Machinery Fault Diagnosis and Signal Processing

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Lecture -08
Time Domain Signal Analysis

In this third module on the course on machinery fault diagnostics and signal processing, we will be focusing mostly into the signals and their analysis. As you all know from the very first fly a few classes which when I had mentioned that the signal is the most important element in implementing condition based maintenance.

We need to have the signals from the machine brought to us in a computer or in an analysis unit where we can interpret and find out more features about the signal. From the signal and then know more about the machine and then we will know the present health condition of the machine and then we can use our diagnostic algorithms, prognostic algorithms to find out the remaining useful life of the machine.

Well, to define what is the signal? Signal is actually an information coming from something. Signal could be a visual signal, could be a physical motion signal or it could be electrical signal as well. In this class we will be focusing our interest or attention more into the electrical type of signals. In the sense we have a transducer or a sensing element because of the mechanical excitations occurring in the machine.

It could be because of vibration, because of temperature rise, because of noise, because of electrical current etcetera. So, this transistor transducer is going to sense this signal, transducers as you know could be an accelerometer to measure the vibration, could be a strain gauge to measure the strength, could be an thermometer to measure the temperature.

But once this signal which is conveyed by this measuring instrument receives the observer in this case being the person who is analyzing he will try to analyze the signal and then try to know what is wrong or what is the present condition of machine.

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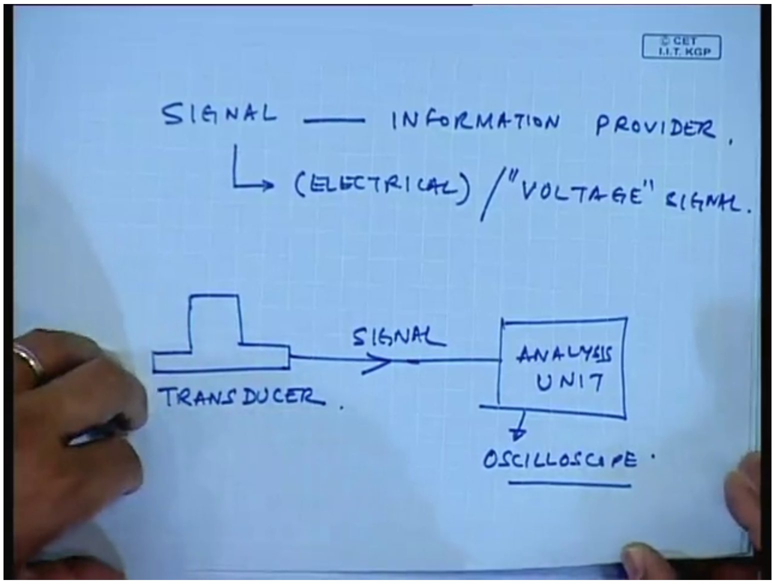

So, signal to begin it is an information provider, so, in this class we will be focusing more into the electrical type of signal or which we very crudely known as call it as a voltage signal. So, from a transducer I will get certain information or signal and then this will come to analysis unit. This began with this analysis unit could be a simple oscilloscope I am sure all of you must have used an oscilloscope in your electrical engineering lab.

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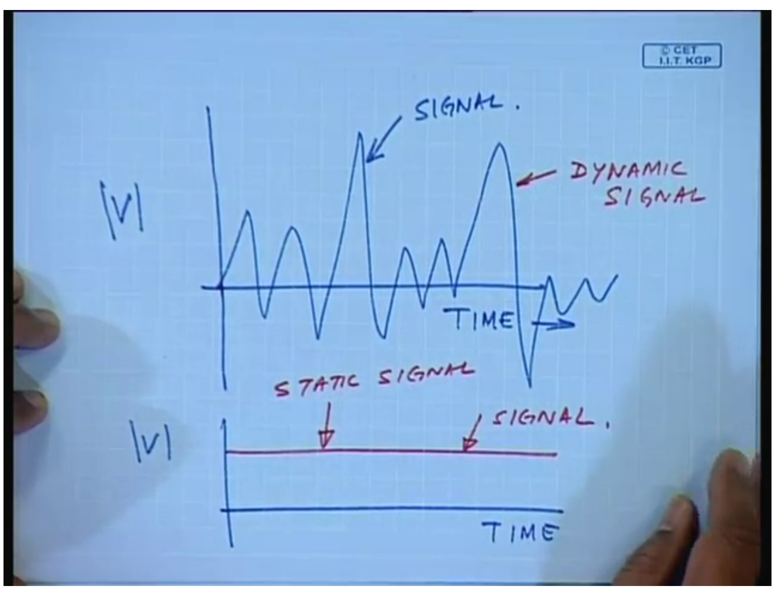

So, what do we see in an oscilloscope? So, in an oscilloscope we have our time base and then we have certain voltage which corresponds to the level of the signal and the signal could be of this nature varying with time so this is my signal. I have drawn the signal as varying with time but the signal could be at a constant level as a function of time.

For example my signal could be like this, this is also a signal but if you look at these two signals the blue one and the red one. One is changing with time, so, this is what is known as a dynamic signal and one which is constant with time and this is a static signal. So, signals could be classified according to their nature of the signal as a function of time. So, one is a dynamic signal another is a static signal.

Another way of classifying the signal is whether this signal exists at all time T or does it only exist at discrete values in time okay of course I know I could use any plotting software to join the lines join the points and get a straight line or curve. But whether the values of the signal at all times are known to me is a question.

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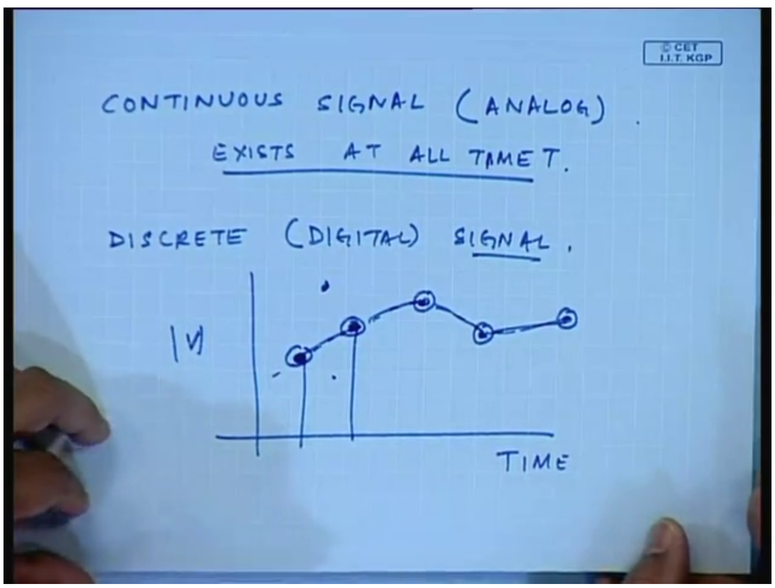

So, if it is known at all times this is a continuous signal or usually an analog signal is a continuous signal that means it exists at all time T all time T as opposed to what is we known as discrete, sometimes digital signal which I had represented as few values here and there. So, I will just join them it is a line okay.

And then these are actually the values where I know these signals, I do not know what is the signal here, whether it is going here going here but I will and there are many ways to assume it I will just draw a straight line fit between them or I can do a curve fit or I could do a spline fit etc. So, this is what is known as discrete signal.

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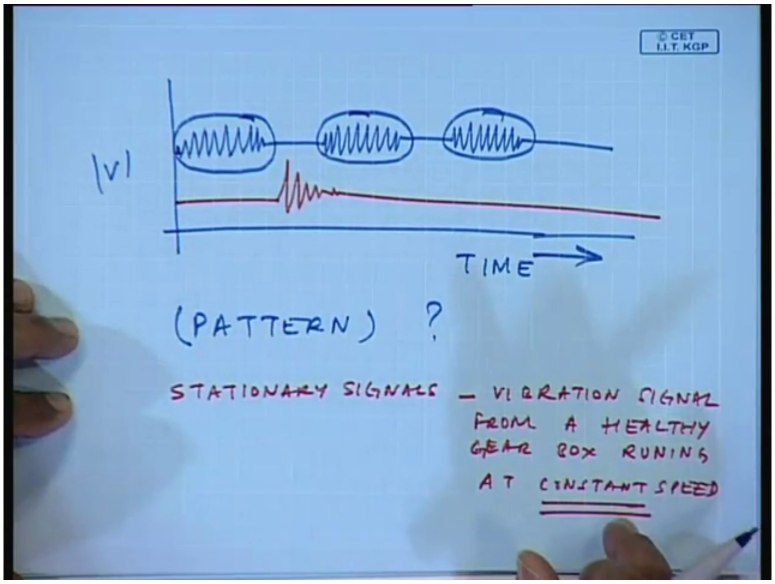

Now well there are other types of signal also in the sense regarding the pattern of the signal by pattern I mean does this signal at a given instance of time repeat itself or it does not repeat itself over time, so this is what we need to look at. So, in this kind of classifications I can classify the signal into two more types.

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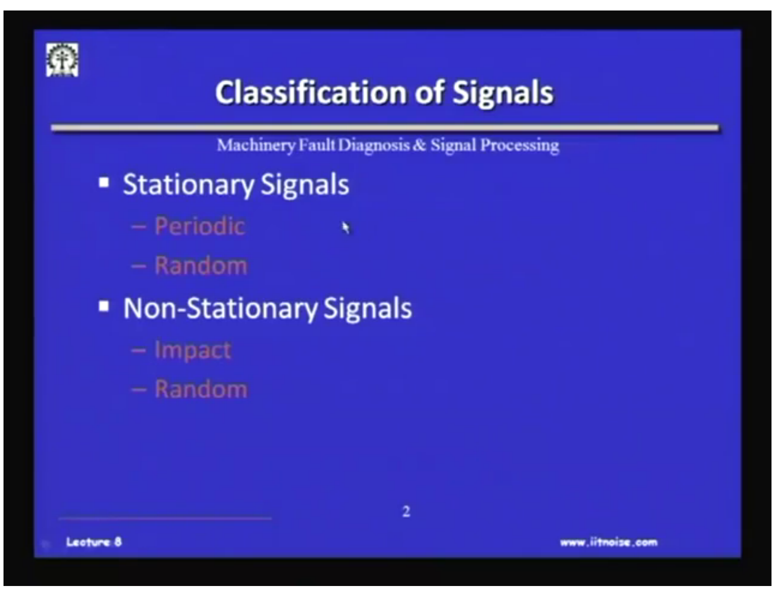

And which are known as the stationary signals or non stationary signals. The reason I did not put the other two kind of classification whether it is a static signal or dynamic signal or continuous or digital signal is because this is obvious and you must have studied them in your first year circuit's courses etc okay.

But the classifications of the signals through by which we are interested in condition based maintenance are these two types whether one is stationary and whether one is not stationary. Now let me draw this kind of signal here. This is the kind of signal you will grossly try to understand. Now that the value of the signal the average value of the signal here in one instance in one block of time.

This is almost the same as this block of time. So, almost the same as in the next block of time, so, such a signal is actually known as a stationary signal that means the average or mean value of the signal repeats itself over a block of time or a period of time and that is the stationary signal okay. And the stationary signals could be periodic or random.

As opposed to the non stationary type suppose I draw a non stationary type, it happens once in a while and then it does not repeat okay. So, this is the case of a non stationary signal for example in machines you will see a lot of impacts happening. Suddenly something fell, something broke there will be a high level of vibration and then nothing will be there.

So, those are cases of non stationary signals I will give you an example of stationary signals is vibration signal from healthy gearbox running at constant speed, underlined the word constant speed. This is the case of a periodic signal okay as opposed to suppose I change the speed what would happen this time domain notes sometimes decrease increase and so on.

So, for the same given time block the average values will be different and that would be a case of a non stationary signal. So, whenever there is speed fluctuation, we will get non stress-reliever signals. Because the signals if you average them over the block the values will not be same as opposed to the periodic or random stationary signals.

We will discuss more of this later on in this class. So, with an understanding of the three types of classification of the signals one is whether they are dynamic or static whether they are analog or discrete and then finally whether they are stationary or non stationary. Now what is the usually the nature of the signal in CBM or condition based maintenance.

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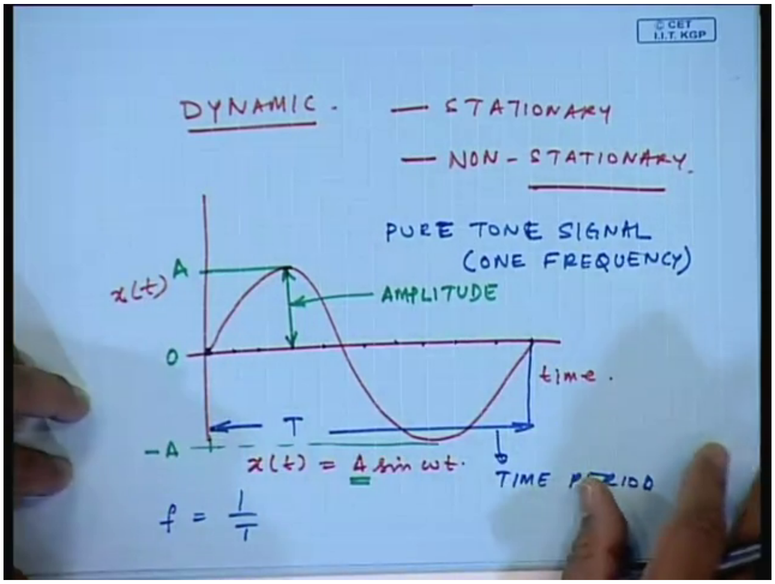

They are usually no vibration signals are functions of time, so they are dynamic. They could be stationary and or they could be non stationary. I will give you an example why we have to be careful while analyzing non-stationary signal because you suppose a signal is coming from a machine and then I am doing certain online real-time analysis.

And this analysis takes certain time what would happen to my analysis if during the time of analysis the signal has changed okay. So, whatever I have attributed about the signal is not right because the signal itself is changing so fast that it is within my analysis time the signal features have changed. So, for such non stationary signals we require really advanced signal processing techniques which I will tell you later on in this course.

But excuse me but we will focus our attention in to mostly into stationary signals which could be periodic like these signals from the healthy gearbox, random signals may be now just as an example what is the random periodic may be raindrops falling on your roof okay. Those are random signals and what could be the example of transient signals or impact signals like you have a gun barrel missile being shot from a barrel okay.

Once upon a time you get an impact a shock wave these are all impact signals and they do not occur continuously they happen once upon a time like a particularly in automobile people do lot of analysis with non stationary signals in sense of suppose you shut a door a car door it makes boom impact, noise. So, people do lot of sound quality analysis on that small fraction of a second of a signal whether how good it sounds.

Whether it sounds good to us bad to us so the door slamming is a typical example of a non stationary signal in typical example of an on statistical signal but in CBM because our machines will be running at almost constant speeds, we will be focusing more on to the stationary signals ok. Now let us see and stationary dynamic signals, so, if I have this time axis here, I could have a signal like this as a function of time, I am writing this of xt.

So, this is xt could be mathematically given as A sine Omega t, this is the periodic signal and this is a harmonic signal, harmonic because it is a sine or a cosine function ok. Now this signal I have represented mathematically here but real wall signals are never like this we will see real world signals. But from this simple mathematical signal let us see what are the features of the signal suppose I see this on an oscilloscope what are the features I can extract out of the signal.

I mean you will be surprised there will be about 20 parameters defining the signal itself and time domain and we will see one by one what they are. For example in the time domain this is the time period of the signal okay from a crest to an alternate I mean either from this position to the subsequent peak or crest to crest and I can take this as the time period, time period of the signal. And this frequency of the signal is f = 1 by T, there is an inverse relationship between the frequency and time and that is in the time domain.

If such a signal was given to me on an oscilloscope I could count the number of divisions in an oscilloscope and then multiply them with the different number of divisions and the units per division and then get the time period, inverse of it is a frequency domain for a pure tone. This is known as a pure tone signal because pure tone signals have only one frequency okay.

So, this is a pure tone signal and then in the; you see here A sine Omega t, so what is A is, this amplitude, so this value is a and it is known as the amplitude of the signal okay. And sometimes the peak amplitude is nothing but zero, this is zero value and then of course this will be r – A.

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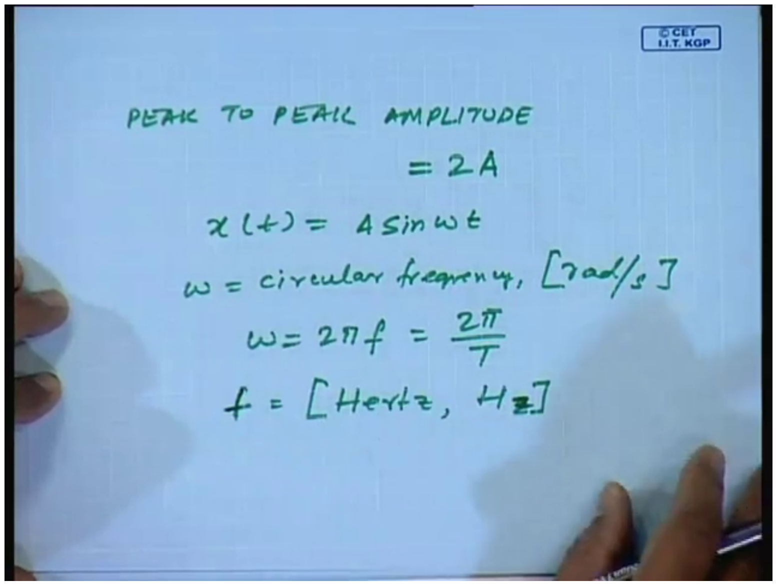

So, the peak to peak amplitude of the signal is nothing but 2A, 0 to A in the bottom in the top and 0 to – A, total value is you know total magnitude is rather 2A, so, I have found out the amplitude, I found out the peak to peak amplitude, I know I could find out the suppose this signal XT is given by A sine Omega t, now how is this Omega related to the frequency Omega is the circular frequency.

It is unit is radians per second and Omega is equal to 2 pi f or 2 pi by T, where t is the time period in seconds okay. Sometimes you know you will see in instruments you know we measured by milliseconds, microseconds. So, you have to be careful about these units for example the unit of frequency is Hertz and it is written as capital H small z ok, Hertz frequency.

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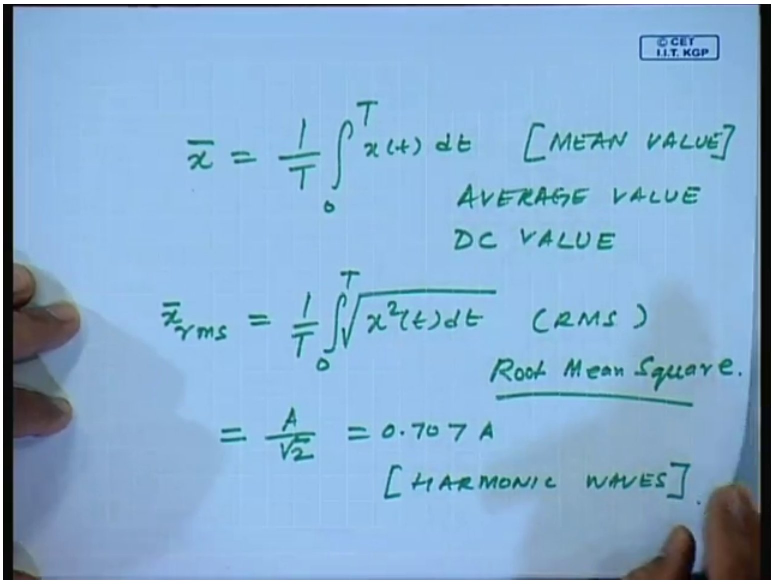

Now such a signal if somebody asked you find out the mean value of this signal, what would you do? You would over a time period the mean value of the signal is nothing but dt okay. Somebody asked you the mean value mean value sometimes we call it as average value, sometimes we also call it as a DC value of the signal okay. So, if I have a signal if I find out its mean value I can subtract the mean value.

To get what is the dynamic value or the value or the signal which is fluctuating over time okay. Now the RMS value is given by this equation root mean square, this is known as RMS root mean square value of the signal okay. Now all of you I recall go back to your first year circuits, you will recall for a sine wave this happens to be A by root 2 or 0.707 A. But this is only true for the case of a harmonic wave form, it would be cosine and sine this is not for any waveform, no, okay only for the case of harmonic waves okay.

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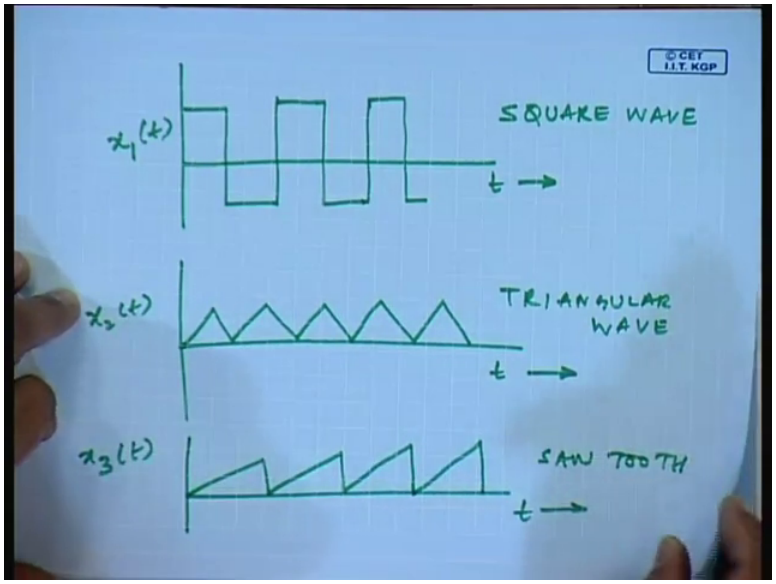

But there are signals which could be looking like this x1 t, so this is what is known as the square wave okay, signals which look like this, this is a triangular wave in fact there are commercially available signal generators where in you can electronically produce such signals either two calibrated equipment or to do check your equipment etcetera this can be done. And we will be using these waveforms in later on to understand the frequency domain analysis.

Because the frequency content of the previous harmonic pure tone signal was just one that was in a 1 by T for the case of a, A sine Omega t, but if I was to ask you what is the what are the frequency contents in the signal well you may think of it well then I will measure the time period and take the inverse and say this is the frequency, you are right, this is just the fundamental frequency.

So if I say my function is periodic and it has one frequency I can always draw a sine wave and why should I draw a square wave. So, square wave also has other frequencies other harmonics other than the fundamental. Same is true for triangular, same is true for the other case which I am drawing here is the saw tooth. So, these are certain signals which you will come across while doing a calibration etcetera ok.

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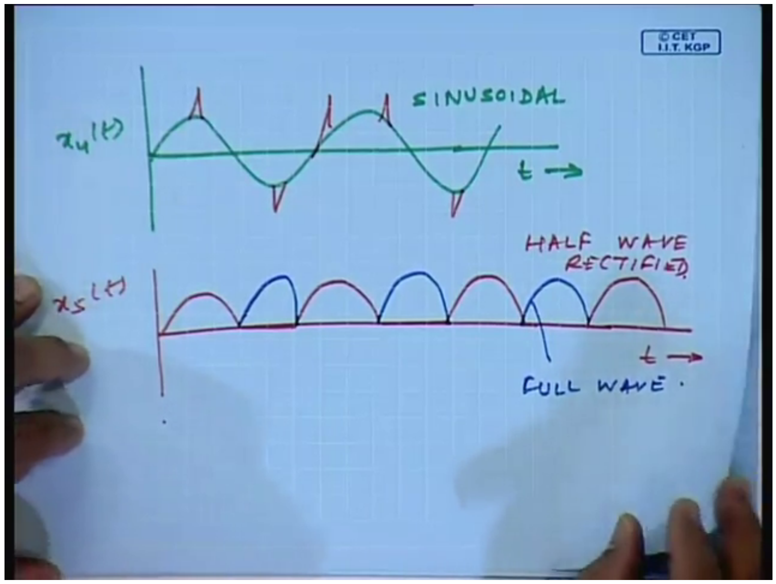

Of course this is the sinusoidal wave usually know when you are dealing with electrical signals of the constant frequency like a 50 Hertz signal, this is a sinusoidal wave. And you know you know in electrical equipment if this power supply is not a sinusoidal there are transients of kind of spikes etcetera in the signal they are known to; though their values will be less.

They are known to damage delicate electrical equipment or electronic equipment. So, that is why you know we have a lot of online search protector, spike protectors. So, that we get a neat 50 Hertz sine wave into the system but that does not happen. So, this sinusoidal could be getting corrupted by such transients and Peaks we will come to that later on.

Another is you know we have the rectified signal in the sense this is a half wave rectified in the sense only the positive parts are, half wave rectified. Another of course is the full wave would be now if I just well my drawings are not that perfect but this will make it a full wave okay. So, we will come across such signals to help understand instrumentation check or calibration etc.

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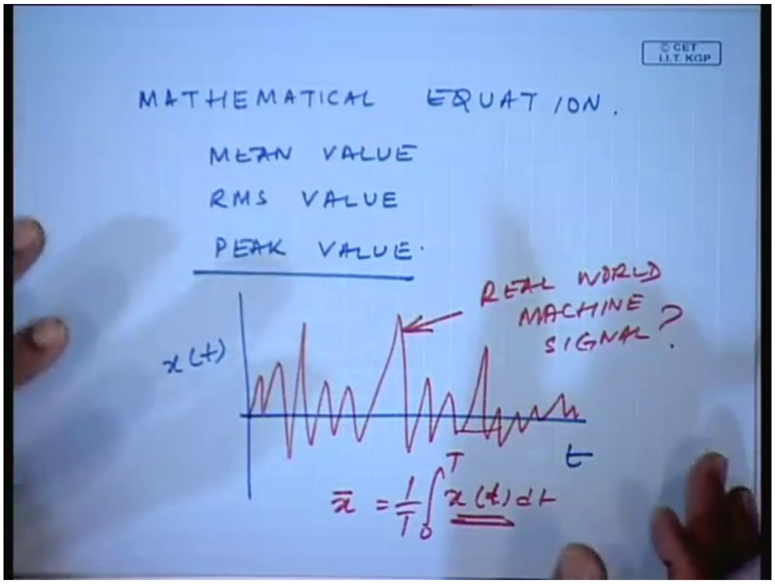

But all this above signals could be very much easily described by a mathematical equation. So, we can find out their features, features mean their mean value, their RMS value, their peak value and there are a few other values which we will talk about in a few minutes. But the question is in the real world machine none of the signals look like this.

In fact they look something ok this is the real world machine signal well. So, the question is how do I estimate its mean value RMS value? Because you know if you recall those equations of the mean value I had what I do not know this as a function of a mathematical function. So, I possibly cannot do this by using this integration formula here.

How do I give had I been given the equation to the signal I could have done everything. So, this is a challenge to us, so well there are very easy solutions nothing to be worried about we will find out how we can find out such analysis. For example, I will just give an example all of you must have used Excel ok.

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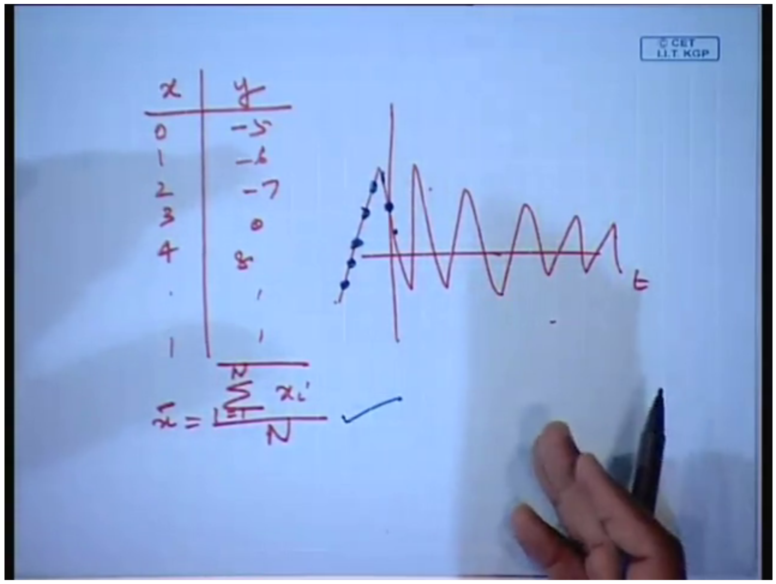

So, if I in Excel if I give you x and y value you have 0 1 2 3 4, I give you two numbers randomly etc and now in Excel I can always ask you to find out the mean value of the signal, if some signal which have randomly plotted I will do is it not you do the summation for the values and then divided by is it not. So, you do the summation, so this is very easily done the same signal; suppose my signal was like this something like this.

So, I can pick up data points very close know the x and y values and use the simple equation like this and do a summation and find out the mean value, I can find the RMS value. So, the sky has not fallen on us, we can do it okay. And so if I if you give me a real world signal all I need to do is, I need to find out these values from the signal.

So, how we do that that is something we will be covering the subsequent classes. I need to acquire this data over a computer. Once the data is there in the computer in the form of a digit, I can do, I can use software's like MATHLAB, I can use software's like Excel etcetera to find out the mean or RMS in this and so on okay. It is a very easy job for us now.

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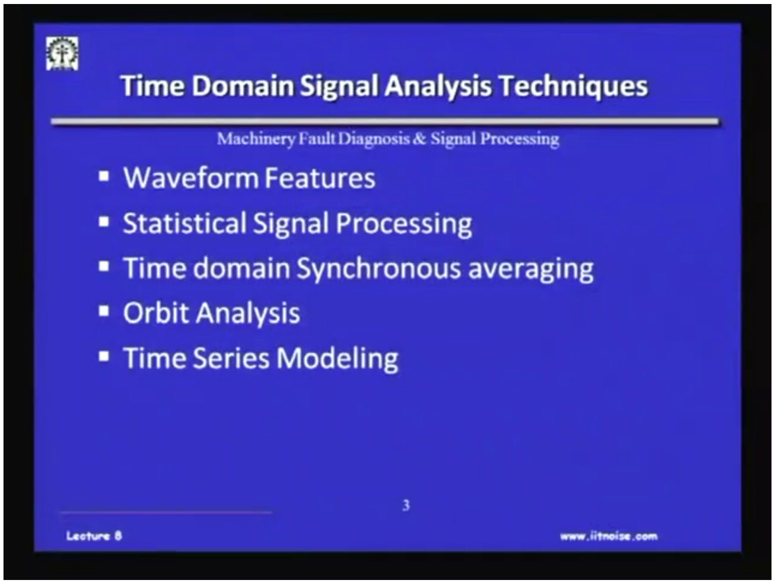

So, now as you know we need to find out the features of the signal. So, in the time domain signal analysis I have to find out the features of the signal like the RMS value, the mean value the first factor, the doses etcetera, excuse me. I can do certain statistical signal processing on this signals. I can do certain time domain orbit analysis; I will be explaining this some of them today in this class.

And subsequently may just make a note of it that in the subsequent classes we will be coming back to some of these points and see the water what do we mean by time series modeling or analysis etc and then see how they can be integrated okay.

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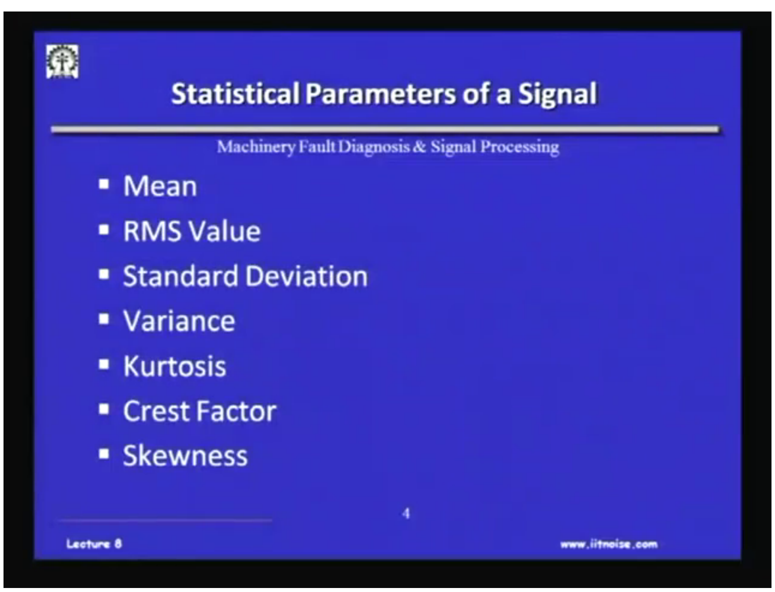

So, some of the statistical parameters of a signal are the mean value, RMS value standard deviation variance etcetera which you all perhaps know by now from your basic first-year courses. But there are certain other facts we people use.

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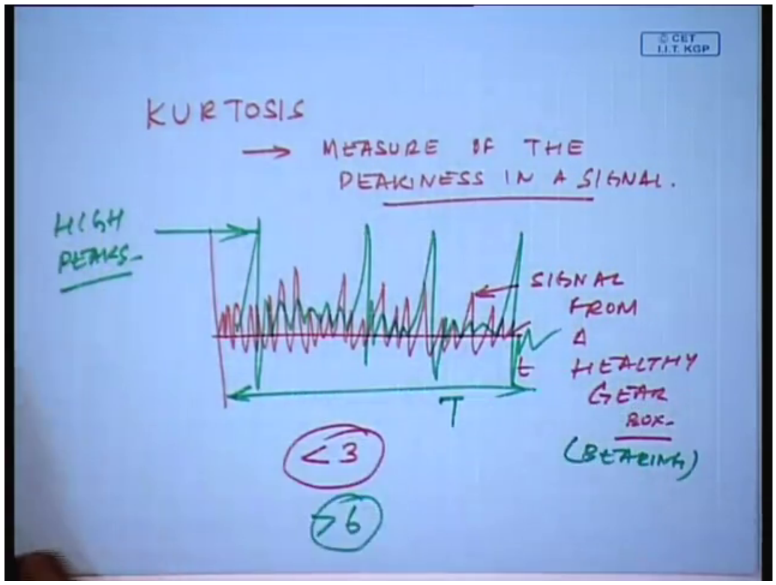

Kurtosis is actually is you can quantitatively say it is a measure of the peakiness in a signal. I will tell you how to calculate this either in Excel or in software known as MATLAB. So, for example if I have a real signal from a good gearbox it may look something like this okay. The red one is a signal from healthy gearbox okay.

So, I can estimate its kurtosis values and then it will; we will get an arm number normally it is less than three. But if the gearbox or the bearing gear or sometimes also bearing, if it was bad there will be lot of these high peaks. See presence of this high peaks visually gives us a clue well something is wrong with the machine.

But if I was to measure the kurtosis of this green signal it would be almost greater than six okay and traditionally over the decades maintenance engineers have used this rule or check to see the kurtosis value of the signal all they need to do is take a signal of certain time duration okay. Put it in an analyzer and then try to estimate the kurtosis. There are actually commercially available handheld ah hum kurtosis meters.

Wherein you can just put the transducer they take the signal out of the transducer put it in a kurtosis meter and then you will see the measured kurtosis value if it is more than six. You can be pretty sure that the equipment, the bearing or the gear is damaged or is not healthy okay and even if you implement that in your industry you will be very happy that you have done some amount of diagnosis whether the machine is good or bad.

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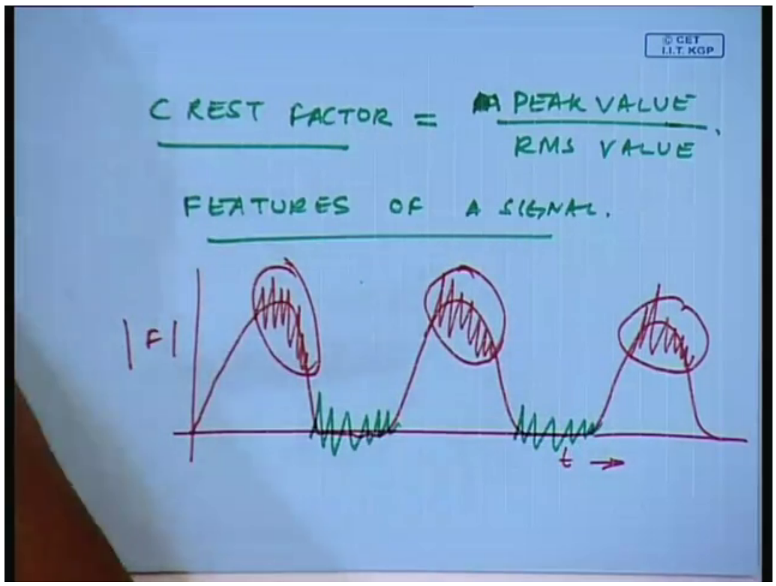

So, I will come to subsequent sections how using MATLAB we can estimate kurtosis etcetera, another parameter which people use crest factor. Crest factor is a defined by the peak value of the signal by its RMS value okay. So, these are these are all parameters, so you know this is what I mean by features of a signal like we use you know the features of an object the size shape, color, okay.

Well this is how surface is rough, what is the color so these are features of an object which you see visually, features of a person the face, the eyes, the nose, the lips, the ears. Similarly for a signal which you see in the time domain and an oscilloscope what are its features? Features could be these like the mean, RMS, standard deviation, variance, kurtosis, crest factor; skewness.

Skewness is another parameter in which whether the signal is lopsided to one side or other. Like you talk on statistics about skewed data whether the data is biased towards one side okay whether we should have skewed data or not is something which we need to see;

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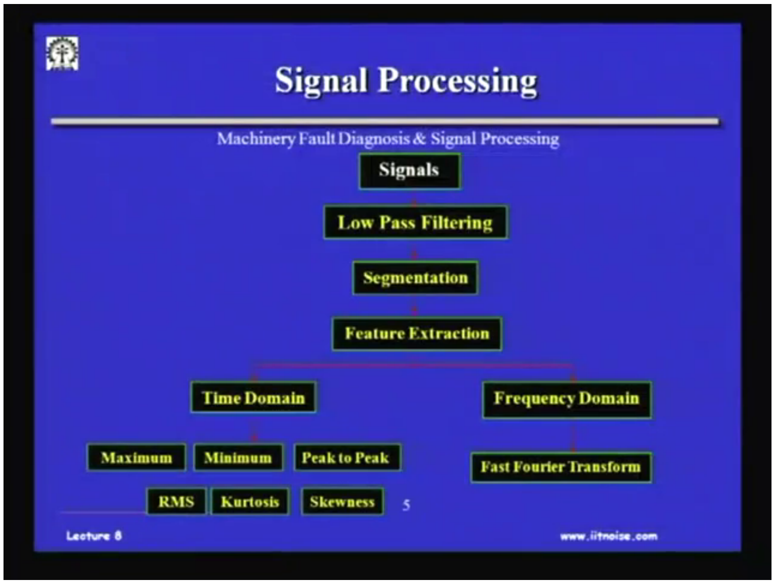

Now I will right now briefly tell you about certain signal processing which is done in general on signals but mostly we will focus more into the signal processing. For example many a times what happens when we captured signals from a machine I will give you an example of a milling machine where there is a cutting force operation occurring every rotation the milling is miller is milling tool is cutting surface are facing a surface the force will go up.

And then maybe decrease and then up and so on. Force and here during the operations there could be some phenomena happening okay. Now by low pass filtering and segmentation I mean that I will allow and this there could be a lot of high frequency noises also in the signal. Put set amount of noise in the signal, so but I know looking at this plot in the time table I know that my information of interest is actually here okay.

So, this the analysis and analyst an intuitive guess as to well I do not look into the entire signal I need not find out the RMS value or the mean value of the entire signal. But let me focus my attention only to this area which I have encircled because this represent the true phenomena while that mailing operation is going on okay. This does happen but this could be because of factors which are not being affected or affect the milling operation.

If milling operation is my prime objective of monitoring I should be focusing only on this. So, that is why we need to first do this low filtration segmentation.

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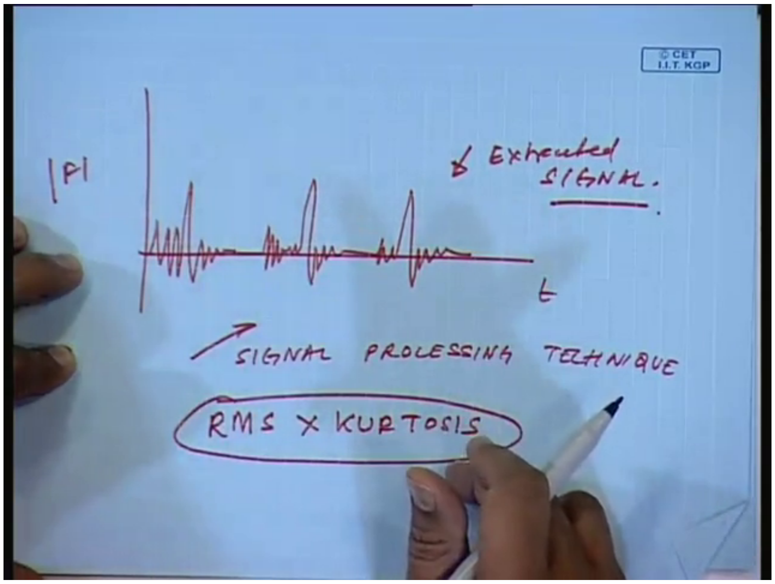

So, I would have segmented them and then I will redraw this red curve maybe I will just something like this is happening. So, out of that earlier signal this is my extracted feature or extracted signal ok. So, now I could be using all my signal processing technique to know more about the signal. For example in time domain which we know by now I can find out the maximum value of the signal the minimum value peak to peak RMS, kurtosis, skewness okay.

I will not cover about frequency domain right now because that will be in the subsequent classes. But so just with an oscilloscope or a computer having a data acquisition unit I can get lot of information about the signal. And there are reported features in the literature that this number could be as high as 20 to 25 features a single waveform like this in the time domain itself. I can get 25 features of the signal.

And they are and you know some feature may change like I gave you just the example of kurtosis. Kurtosis traditionally has been a sure indicator of a bearing fault or a gear fault kurtosis is high more than six I know for sure that the machine is bad. Now it is recently people have reported in the literature a parameter known as RMS value times for kurtosis okay. There are few references from this people.

Find out the RMS, kurtosis and multiply them and this is a strong indicator if its value is high. It is a strong indicator that something wrong with the machine okay.And you see the cost of implementing this technology in your machine, so it is very cheap all you need to do is just have a transducer cable oscilloscope or a signal analyzer doing only the time demand analysis.

Signal analyzer could be a computer or a laptop but you need to get the data into the system okay. And then once it is there could be doing the simple signal domain analysis.

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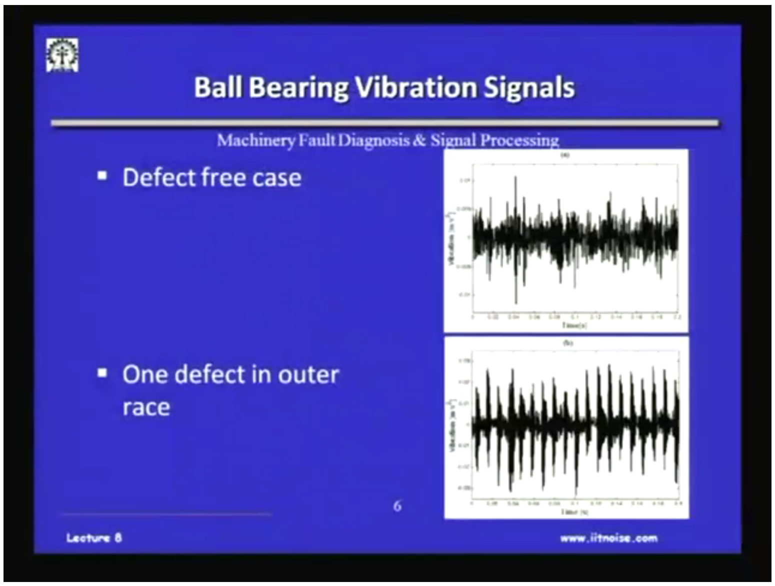

I will now show you some signals real world signals which occurs in the machine for example this is for the ball bearing signals okay and this is in time domain about 0.2 seconds. This is the vibration signal, this is for a defect free bearing which was loaded and run. And this value perhaps cannot read it, but let me tell it to you this is 0.01 meters per second square.

And this is -.01 meters per second square, so the signal looks something like this and it is very, very or low level compared to once we have a defect in the outer race of a bearing.

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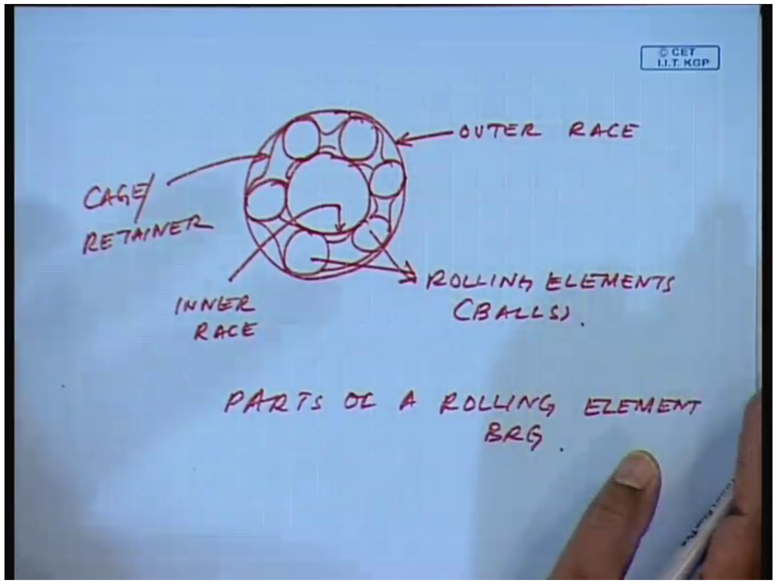

Let me just draw the bearing for all of you we have this so this is the outer race this is the inner race; these are the rolling elements or the balls. In this case and there is actually a cage or a retainer which are not drawn here which makes sure that this none of these two balls or rolling elements come in contact with each other? And this is known as a cage or sometimes known as a retainer part of a rolling element bearing.

Usually ah either the outer race or the inner race is stationary but usually the inner race rotates okay and the outer race is fixed in a casing. But if you recall our common ceiling fan it is just the reverse, common ceiling fan the inner race is fixed the outer reciprocates and then the blades are attached the and the blades are attached just example.

So, in this case we had an artificial defect okay because we have a bearing manufacturer next door in Kharkpur, so they helped us, to do this experiment. In fact we could see default the fault in this bearing. So, in one case we had a defect in the outer edge where we had a pitting mark, so in with just a small defect of that if we look into the ball bearing signal.

You will see that the levels have gone up point 0 8 and -.08 sorry .03 and -.03, but you see the nature of the signal if you compare the top and the boredom you see a lot of peaks. So, each time these rolling elements come across this defect there will be an impact okay and because of this impact these levels go up and down.

So, one is not just if I was to observe the peak values or the mean values of the RMS values they may be very close okay sometimes. So, that is why it features like RMS and peak values need not be the true indicators but say for example if I measured the kurtosis of one over the other you will see kurtosis of the second one is considerably high.

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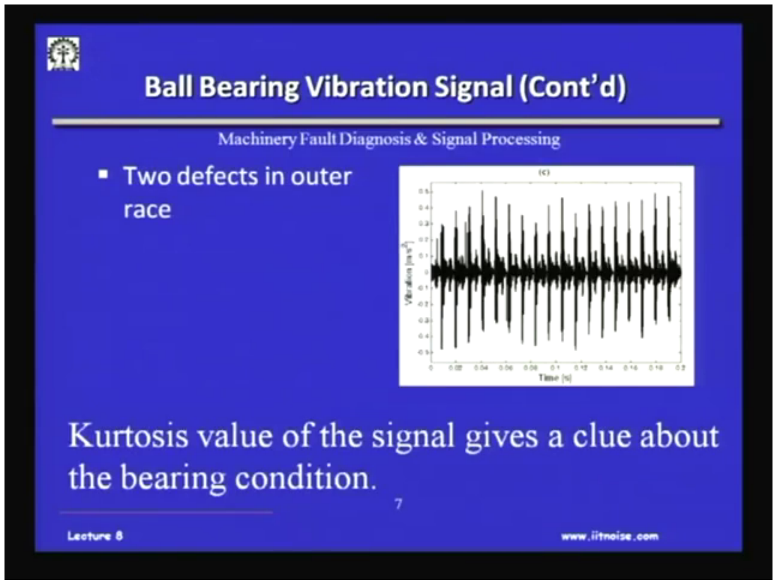

I will see the case when there are two defects. So, we made two defects this severity of the bearing increased defect increase and the values are very, very high .5, .4 and you see the nature of this so just by a time demand visualization of the feature of the of the signal we can say well something is good or bad in the bearing okay. But to be more correct we can always estimate the kurtosis or the RMS time kurtosis and then find out the such conditions of the bearing.

So, kurtosis value of the signal gives a clue about the bearing condition. So, this is just a beginning of what you are going to see in this course in terms of the feature extraction from the signal how we are going to do that using software like Matlab, Excel and then find out the features and then try to diagnose the kind of faults which are there in that machine.

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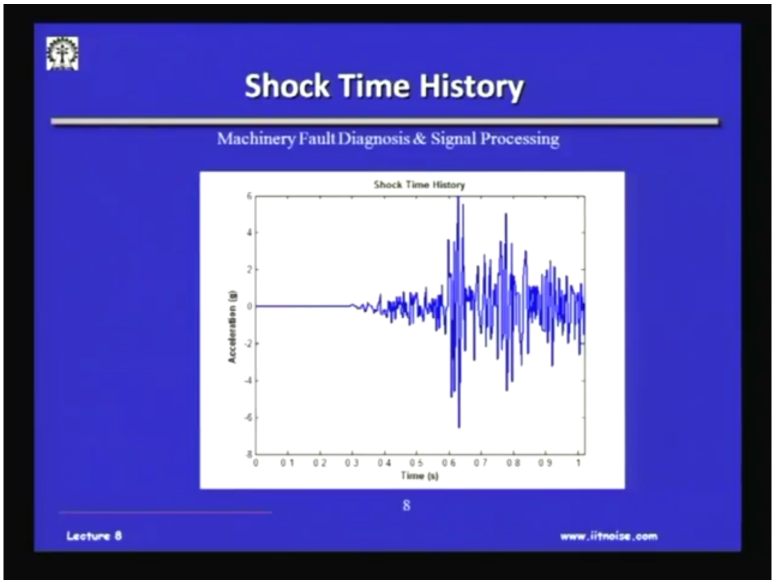

This is just to give you an another example we are talking about in vibration isolation yes this is a typical case of a shock which occurs in a machine and this is how it looks in the time domain and this values are actually -6 to 6. Well these are actually values measured from an earthquake and this is the ground and this is a very, very low level of; I mean this levels could be 25G okay.

And this is what a time history of the shock wave looks like. So, what kind of features are we going to extract from this because signal also can is not only information it also conveys energy transmits energy. So, how much of energy is coming through the system is also to be considered.

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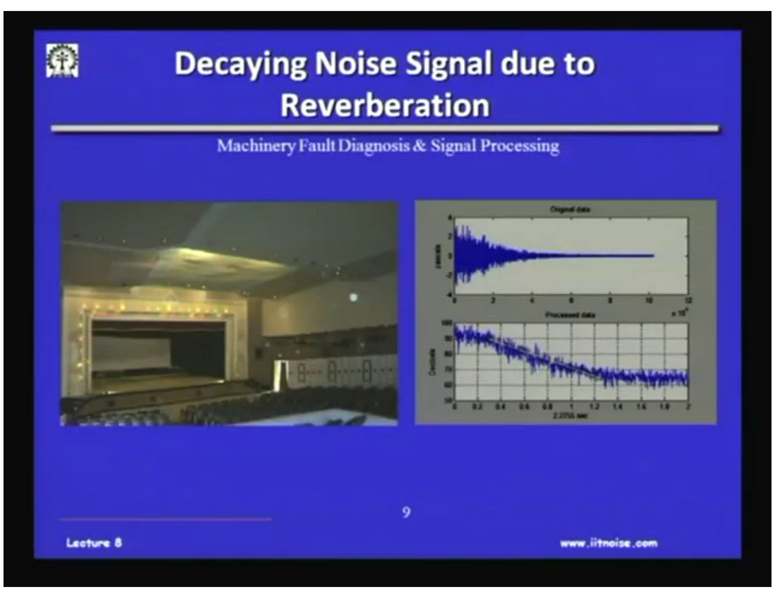

And this is just to give you an another example of a signal. So, this is an auditorium where you know we people in our because of the reverberation or because of the absorption in the wall this if there is a loud noise level and suddenly it is shut down. This is the time history this level is going to come down right so the quicker it comes that means the more quickly the sound has been absorbed.

So, these kinds of studies are used to estimate the reverberation time in the room. Imagine if all these walls were reflecting it would take a longer time for this sound to come down you almost have seen in the indoor gymnasiums you know when people shout the whole thing is reverberating because there are no acoustical absorbers.

Imagine in your cinema halls if this reverberation was very high when the actor says a dialogue it will be ringing, ringing it will be not decaying and then another actor would be saying something and he will get all jumbled up. So, reverberation time is estimated by this method and you know this is how a typical signal looks like, like you see the decay and then the time taken for the noise level to come down by 60 decibels is the what is known as they reverberation time.

Some of the opera houses have typical values of 2 seconds like the Sydney Opera House, now if you clap you can hear it ringing inside for about 2 seconds okay. but we cannot afford to have that in a classroom or a conference room it has to be much, much less. So, this is typically one of our times. So, you would characterize this as a non-stationary signal because this is happening once on a time it is not repeating it is not stationary.

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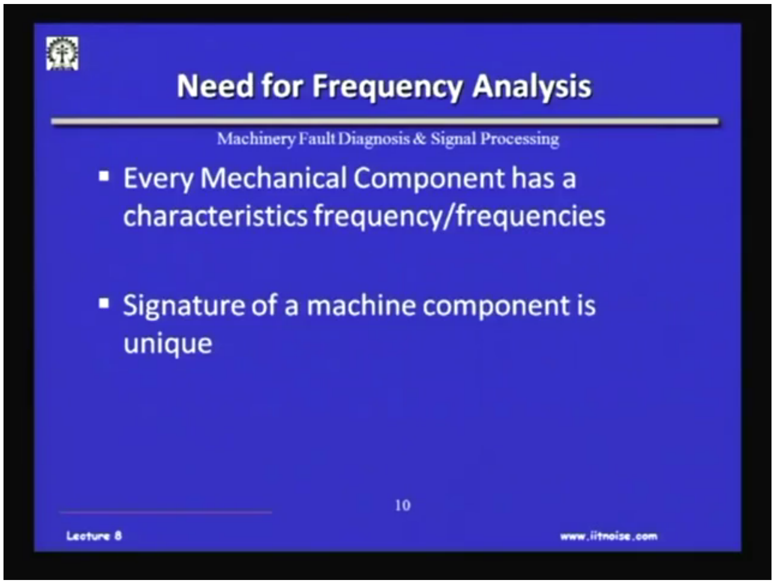

So, with this kind of on background you will see that you know well it is good that by time domain analysis we have some idea about the features of the machine. Sometimes you will see that we need to do a frequency analysis of the signal because of the fact that every mechanical component has a characteristic frequency, character frequency or frequencies is okay.

And this characteristic frequency which show up in the frequency spectra are actually the signature of your machine like every human being has an index signature. Every machine has an unique vibration signature. So, if something is wrong with the machine the vibration signature would change. So, if today I would have taken the vibration signature 2 months down the road.

I will take the vibration signature again of the machine if things have the signatures have changed I know something is wrong with this machine okay.

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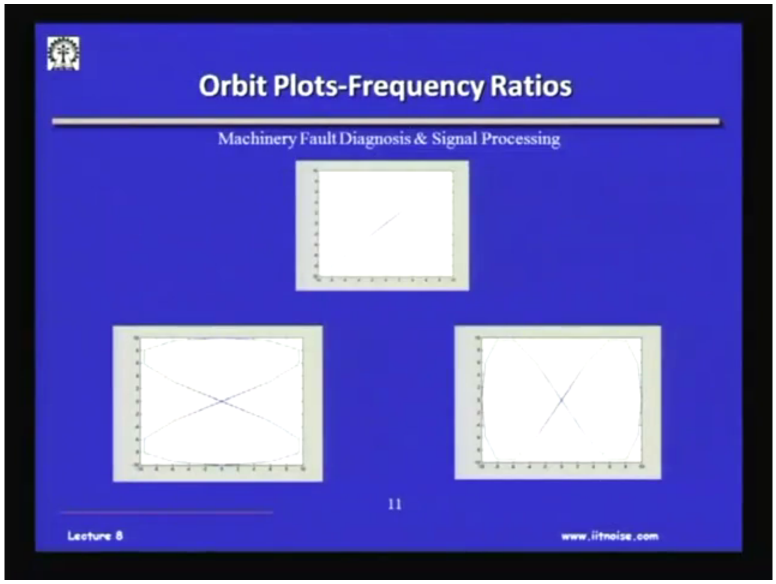

And then we will come to more about orbit, plots and frequency ratios and know once we discuss more about the frequency because but essentially there are two time signals. If I know one signal time period, I can know and their signals time period depending on whether they are know related as same the two frequencies are same or two frequencies are different, two amplitude are different something is what we are going to talk about in the subsequent classes okay.

So, I will expect that you all become familiar with Excel while we do this course and I will be also telling you about how to use MATLAB in the course okay, thank you.