

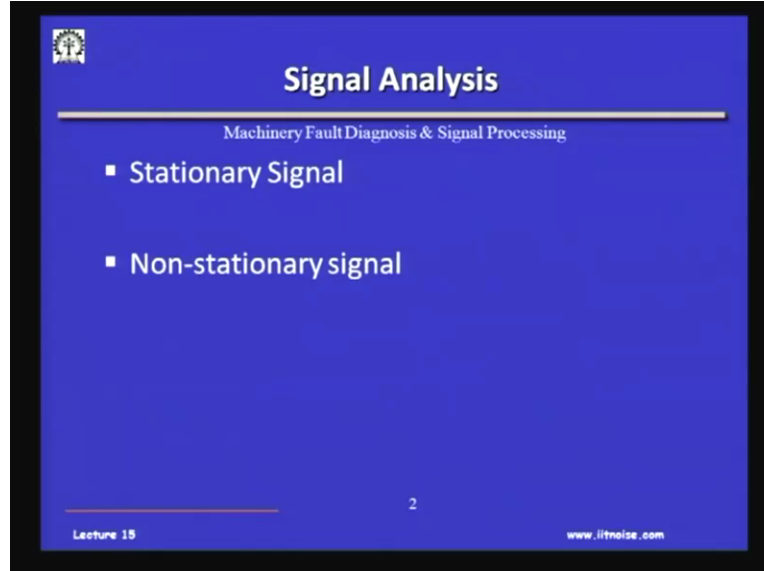
Machinery Fault Diagnosis and Signal Processing
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Lecture -15
Order Analysis

Today's lecture is on order analysis after having discussed, the Fourier transform, Fourier series, Fourier analysis, usually; I would have seen that in Fourier analysis we dealt with stationary signals wherein, the signal was not changing during the time the Fourier operation was being done. But in real life, you will see instances, where the machines speed do not remain constant and they change earlier doing either the data acquisition or doing the analysis.

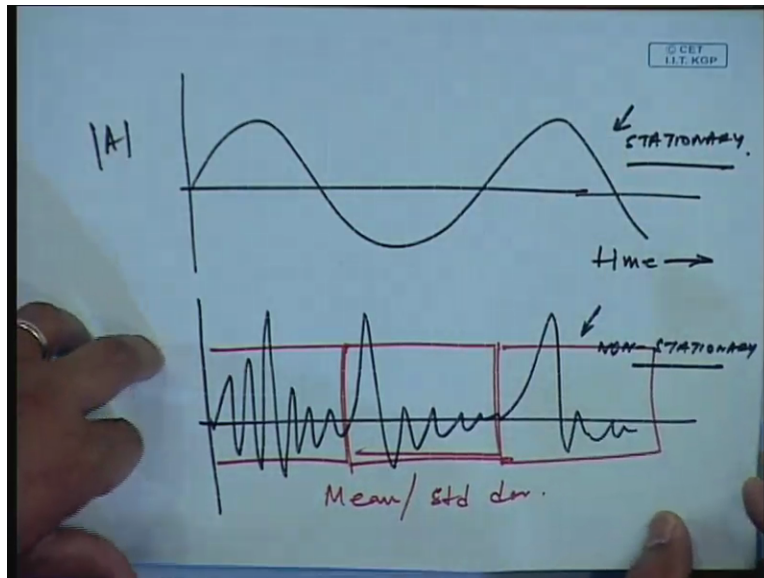
We had discussed about Cepstrum Analysis wherein we could find out the families of sidebands. But today, in the last series, on signal processing that would be completing module 3, we will be discussing about order analysis. So, let us see what this order analysis is.

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To begin with, I will just recall our discussion on ideas on signals.

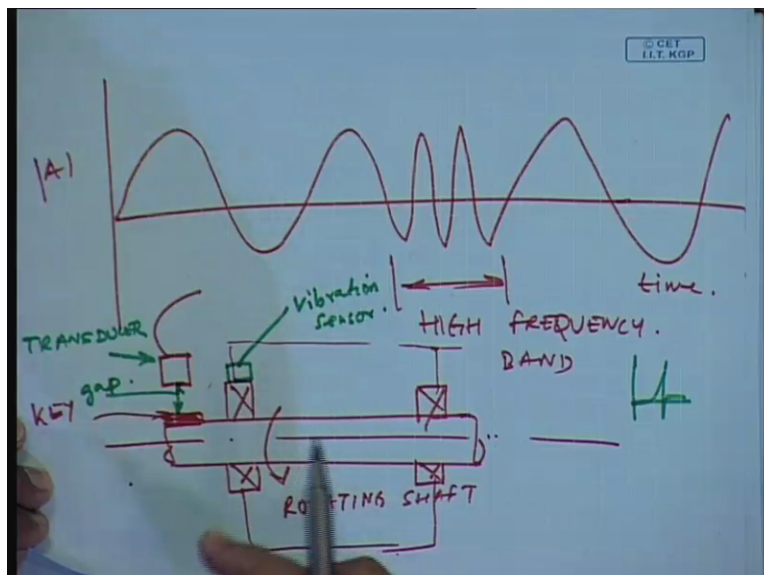
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Signals could be periodic and very deterministic or Siren signals could be. This could be an example of your stationary signal and another could be non stationary in the sense, the features of the signal over a given block of time, are different. Like the mean, standard deviation, etcetera could be different over different blocks of time, which is the reason, why we call them to non stationary.

As opposed to stationary signals, whose RMS amplitude whose mean, whose standard deviation is the same. No matter, how long where you take the sample or take the signal. But let us take the case of a signal from a rotating machinery, wherein the speed was changing.

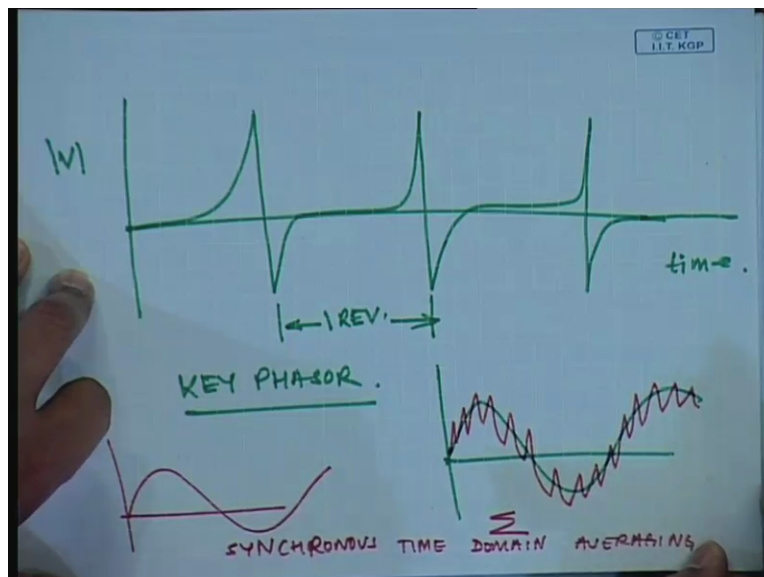
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And you will recollect maybe the frequency was increasing, again decreasing and this kind of time period will be obtained. This is the high frequency band and this is the relatively low frequency and this is the amplitude. Now, how is such a signal generated is possible, we will see and I will take it to the one experiment, wherein I will show you how this has been collected.

Usually, if I have a rotating shaft and there is a usually a key way in the shaft is rotating, if I, and of course, I know, this is held on bearings, may be, well, and these are my bearings and of course, there is the casing etcetera. This could be any machine and if I put a transducer here, this is my transducer, okay. Now, what would happen is, this transducer if it was going to sense this gap.

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Every rotation what would happen is, this is the time, this is the voltage has generated by the sensor and this should nothing but one revolution of that shaft. Now, if the speed of the shaft was changing because of the dynamics of the machine, what would happen? This time period would either decrease or increase but that transducer or which is sometimes, known as a key phaser, by some commercial companies gives the signal as to indicate, whether the shaft has come just below, the key has come just below, the transducer.

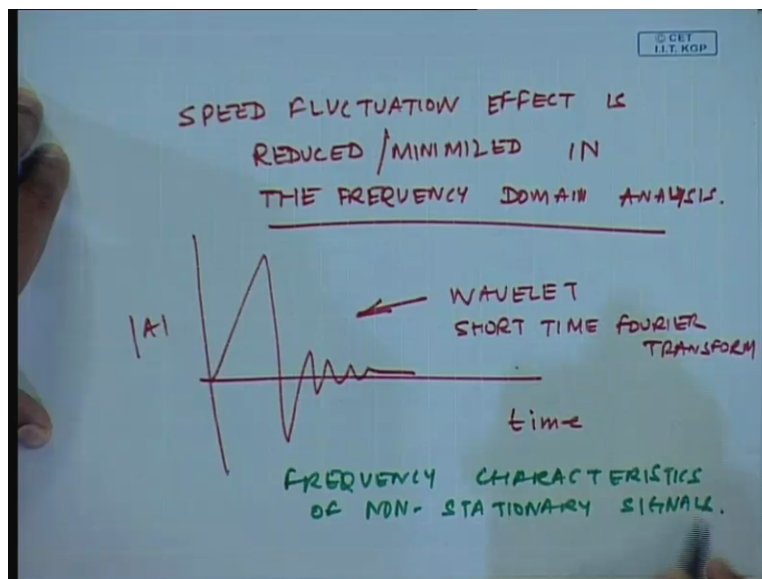
So, any speed fluctuation is captured by just knowing that one rotation of the shaft has been completed. Now, if while we are doing a detection, for example, if I had put an accelerometers

here, or a vibration sensor here and through the appropriate software a command was given that, only when this transducer senses a spike, then only, you acquire the data.

So, in that sense, it always becomes that this is kind of synchronous to the location of the key way, below the transducer. So, if the speed is changing I did not worry. Each time I will be capturing my data just from one single point and this could be my vibration data. And if this vibration data had noise, this would look something like this.

And then, if I repeatedly added such signals from the vibration sensor, and did I mean I would get a neat signal like this. And this is what we had perhaps discussed earlier. This is known as synchronous time domain averaging, okay, so, such synchronous time domain averaging, if we are collected by key phaser triggering. What we could do is, we could remove the non-stationarity out of a signal because, how this order analysis helps us?

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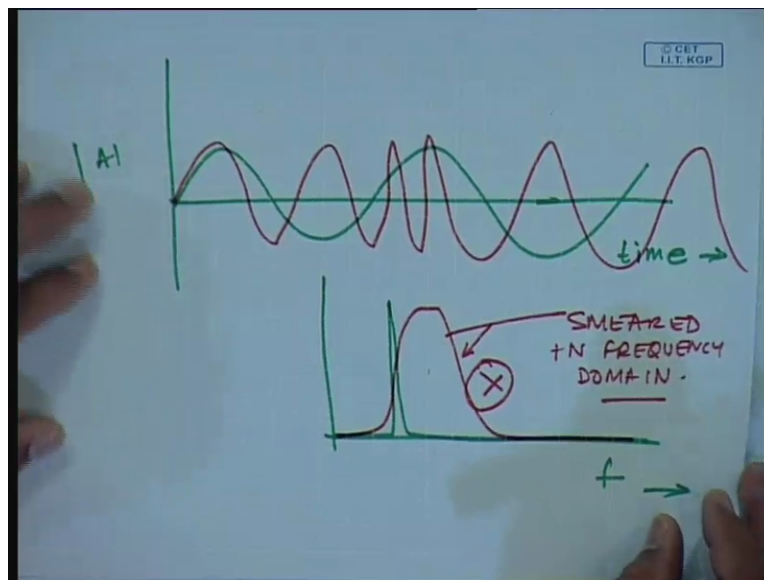


Because I do not want to bring in a speed fluctuation effect is reduced or minimized in the frequency domain analysis. Well, what does this mean? Just to recollect, I have told you only about stationary signals and non stationary signals. So, I want to remove the non stationarity, out of a signal and just find out this stationary component of the signal. But that does not mean that non stationary signals have no use in condition monitoring. That is not right. For example, if I take the case of a, some impact, okay.

I could do the frequency characteristics of such an impact, by techniques of signal processing which are known as, you know, wavelet analysis, short time Fourier transform, etcetera okay. Just to understand the frequency characteristics of such non stationary signals. So, there are a well-established signal processing techniques like wavelet analysis, STFT or short time Fourier transform to find out the frequency characteristics of non stationary signals.

Or which are known as the time frequency characteristics. We are not going to discuss about this. But we are rather going to discuss, whether in a rotating machine, if there is a small fluctuation of speed, it leads to non stationarity. But I, am still interested to find out the stationary component in the signal. So, what kind of analysis we do? Like I just explained you we do the time synchronous averaging by a key phaser signal or by a trigger signal obtained from the key.

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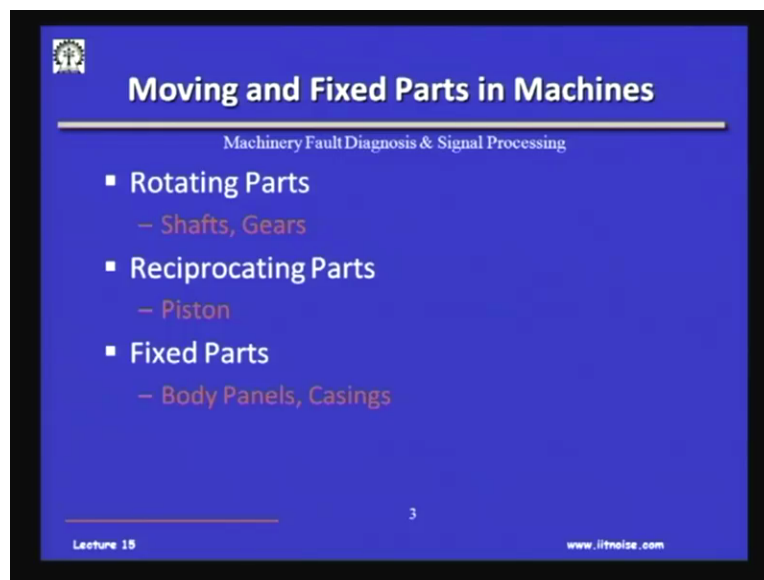


Let us see, if this speed was fluctuating, while we are doing a, for a frequency transformation. What would happen? See, if I take such a signal and do the frequency domain analysis? I will see just one peak, perhaps, right; because this one signal, but imagine, if for some reason, there is a speed fluctuation in the machine, so what is going to happen? So, in such a case, what would going to happen.

As you know, we will start with the low frequency, maybe during the process of operation, I will see in the FFT, many frequencies: One because of the low frequency, one because of the high frequency. So, I have mischaracterized my signal because the signals transmitting a frequency had changed while I was doing the FFT operation. So, this is not right. I would not like to have such an analysis where the frequency representation is smeared bandwidth, smeared in frequency domain ok.

So, rather we will now see how such a smearing can be avoided, rather than looking at the frequencies. Had I looked at how many revolutions it had completed, I could have got. This, I will remove my time index from time to maybe number of revolutions. And that means actually orders. How many orders are present? So, no matter of whatever is the time taken as long as one complete revolution is not completed, I will not be getting affected.

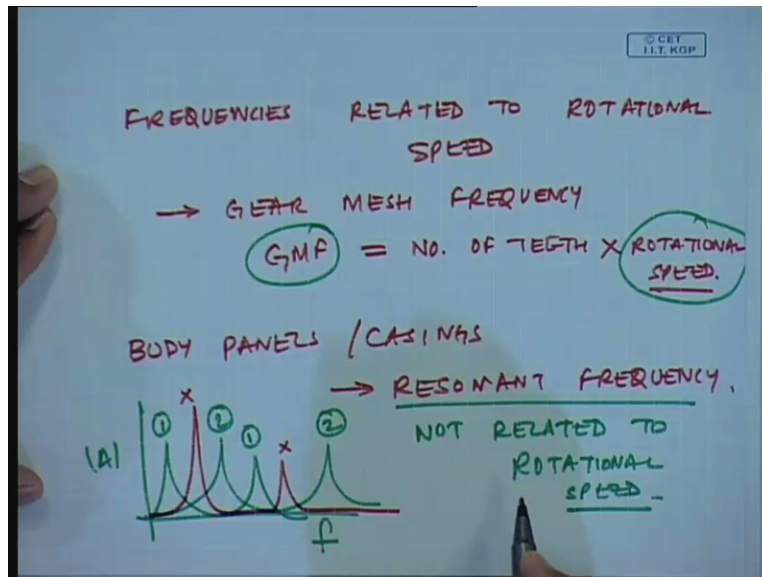
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So, we see, in many machines, we have moving in fixed parts in machines. For example, this moving parts could be rotating or could be reciprocating, rotating parts could be shafts and gears; reciprocating parts could be a piston, etcetera. So, the frequency of these rotating parts all these reciprocating parts are always related to the rotational speed.

If my rotational speed changes, these frequencies would change. But there will be also certain fixed parts like the body panels and casings. They will have certain resonance frequencies and these frequencies are not going to change, no matter what happens to your speed.

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So, you can see that there are some frequencies related to rotational speed. Speed like say for example, gear mesh frequency or GMF. This is nothing but number of teeth times multiplied by the rotational speed, right. So, you see these, the rotational speed changes the gear mesh frequency in the spectrum is going to change. And if the machine, there is a small fluctuation in speed.

This fluctuation in speed could be because of power supply variation, could be because of the supply frequency variation, could be because of the load on the machine. So, there will be momentarily a speed change. So, this is going to have, to get frequency because if you know, if you are doing 100 averages of an FFT operation, it takes certain time; within that time taken to do 100 averages.

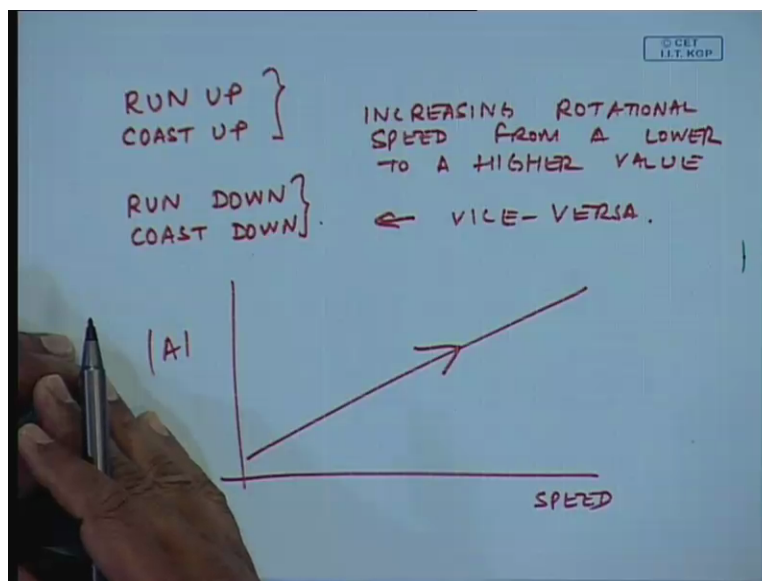
The speed change, change you would have got a smeared frequency spectrum. And that is what we want to avoid by order analysis rather than let us look into how many complete revolutions have occurred. But in there are also n machines certain fixed parts like the body panels, casings

and because they are structural components, they have mass, they have stiffness; they will be also having a resonant frequency.

So, you see in the same machine, there are two classes of frequencies. One is the one, like example, the gear mesh frequency related on rotational speed. And other resonant frequencies which is not related to rotational speed, speed, okay. So, this is very easy to detect. For example, in a frequency spectrum out of a machine, suppose, I had the liberty or the convenience of changing the rotational speed, what would happen?

Every frequency which were not related to the rotational speed like a structural resonant frequency would be constant, right. They would not change but anything which is related to the rotational speed will change this is one set, maybe this is another set, okay; set 1, set 2, but this is a these are fixed. They are fixed so very easily I can find out the resonant frequency or the sets of rotational speeds. So, usually when I have the opportunity of ramping up, or run up

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A run up or coast up or run down, coast down, they mean the same thing. This means, I am increasing the speed, rotational speed, speed from a lower to a higher value. And this is vice versa, is the reverse, okay. That means, if I was to plot the speed and maybe the vibration amplitude, this should be a run up case, okay.

I will give you an example, where they used a lot of run ups. Let us take the case of a gas turbine, you know, gas turbines have to run at almost around 20,000 to 30,000 rpm. So, one has to start from, and start from rest from 0 Hertz, all the way up to 20,000 rpm. So, what happens in this 0 to 20,000 rpm, you can understand that, there will be many modes of natural frequency of these rotating shafts?

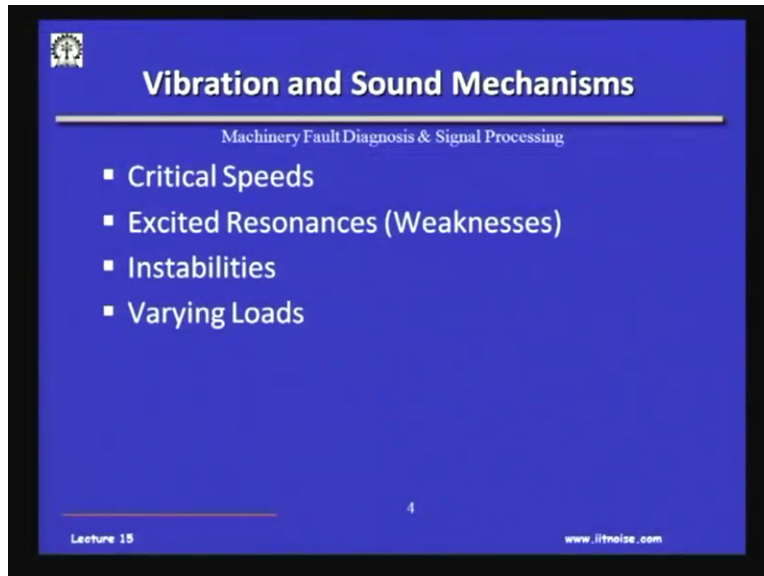
So, imagine if I was to very slowly you know, increase in the speed from 0, 100 Hertz, 200 Hertz, 300 Hertz. And then, I am sure to pass through a couple of resonances of these rotating speeds of the rotating shafts of the turbine. And if so happens, if I stay for a longer time at one of these resonating speeds, I may be maybe creating harm to the shaft, in the sense, and the shaft could be subjected to high fatigue loads.

In fact, when the switch on a gas turbine, they usually ask you to accelerate up to the rotational speed, well, at the same time, not stay at a particular speed, for till you reach the final speed; but, for a longer time because as you know, you will see in the rotordynamics that it takes time for the amplitude to build up at resonance, okay. So, you have to quickly pass through the resonance, okay. And if you have certain aircrafts and the pilot was starting the engine.

You would have experienced that once it goes up to the, the highest rpm of the gas turbine, you will go through regimes of different resonating frequencies. Then, you will you can feel that kind of jerk or loud noise at particular frequencies. That is when you are passing the resonances, okay. So, that is what is known as they run up or a coast up. And then, similarly when a switch off a machine.

It will come down to the rest and that will be closed down or run down. So, if I was to measure the acceleration of such a coast up of, Coast down and do a frequency domain analysis, you will see that, how the frequency distribution will get smeared rather than of this. If we measure just the order of the rotation of the machine, you will see that the fixed speeds will be not affected by these rotations, changing the rotational speed of the machine.

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Vibration and Sound Mechanisms

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- Critical Speeds
- Excited Resonances (Weaknesses)
- Instabilities
- Varying Loads

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So, why this vibration and sound mechanisms are generated because of the critical speeds of the rotating shafts, because of excited resonances and stabilities and varying loads. And this is what is responsible for vibration and sound generation in machines, okay. Instabilities could be because of the operational difficulties, because of the dynamic conditions, loads could be varying, because depending on the applications;

And some of the resonances in this structure or in the machine could be excited, while you are doing a coast up or coast down. So, we will see how such frequencies can be identified by this very convenient technique of order analysis. So, to summarize, you know, you recall order analysis is a technique by which instead of looking at the frequency domain in the x-axis, we are looking in the orders or and how many rotations the shaft has undergone. And one rotation means no one complete order and so on.

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Principle of Order Analysis

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The key to sound and vibration analysis on rotating machines is measurement of the rotational speed of the machine simultaneously with measurement of sound and vibration.

When the analysis is related to rotational speed it is called ORDER ANALYSIS

Rotational Speed=RPM=Revolutions/minute=First Order

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So, the, what is the principle behind this order analysis? It is the key to sound and vibration analysis on rotating machines; because the rotational speed of the machine is simultaneously measured with the measurement of sound and vibration. I just gave you an example, how the key or the key phaser signal, was measuring the rotational position or rotational speed. And simultaneously, it was triggering the accelerometer, kept on the bearing to measure the vibration.

So, this is combinedly measured and when the analysis is related to the rotational speed, it is called as order analysis. So, rotational speed given by rpm is nothing but the revolutions per minute and that is the first order. So, remember, if a machine is running at 1000 rpm, the first order is 1000 rpm, its harmonic would be 2,000 rpm and so on.

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Methods of Order Analysis

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- FFT Based Order analysis
- Time Signal Recording and Short-Time Fourier Transform
- Vold-Kalman Order Tracking Filter Technique

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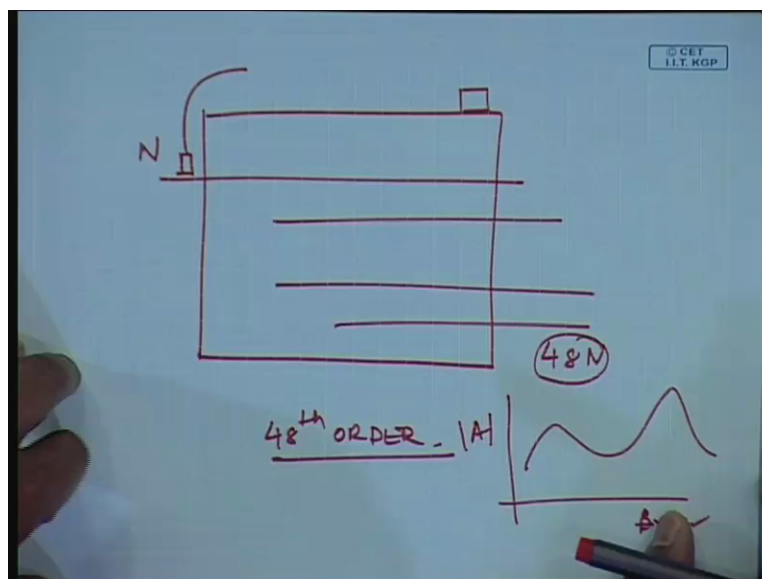
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So, well, what is the, what are the methods of order analysis? We will be in this class discussing on FFT based order analysis. But then, there are certain two other techniques time signal recording and short time Fourier transform and Vold- Kalman order tracking filter technique, you know. These are techniques which we will discuss in the advanced level courses, on either on signal processing or machinery for Diagnostics.

But this suffices to say, for example, in a multi-stage gearbox or a turbine, if there are just not one single shaft.

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But you know, there are multiple shafts one turbine many rotating shafts. If this was a rotating and N rpm, this could be 48 times N and so on, okay. And suppose, from the vibration monitoring of this machines, I just want to know, what is the condition of this shaft? So, I know this shaft is occurring at 48 times the rotational speed. So, I would like to see the vibration spectrum of the 48th order, okay.

If I capture the order here, by a key phaser signal by a certain estimation techniques, like the Vold Kalman filtering technique, I can find out how in the total vibration spectrum, how is the 48th order changing. And then, I can find out the only the vibration response of the, this will be in orders or the 48th order into something like this. So, I can find out, what is the variation of this.

We are not going to discuss this in detail but we are going to just focus our attention to just a single shaft, how by doing a rotational speed analysis, I, we can find out the order.

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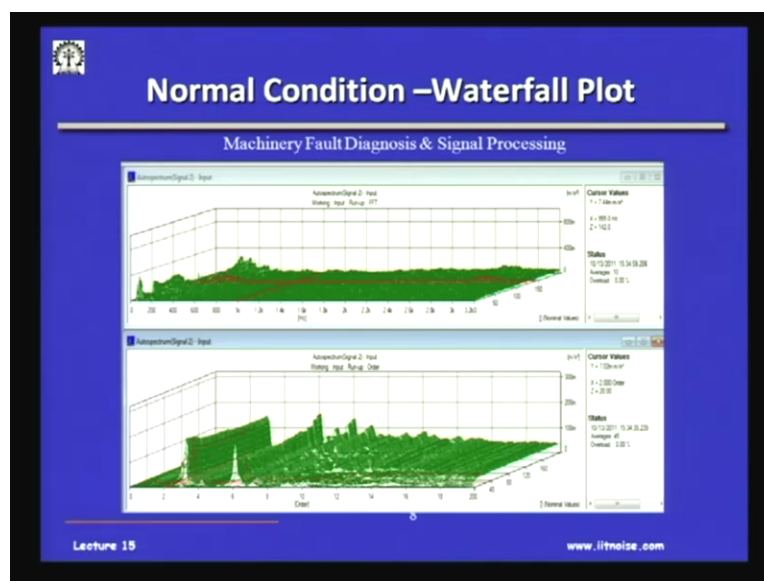
So, I will take you to an example, which we do in the lab. So, let me first explain you, this setup here, what we have is, you know, this is a rotating shaft which is supported on two bearings, okay; bearing one, bearing two. On top of bearing one, I have put an accelerometer which measures the vibration in the vertical direction.

And this disc has the provision to; we can introduce unbalance, by just putting in the bolt here. And this is there is a motor driving, the shaft motors behind this panel. And we can set up the speed of the motor in terms of, whether you want to run up, run at a constant speed or you can by varying this potentiometer, we can do a run up or run down of this machine.

Now to measure the very important rotational speed, this is the photoelectric tachometer as in is a, optically reflective, reflective strip here. So, a light will be focused or pointed at this shaft and this light is going to reflect back. So, every rotation of the shaft I will get a one light pulse back. So, this is how this tacho pulse will generally will measure that one rotation of the shaft is complete.

And simultaneously it is going to, through the acquisition process, capture this accelerometer signals of the vibration signal and then, it is going to plot it. So, there are many ways of representing this order case.

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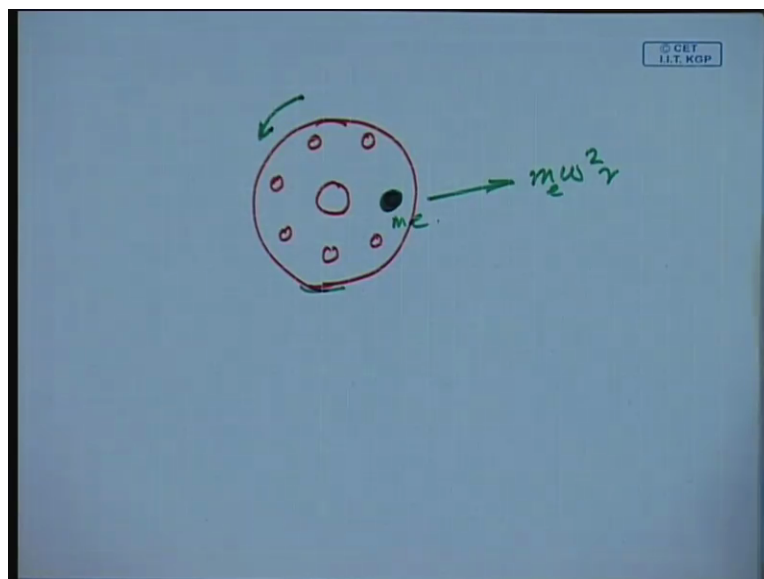
One is: this is the normal condition of the shaft wherein there was no unbalance. And the top one, this is the y-axis, here is the amplitude of vibration, the x-axis is the frequency and this is up to 3.2 kilo hertz and the z-axis is the rotational speed in rpm of the shaft, okay. And the, such a kind of plot is known as waterfall plot.

For example this takes time to build up. So there is one spectrum behind which is another spectrum another spectrum and so on and all these spectrums are stacked behind each other, okay. And this looks like a waterfall plot but what happens you will see here, there is it is very difficult to distinguish the frequencies, because the frequencies have got kind of smeared.

And then rather if I looked at the order here, this is the same thing time axis or the RPM axis, this is the amplitude and this is the order, I see a peak in the third order, in the sixth order and so on, okay. And so, this means, that the vibration here is related to the rotational speed is what I can very clearly see. This is the first spectrum behind; it is the second spectrum, third spectrum and so on.

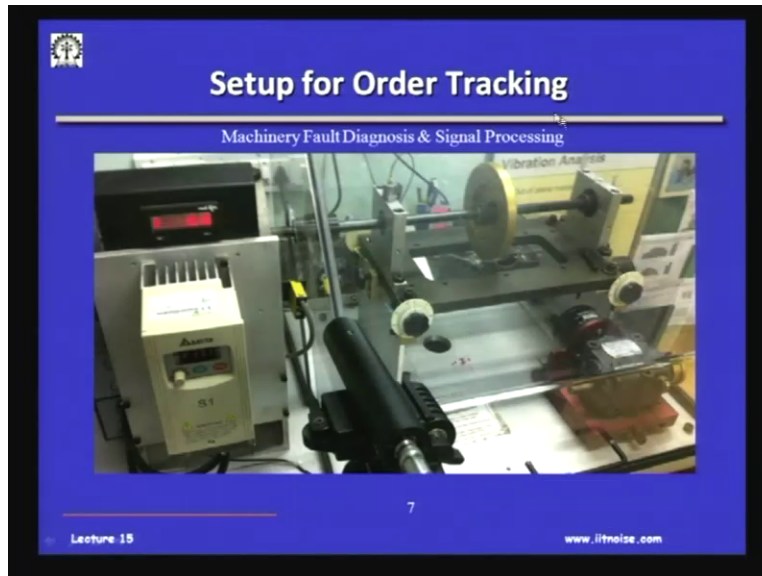
So, all these spectrums are stacked. So, I can see all these frequencies which you see this plot here, they are related to the rotational speed unfortunately in this experiment because this experiment was, this setup is designed so that none of the natural frequencies are there in the operating zone. I do not see a fixed frequency sticking up here. But you will see something very interesting happening, once we go to the; what to the unbalanced case.

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If we look at this disk, yellow disk in the middle;

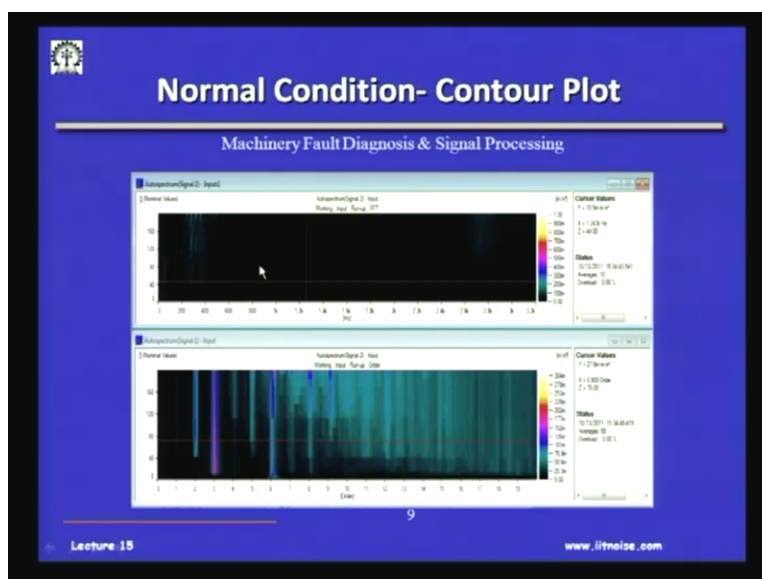
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This yellow disk in the middle, there are many holes, ok radially placed. And if I put one if I physically put one bolt and this is made to rotate, so I will get an unbalanced force $m \Omega^2 r$ where m is the mass of the unbalance. So, this unbalanced force is going to give me a force for every rotation, okay.

So, here you look on the third rotation and sixth rotation and so on and some higher rotations, I am getting a lot of vibration levels. And that could be something related to the other phenomena in the ring.

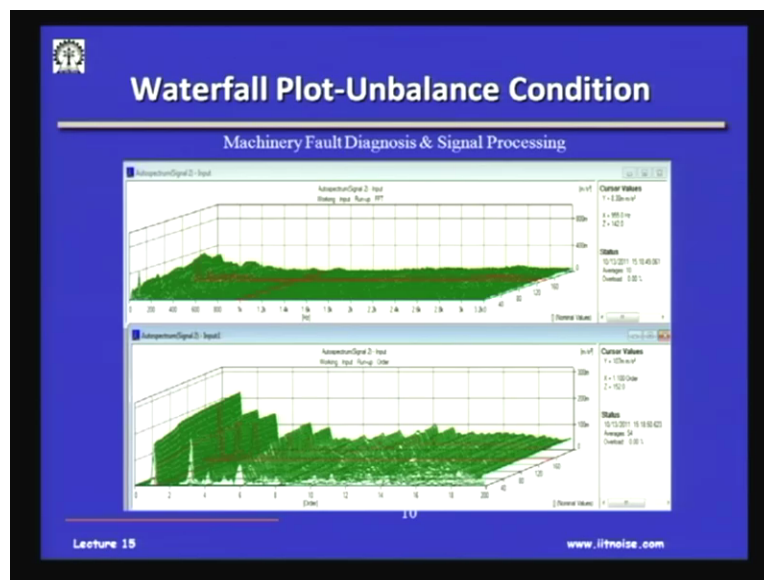
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But if I go to the, another plot of this and this is nothing but the same thing as on a contour plot, where you can see the, because that was a little skewed. And you see this is the, the colour of the amplitude band and that is the amplitude; and this is the frequency and this is the order. You see, looking at here, particularly in the third order, you can see this red strip; okay the amplitudes of vibration are high, okay. This is related to the third rotational speed.

Now, what we did was we introduced unbalance on to the system. Once we introduce unbalanced into the system and what we did was, in all these cases, even in the previous cases, what we did was, while this data has been collected, we physically move these rotated the potentiometer, so that the speed went from 0 Hertz to 4000 rpm or 0 rpm to 4,000 rpm, okay . While the data was being collected so, we have swiped the entire frequency spectrum.

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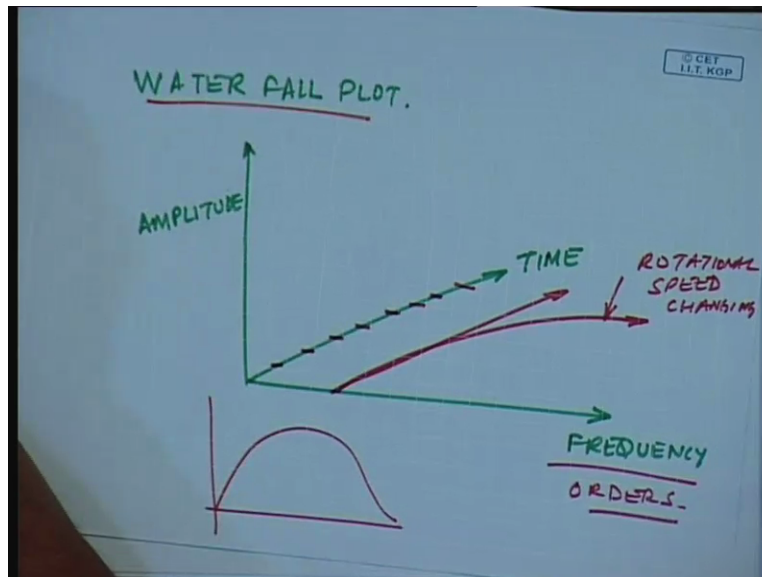


And this is a collection of such a frequency spectrum because had I just then, a simple FFT and all the frequencies will get represented. And you will perhaps not see here, but there is a small because this is only here till 160 Hertz; these lines are not straight and there are a little bent but if I sorry, if I go to the case of the unbalanced. And there is frequency smearing but the most simple thing is, in the very first order, the frequencies have shown up.

The amplitudes are high in the first order, because they are related to the first rotational one X component, okay. So, this becomes very important to find out because in this frequency

spectrum, it is very difficult to know whether my 1x is the most offending frequency or 2x or 3x. But if I do an order analysis you see things which are related to the rotational speed, they show how, okay? And then, you see these frequencies.

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Now, the same waterfall plot, I mean, just to show what a waterfall plot is, it is a three-dimensional plot. This is your frequency, this is your amplitude and this is your time. You all are familiar with the single frequency amplitude and that does nothing but the spectrum. But with time, if you stack up all the spectrums, right and the frequency was constant if the rotational speed was constant, what would happen? In this line, you will get a peak like this, agreed.

But if the rotational speed was changing, you will get something like this, is it not? If you stack up and if I just picked up the peaks, okay and if you, so this is, if I this was just for a swindle single spectrum, if I average all of this together, I would get a frequency smearing. But if I just stacked them up, in terms of the orders, I will see the phenomena which are related to the rotational speed, okay.

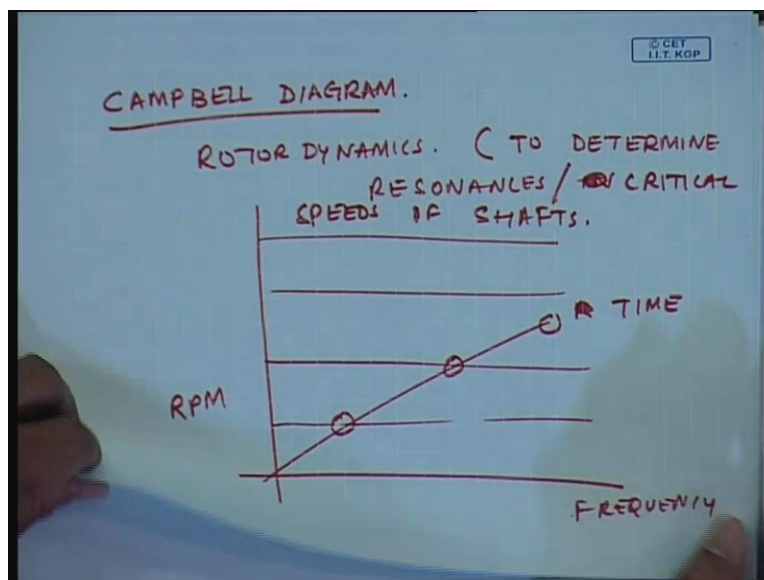
So, waterfall plot is a three dimensional plot. Instead of frequency, I could also be having orders. In orders, in, in this example, you see for the unbalance condition, a lot of smearing occurring, okay. Like if you look at this red curve here, you cannot see whether this is because of a

rotational speed or something else. But if you look at the orders here, you see distinct Peaks coming out frequency smearing has occurred here, with the top axis.

This is frequency and the top plot this is frequency, in the bottom plot, this is order here; frequency smearing has occurred. But in this case, nice distinct orders have come out and the first order is related to the unbalance condition, okay. So, waterfall plot is the three dimensional plot which gives us an instant recognition of the change in frequency, in the spectrum.

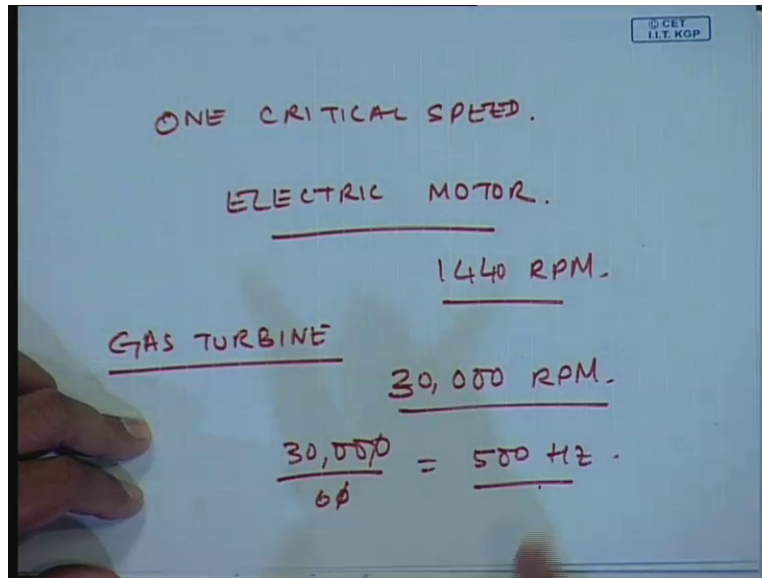
And then, if you look at the contour plot, this is another way of representing that same three dimensional plot, you see the first order is very strong here in case of the unbalance. And again if you cannot, perhaps see this, in the black curve here, because we had done a ramp up operation, there is a speeding up or the change in the frequency.

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Now, once you have talked about the waterfall plot, there is another plot. I will just explain you or either tell you, Camp Bell diagram. This is used in our rotor dynamics where as a function of RPM, the RPM are the, with time, frequency and RPM, okay. They will at different RPMs, you generate the kind of the amplitudes. And wherever, they kind of meet, you can find out this, to find out, I will suffice to say that, to determine resonances in. Or resonance of critical speeds of shafts, okay.

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Shafts need not have only one critical speed. Particularly, when we design, say for example, an electric motor say, an electric motors or the gearbox, etcetera, we run, it is at 1440 RPM, okay. As a designer, I can very well design this shaft depending on the mass and stiffness. You would have studied that in vibration, so that the rotational or the critical speed of this shaft, of the resonating frequency of the shaft, is well beyond 1440 rpm, okay.

If we take it 1500, 1560 is about 30 Hertz, so I can design a shaft that its resonating frequencies based beyond 30 Hertz, right. No problem. But, say for example, I have a gas turbine, okay gas turbine on 100 mega watt gas turbine, so which rotates at 20,000 or maybe 30,000 rpm, okay 30,000 rpm corresponds to 30,000 divided by 60 is 500 Hertz. So its operational speed is 500 Hertz.

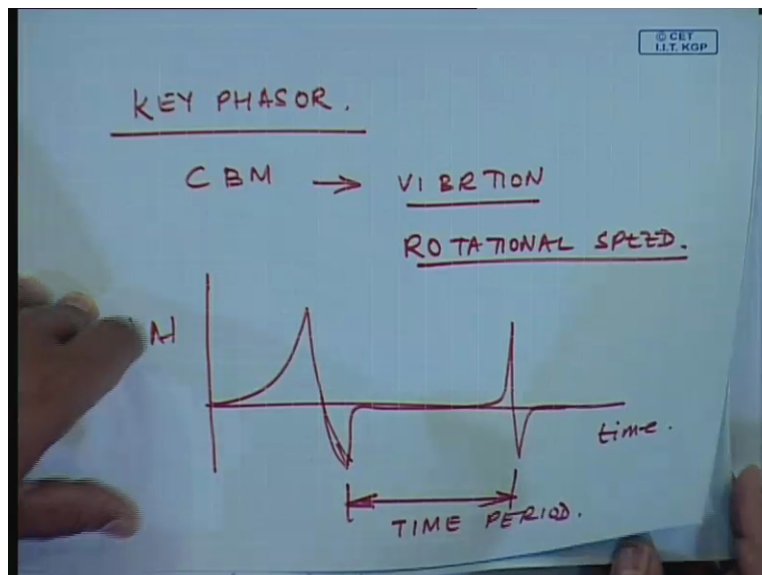
And it would be almost impossible to have a resonant frequency only above 500 Hertz; or designer would have a tough time, designing such a system whose resonating frequency is only beyond 500 Hertz .So, that would require for that will require a very, very thin shaft. And obviously a 100 mega watt gas turbine cannot be so thin that its resonating frequency is beyond 500 Hertz. Well, as a as a designer, why do you require it beyond 500 Hertz.

Because you should not excite or it should not get excited by the operations and speeds, but that is not the case. There will be maybe 3 or 4 frequencies, resonating frequencies below 500 Hertz.

So, it suffices to say that there are shafts whose resonant or resonating frequencies are within the operating zone, right. So, I have to find out what these resonating frequencies are and only during operations, I can make sure that I do not excite these resonating frequencies.

So, Campbell diagram is used by designers by a maintenance engineers to diagnose and find out rotating speeds, critical reading speeds of large rotating machines or machines operating at high speed, high speeds, okay 500 Hertz and so on. For electric motors where we are talking about single speeds we do not talk about Campbell diagrams. But when there are flexible motors of lot of rotational in critical speeds, we will talk about Campbell diagram. So, right now I will not focus more on the Campbell diagrams.

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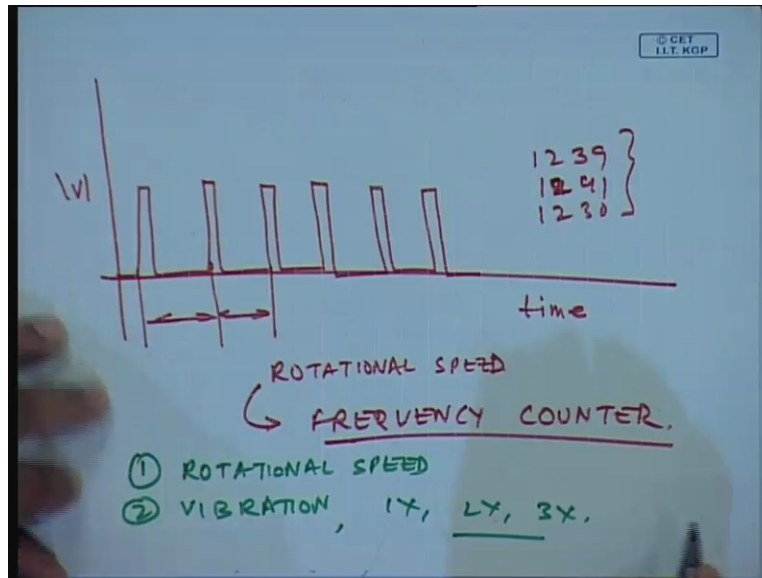


But let us see the importance of this key phasor. You will see in condition based maintenance, where vibration is an important parameter to be measured, rotational speed is also a very, very important parameter, which is to be measured; because you just saw an example, where in many of the frequencies, which we see in the frequency spectrum, they are related to the rotational speed of the machine.

So, it is but important for us that we must measure their rotational speed. So, the key phasor technique is used as a very convenient means, to measure the rotational speed; wherein it just gives a voltage signal, okay. And this could be through inverse of this, because inverse of this

time period is the rotational speed. If the time period changes, I do not care the rotational speed would be measured.

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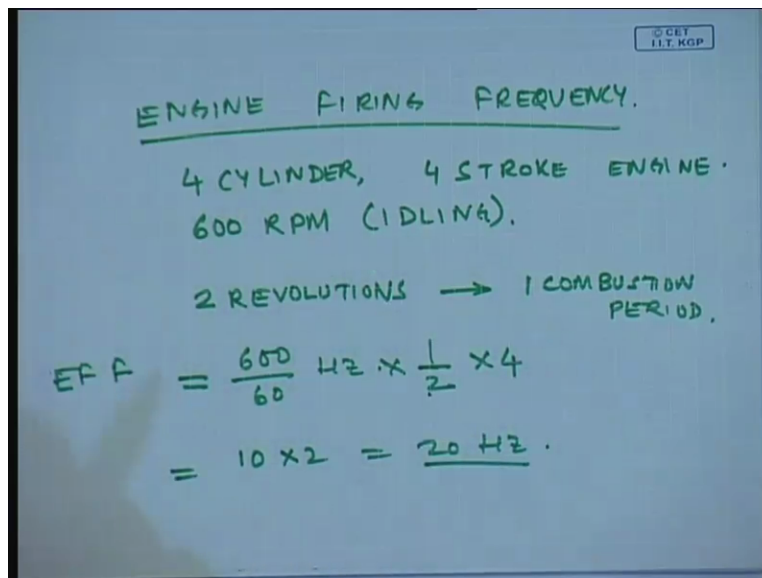
The rotational speed could be changing, but there are again algorithms. If I will get a pulse train square pulse, out of such, certain voltage the average spacing between these will be my rotational speed. So, there could be, you know, in there could be a digital indicator of the rotational speed just by measuring. It is nothing but a frequency counter, just by putting a frequency counter, digital frequency counter; I can get the rotational speed.

But mind you this rotational speed, you know, if, if these the digital display or the your sampling was very quick, you will see these numbers jumping down and that happens in many of the machines which will go out to the plant and see that the numbers will be jumping around. May be 12:39, 12:41, 12:30 etcetera; these numbers jump around because this speed is fluctuating, imagine while the speed was fluctuating, if you are doing an average of 50, you will have disastrous results.

The results will have no meaning. So, that is the reason why we synchronize our acquisition process by just the triggering signal. So, order tracking or order analysis requires two very, very important measurements: one is the rotational speed and other is the parameter, which could be

the violation. It could be noise etcetera also and then, we will see anything which is related to the rotational speed will show up as you know, 1X, 2X, 3X and so on.

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ENGINE FIRING FREQUENCY.

4 CYLINDER, 4 STROKE ENGINE.
600 RPM (IDLING).

2 REVOLUTIONS → 1 COMBUSTION PERIOD.

$$E F F = \frac{600}{60} \text{ Hz} \times \frac{1}{2} \times 4$$
$$= 10 \times 2 = \underline{20 \text{ Hz}}.$$

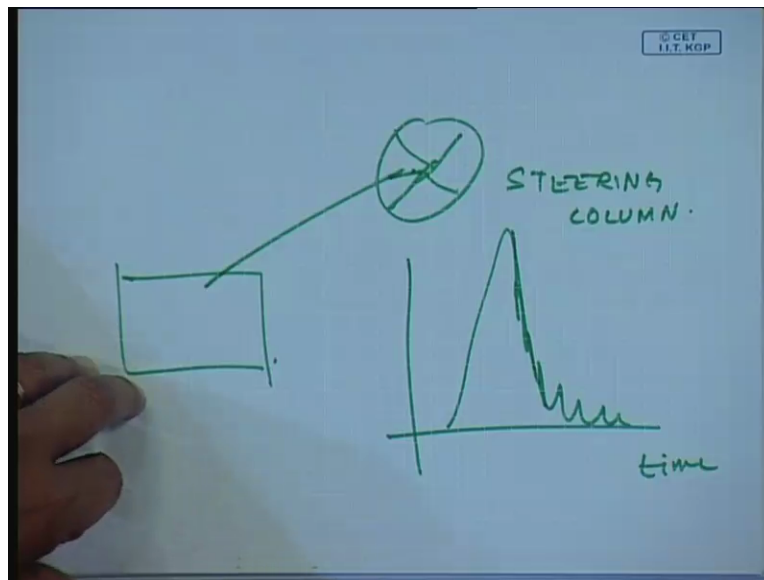
One very important application of order analysis is the engine firing frequency, okay. Let us take the case of a 4 cylinder, 4 stroke engine, say, this is running at 600 rpm idling at 600 rpm, okay. The question to you is what is the engines firing frequency? By firing frequency means, at what frequency the combustion is occurring? Imagine for a 4 stroke engine means for every 2 revolutions, I will have one; combustion is it not, right?

So, in 600 rpm, that means 600 revolutions per minute, 600 by 60 Hertz, ok divide by 1 by 2 is the firing times 4, is the firing frequency; because there are 4 cylinders. Now, if this was a 2 stroke engine, this would have been 1. For every rotation, I will be getting a firing. So, this is what is the engine firing frequency? And that will come down to 10 to 20 Hertz, okay. I don't know, if you would have experienced this.

But now if you have sat on the, the Jeep, you do not see them, you know, in the models SUVs or in MPVs, etcetera. But if you are talking about those old Jeeps or the taxis which come from the railway station, you know, very ill kept taxis, if the driver was idling, you will see you will kind of feel this rattling or gir-gir-gir noise. And that is actually at the engine firing frequency, okay. And if you measure that you will see this 20 Hertz component.

And you will be perhaps, being sometimes, even see, the steering column shaking; because the steering column which is fixed to the firewall and next to it is the engine with the engine is running; once you are idling the engine is running at 20 Hertz. So, there will be instances, where the steering columns natural frequency could be close to 20 Hertz, okay and there will be the steering column would be rattling. And how many of you have observed that particularly, in old Jeeps and cars particularly, in the case of diesel engines, okay where the forces are high.

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You will see that the steering column of the vehicle gets excited one at a particular speed particularly in Idle. What was the source of excitation here? It is the engine firing frequency; because engine by engine firings I mean the engines combustion cycle, okay. There will be a sudden build-up of pressure and this will come down with time. And this is like a burst, okay every cycle, one burst is happening, okay.

And this burst is an excessive pressure wave. So, this pressure wave is giving the forcing function and this forcing function is coming at 20 Hertz. And then, it may so happen that the steering column is having a resonant frequency. In fact, you know, we are I was doing some work for a tractor company they had a tractor as soon as the tractor was switched on, there was a lot of shake on the steering wheel.

And imagine if a driver is going to, you know, hold on to the steering wheel and the steering wheel was having lot of vibrations, okay to not be very convenient or comfortable for the driver to hold. So, we finally find out that that steering column of the steering wheel in fact, steering wheel actually it has a steel structure inside it.

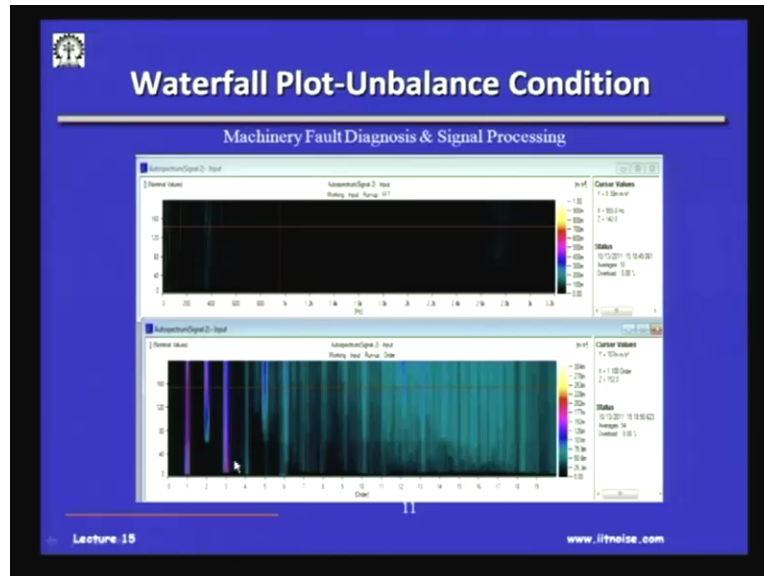
Steering wheel had a natural frequency of 29 Hertz and somehow that that engine firing frequency was very close to that, 29 Hertz during idling, at a particular rpm, rpm was about 780 was the RPM engine idling rpm. In this case example we took at 600 rpm I vaguely remember it was around 750 rpm was the idling speed.

And the way to do this was, you know, we could not do anything with the engine, engine was made by somebody else. So, engine had its idling has the frequency at about firing frequency are about 30 Hertz. So, what we did is by changing the mass and stiffness of the steering wheel, we could shift its frequency, natural frequency so that, henceforth, once this engine was running if the steering wheel was no longer vibrating.

So, this is how we can diagnose, you know, this was not in case of diagnosis for mostly a case of a design. But by such techniques we can find out the natural frequencies and how to avoid them in design. I was telling you the example of gas turbines. We cannot possibly avoid them but at least if we know these natural frequencies, we will not operate at their natural frequencies.

But for the case of a tractor, I mean, you can always idle the engine and stay still. But this idling frequency if it is close to the resonant frequency of the steering wheel it is going to either have large motions of the steering wheel, so that is to be avoided. So, order analysis is one technique by which we can find out the frequencies which are related to the rotational speed of the machines.

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So, if in this spectrum, say, some of the, of course, in these examples here, some of these frequencies are not related to the rotational speed. If they were related to the not related to the rotational speed, there could be lying in between these. And perhaps if you go to the higher frequencies you will see that some of the frequencies do show up, okay. And they are beyond the operating zone of the rotational of the test ring, okay. Thank you