reduce that we can do put an enclosure wherein you can put in lot of learning material we will come to this later on.

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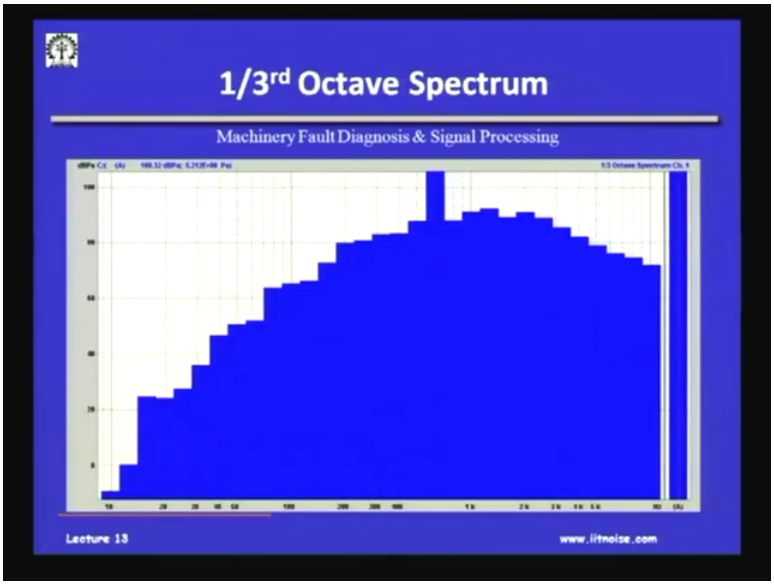

But I will just show you another spectrum of this noise which was measured by the; by which was measured and then we had analyzed this at that frequency. Now thi; what is here is a 1/3 octave spectrum.

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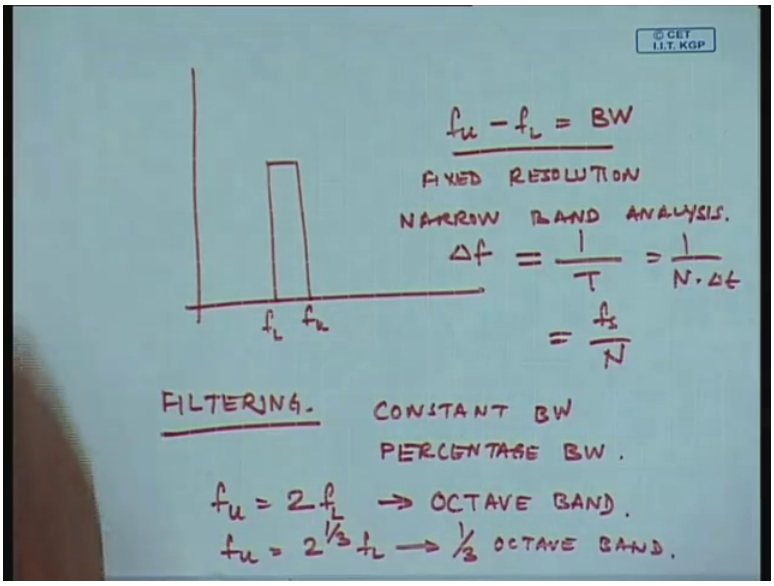

We have talked about the different types of filter wherein I can have a fixed resolution filter wherein if a filter has an upper band and a lower band okay, the bandwidth of the filter is upper band minus lower band. In the fixed resolution case like we do in the narrowband, when you do the narrowband analysis what happens is delta f, we specified delta f how do you specify? It is 1 by T, it is 1 by N delta t, it is equal to fs by N.

And that is fixed when we do the narrowband FFT analysis. But FFT analysis was not done but I am doing frequency domain analysis by filtering I can set filters of different bandwidth. I can set filters of constant bandwidth or another world another filter is percentage bandwidth. In percentage bandwidth there is a relationship between this upper frequency and lower frequency.

If the upper frequency is equal to twice of the lower frequency this is what is known as an octave band and if the upper frequency is 2 the power 1 by 3 fl, this is a one third octave band okay. The reason we have octave band and one third octave and there is a history behind it because in our human ears can distinguish octaves or frequency very easily.

I may not; my ear may not be able to distinguish 10 Hertz and 10.5 Hertz, I may require narrowband and unless it was distinguish between 10 and 10.5 Hertz or 10 and 10.25 Hertz. But perhaps or human ear some of you can perhaps distinguish 100 Hertz or 200 Hertz or 400 Hertz

or 1000 Hertz. Because they are almost multiples, so traditionally when FFT analysis was not being used people were using fixed band filters analog filters to do filtering.

And nowadays also since this has been predominantly used in the industry people stick to what is known as one third octave band. And if you look at this spectrum here this closely corresponds to about 500 or 600 odd frequencies which happen in this band. You will see all the levels are pretty low but it sticks up around 6 this is 400 this is 1 kilo hertz. There is a one third octave spectrum so this is a percentage for a bandwidth here.

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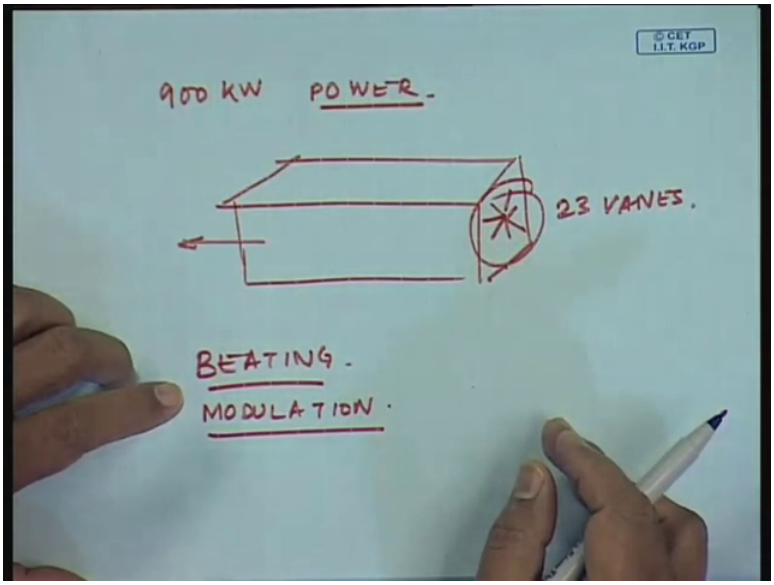

Around this is nothing but the electrical motors blade pass frequency because behind the electrical motor in on such large motors traditionally each of these motors was close to about 900 kilowatt of the power ok and now this large motors ok and the shaft which is rotating and this motors and running continuously and then they are all blowing in hot air.

You know this air finally goes to the furnace ok at a very, very high flow rate. So, these motors would all become heated up so in fact and that rear of the motor there is a blower and this blower has a fan and this fan there are number of I think about 23 vanes. So, this air gets sucked in into the motor and this motor is getting cooled and then on this vane creates, you know because it is a fan rotating at very, very high speed.

This is what is responsible for the motor noise and this frequency has shown up here and if there are 5 such motors in that plant and there is a small variation in their speed this is giving rise to beating okay. And obviously I cannot bring down the beating phenomena because for operational reasons some of the fans would rotate at slightly lesser spin the other one.

So, all I can do is to reduce the effect of the large noise which is heard because of the beating is too potent and encloser on the motor of course there are other issues that design enclosure should not introduce you know should not increase the temperature inside the motor because the bearings which are there they are some there are certain class they should not get overheated more than 75 degree Celsius.

Because if you enclose it the cooling air capacity to the motor reduces and the bearings become hot, so bearings may seize, you know it is there all it is like a domino effect. So, any plant if you see there are enough protections for the motor, for the bearing, for the vibration, for the noise particularly for the bearing they we need to also have around the clock temperature indicators to see whether the temperature is increasing or decreasing or staying.

Still if the temperature increases we need to take precautions as to how to reduce the bearing temperature maybe we should have an chillers on the enclosures when we have you know hot environment where in the machines effect, machines will get heated up because of an enclosure we need to have one of chilled cool air going in okay like an air conditioner small air conditioner put in fact such enclosures are there.

Enclosures to having chillers and then so the temperature does not okay. So, the purpose of this lecture was to demonstrate to you the two phenomena which occurs in machinery one is beating, beating has occurred in this case of the blower. Another is a signal modulation these are two phenomenon's which occur. And then we have to find out methods how to distinguish them.

To distinguish beating I have to have the frequency resolution reduced, to distinguish amplitude modulation I have to do what is known as the envelop analysis and envelope analysis could be

done by low pass filtering or it can be done by Hilbert transform okay. And once we have understood the signals we can now diagnose the fault in the machine okay, thank you.