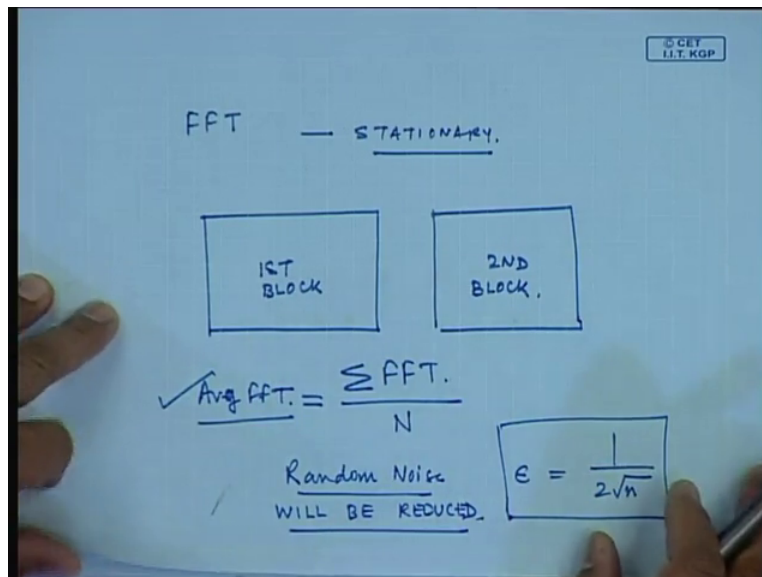


Machinery Fault Diagnosis and Signal Processing
Prof. A R Mohanty
Department of Mechanical Engineering
Indian Institute of Technology-Kharagpur

Lecture -12
Modulation and Sidebands

Today we will discuss about modulation and sidebands well by now I understand you must have got a feel of what the different types of signals are whether they are stationary, non stationary and then how we can distinguish these two just by looking at it in the time domain. But more importantly we can look at them in a frequency domain know their frequency contents and then try to characterize the signal.

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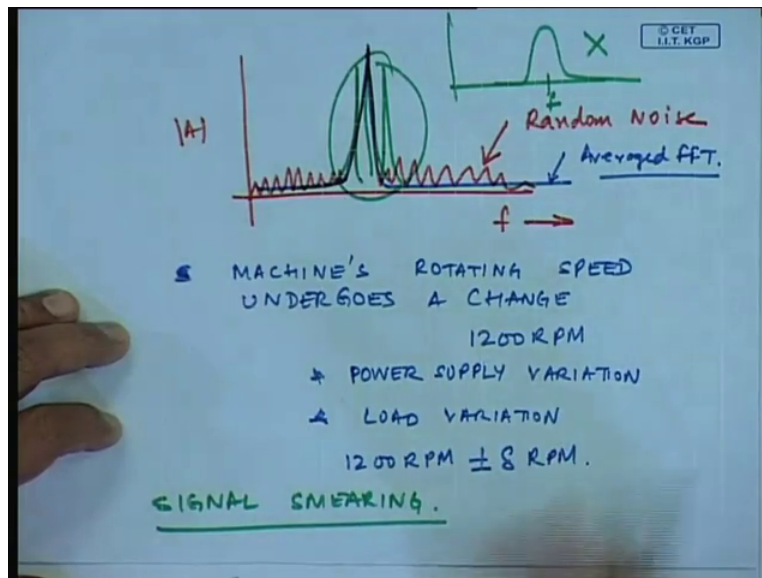
One thing you will realize and we are going to do FFT we always assume that the signal is stationary ok. But you know that the process of FFT takes some time. What would happen if the signal was varying the instance you are doing the FFT. So, if you are; so, for example you are doing a number of FFTs you have taken the first block of data first block and the second block we are also being digitized and ready for FFT.

But if the you are trying to do and similarly you will be doing an average FFT you will be doing summation of all the FFTs and then dividing that by the number of FFT, so that you get here averaged FFT. The reason we do this averaging is because to reduce the random noise okay and

this random noise error will actually reduce by this equation where n is the number of averages okay.

This equation comes from the probability theory and we will not go into details of this. But it suffices to say that once we are doing the FFT of a stationary signal if I do increase the number of averages the random noise will be reduced okay. So, averaging helps us to improve the signal characteristics or signal features while doing an FFT by removing the randomness.

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Otherwise let me just give you an example here that if you did an FFT of a signal you will perhaps get a lot of low frequency, high frequency and this could be because of the random noise present in the signal this the frequency, it is the amplitude. So, my objective is to reduce this random noise by having more number of averages of this stationary signal okay. Then I will have a sharp peak and this is the averaged FFT okay.

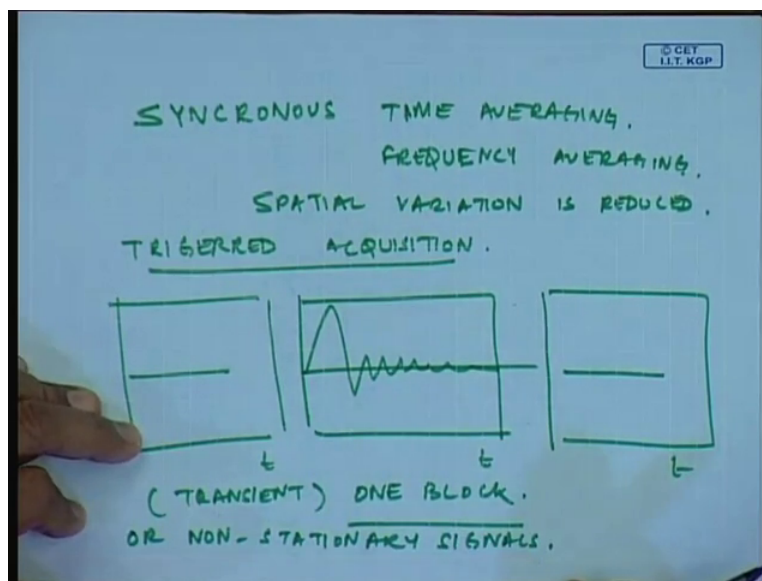
But this is very realistic very ideal but what would happen if the machines rotating speed undergoes a change. By change I mean not that you know you are running a machine at 1,200 rpm, you want to run it at 1600 rpm and so, on. No I am not talking about that I am talking about say for example if you are running at 1200 rpm because of a power supply variation because of a load variation which could be intermittent on and off.

So, this 1200 rpm will then vary by an amount of Delta RPM, it could be very small, it could be one or two rpm. But what happens if you are taking this data continuously you had assumed it to be stationary. So, you are violating the definition of stationarity, so what happens one average you know maybe I will draw them by different lines.

These frequencies you know once it can be here another time it will be here another time it will be here. So, once you have an average of this you may have a signal something like this and this is not desired, this is something, so I cannot identify this frequency of my machinery because of the; this is because of what is known as signal smearing.

Signal smearing has occurred because the signals frequency has changed while you are doing the FFT or a while you are doing the averaging. But if it is a noise constant steady state constant speed machinery. If such averaging's are done then we will not have the problem of signal smearing.

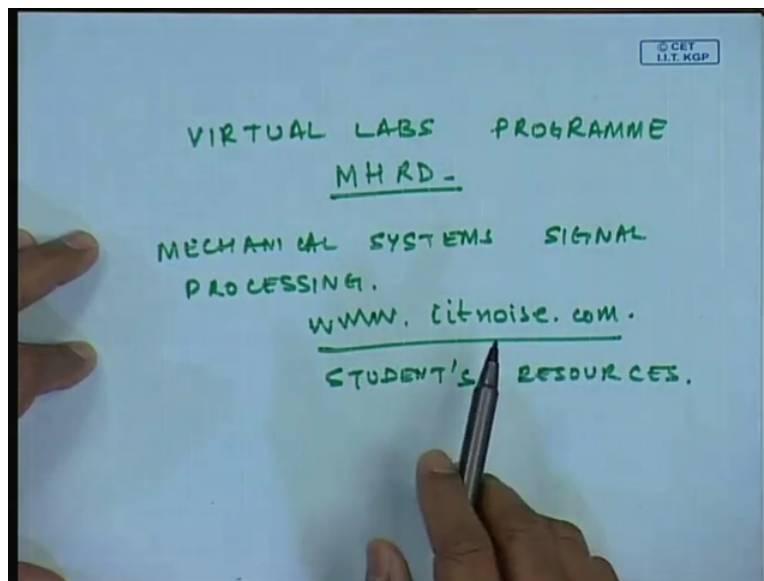
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To avoid this sometimes we do, what is known as synchronous time averaging or frequency averaging. Once we do that the spatial variation is reduced and another method is by having a triggered acquisition okay. So, some of the features will be prominent when you do such time. I have synchronous time everything and frequency averaging okay. But many a times even sometimes just a single equation is good enough.

For example once you know the signal is fluctuating quite often so we should be able to capture the signal just by taking one block of data. Particularly while we are dealing with transients kind of signal this happens only once. So, in the next block there may be no signal. The previous block there could be no signal. So, in such a case maybe just one block of data processing is sufficient. Particularly once we have such transient signals or for non stationary signals okay.

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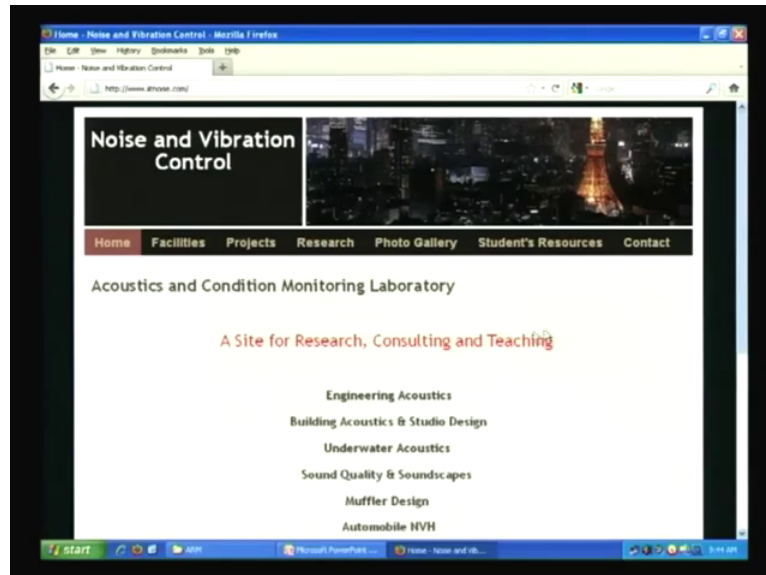


Now here I would like to draw your attention to a signal processing module which we have developed at IIT, Kharagpur, under the virtual labs program of the Ministry of Human Resource and development, MHRD. So, I will; there is a lab on mechanical systems signal processing which you can access through my website sorry www.iitnoise.com. It is linked to this website and once you go to the student resources.

You will click there and I will take you there then because a course on machinery condition and signal processing cannot be just 40 lectures. It has to be also done through some bit of labs. We possibly will cannot go to the lab so I have tried to bring the lab to this classroom ok. So, there are a few experiments in this portal where you can do the virtual lab at home, at your leisure and then try to generate signals, try to do their time demand analysis.

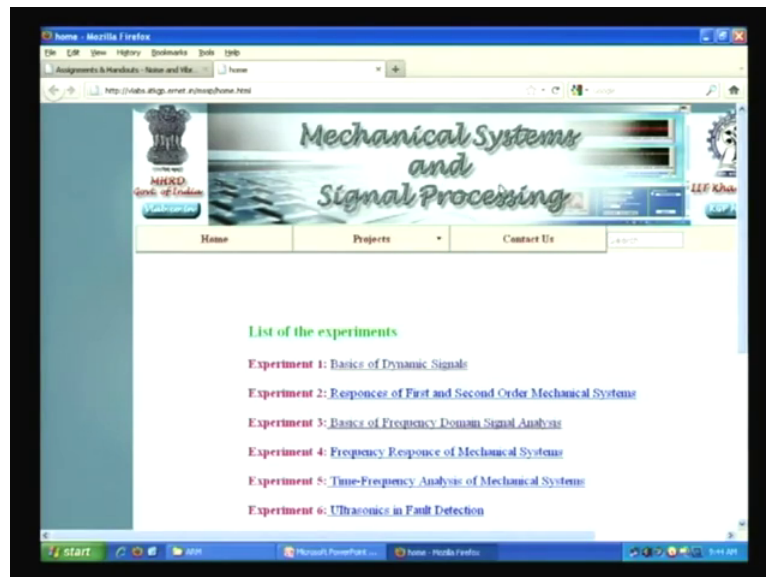
Frequency domain analysis I will not take it as a detailed exercise in this class but I will just show you how to access it.

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So, what you need to do is you can go to this website on itnoise.com and this is the address. So, once you come to the student resources and there is a virtual laboratory and mechanical systems and signal processing.

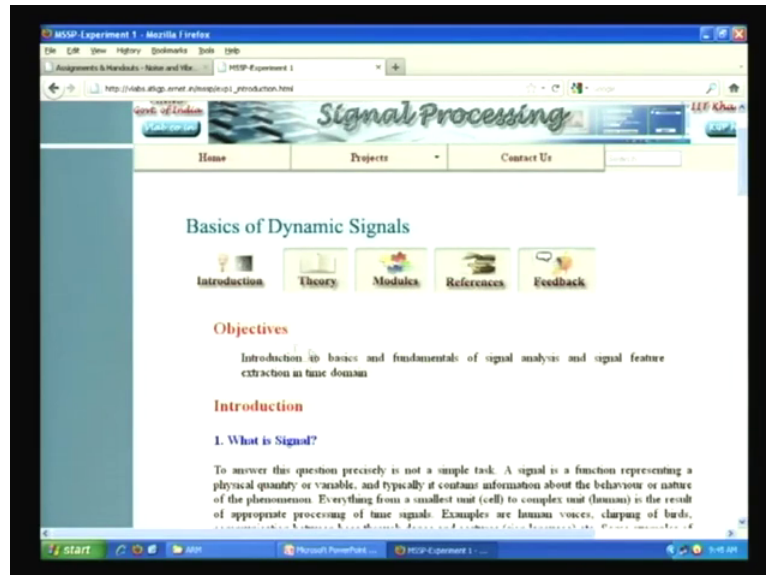
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If you click here it will take to the NPT MHRD website on virtual labs and this is the lab for mechanical systems and signal processing. In fact throughout the course of this extra course when we are going through the other examples, other lectures we will come to these experiments

one by one. Right now I can; you can access basics of dynamic signals basics of frequency dimension I mean the first four you could perhaps do right now.

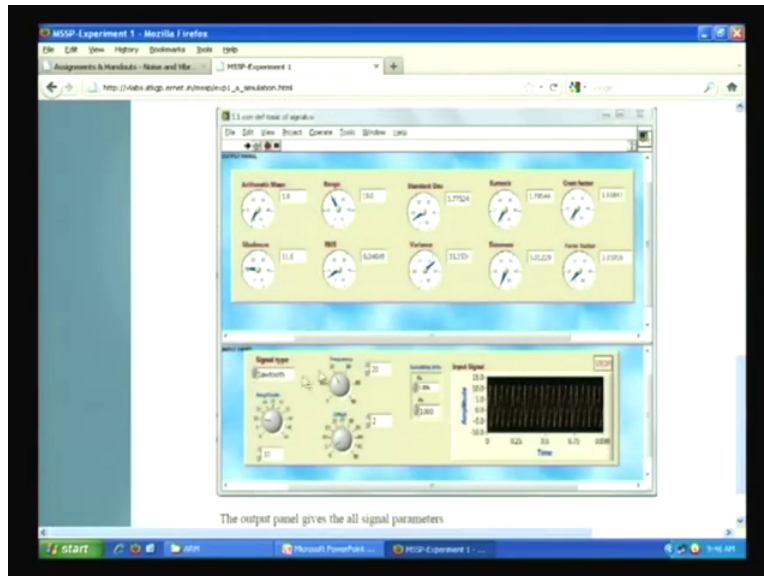
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I will just show you how to invoke basics of dynamic signals all you do is click there and then there is an introduction of understanding about the signals there is a bit of a bit of theory on this topic and then how do you measure all the different time domain parameters. And then you can go to the different modules. There are three models by which you can generate the signal one is by user different waveforms.

Other is by a mathematical function and the last one is your actual measured data. So, then in the user defined where forms you could generate a square wave, sine wave, triangular wave sawtooth wave. You could write your own mathematical expression of further signals you can add signals see the beating phenomena etcetera or you may have your own real world data which you could perhaps bring into these files. So, the module one, go to the simulation

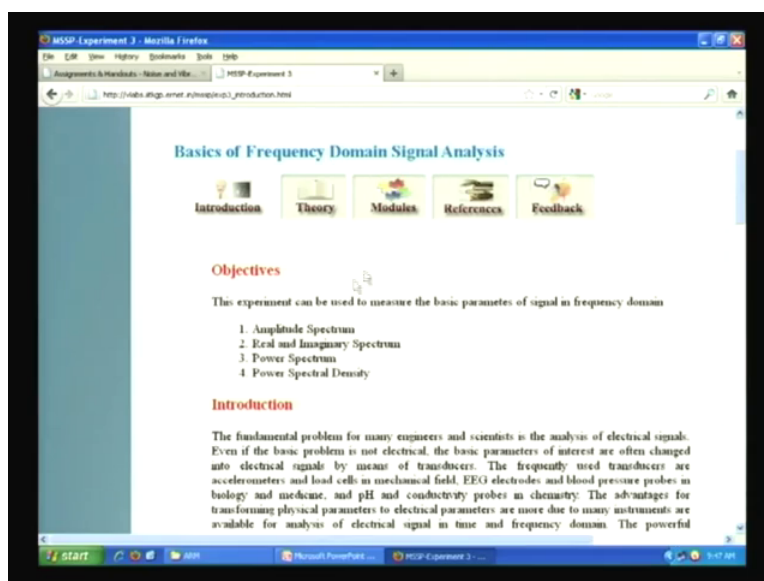
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I will just show you the screenshot of this signal what happens here is, you know this is the screenshot you will be having, so you can generate your signal right turn it is sawtooth you can increase the change the amplitude given offset to the amplitude change the frequency, see the waveform and then this program itself will calculate, the mean, the maximum, the standard deviation, kurtosis, crest factor form factors skewness variation.

So, you get a feel of the signal, feature of the signal just generating yourself as if you do not need a signal generator or an oscilloscope or a computer to do the analysis. You go to this website.

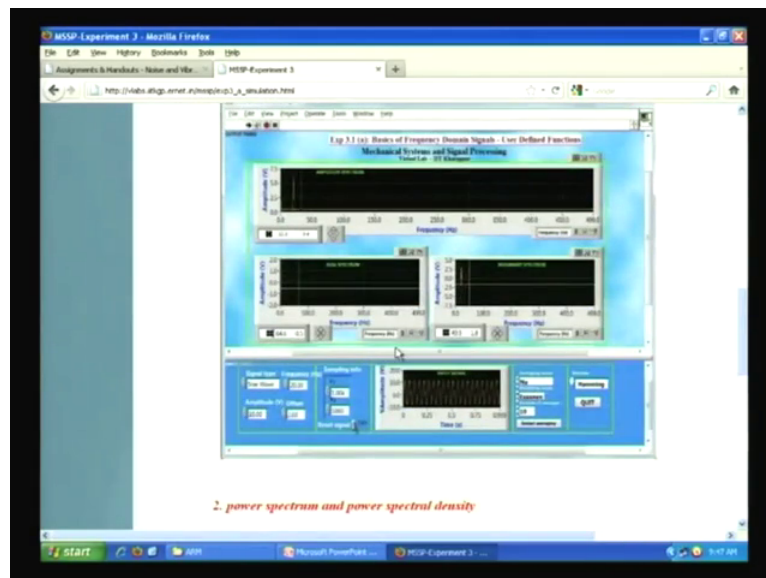
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And next model of course is you could add your own sorry you can generate your own signal and then you could also see the same effect. And the second experiment is on the responses of first order and second order systems you need not go through this right now for this course. But the most important for the frequency analysis is you can find out in the third experiments.

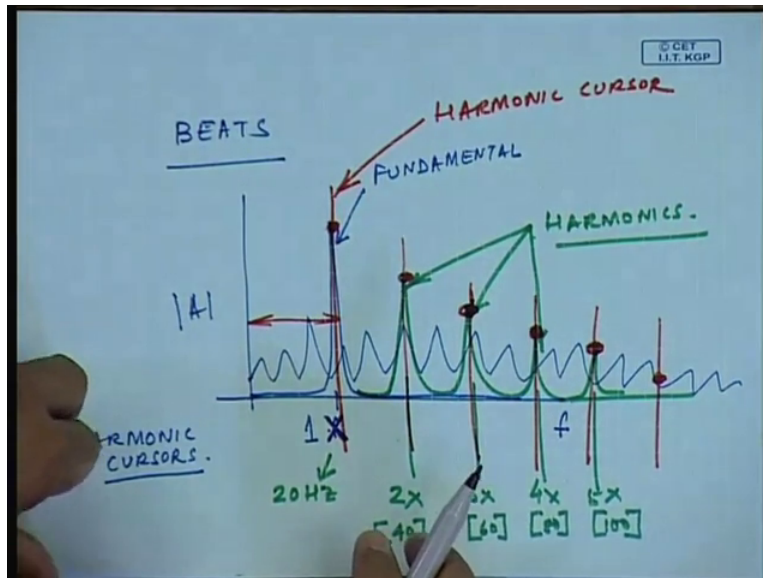
Basics of Frequency Domain Signal Analysis you could be measuring the finding out the amplitude spectrum they really imagine it a spectrum power, spectrum power spectral density of any type of signal which you want to give. Similarly, here it could be user defined functions mathematical function a measure data.

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And then in fact this is how the screenshot of the frequency analyzer looks like again here you generate the signal you can decide on the sampling frequency. You can decide on the averaging mode on the type of window and then you can see the amplitude spectrum you can see the real and imaginary spectrum here. So, you could use this at home to understand more about the signal analysis. And the link through this is this website www.iitnoise.com.

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Now, let us come back to this frequency domain analysis regarding modulation and sidebands which I will focus mostly in this course here rather in this lecture here. We have discussed about beats in the last class.

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Harmonics and Sidebands

Machinery Fault Diagnosis & Signal Processing

- Harmonics are at multiples of the fundamentals
- Sidebands are on the either side of a single carrier frequency

Lecture 12
2
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A beating occurs when we have well before I come to beats I will tell you something about the harmonics and sidebands. For example I have a frequency spectrum I have certain amplitude so I have got a certain frequency, the first frequency this is the fundamental okay. So, this is at a function of say X , I am writing this as X , and you really write it as $1X$ in the literature of condition monitoring.

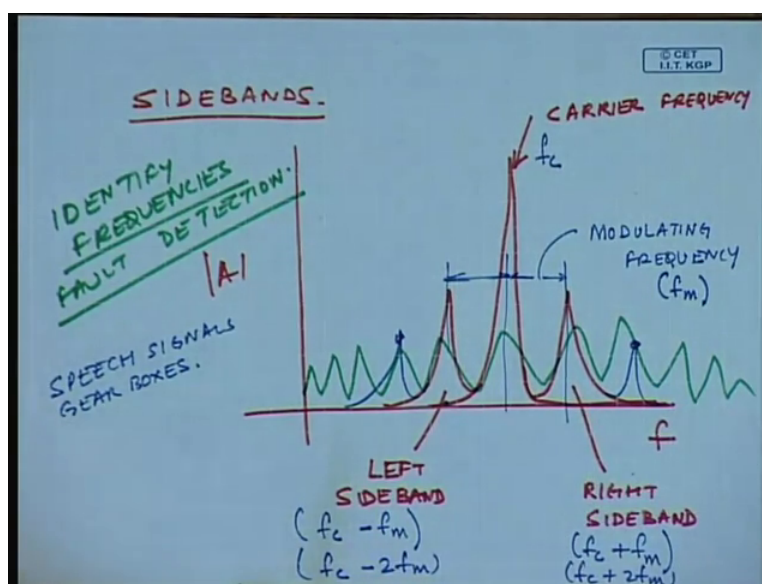
It may so happen this signal and this is one type of signal there could be spectrums peaks which are equally spaced and this is an exact multiple of the value here. So, these are known as the harmonics, this helps us to know whether these harmonics are multiple of the fundamental. Suppose this value is for example if this corresponds to 20 Hertz okay. So, if I see a value at a peak at 40, a peak at 60, a peak at 80, the peak at 100.

I know that these frequencies they are the harmonics what happens this is a very ideal situation in the real one once you go to the FFT analyzers. You will see that there will be a lot of noise like this buried okay and these harmonics are perhaps buried in the FFT. So, to our naked eyes sometimes it becomes very difficult to determine what the harmonics are. So, sometimes there are what is known as the options are available which are known as harmonic cursors.

So, once you set at the fundamental a cursor which happens to be the harmonic cursor automatically it will calculate because it knows this distance or it knows this value. So, it will calculate and put the harmonic cursors in all the places in the spectrum. And then you can very easily identify if there is a peak, you know well these are the harmonics and so on.

So, this is what is one of the harmonics and harmonics occur because of particularly in unbalance in misalignment. You will see lot of such things occur they are all multiple variations ok.

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Then we have what is known as side bands. Side bands occur in the frequency spectrum around a particular frequency for example I have a peak here, I will also notice that there are two very prominent peaks almost equally spaced about; this is usually known as the carrier frequency and this is the left side band and this is the right side band okay.

And this value is the values of the; what you know as the modulating frequency. So, the modulating frequency was value is f_m and this is f_c . So, the value here the f_c side band will be $f_c - f_m$ and here it would be $f_c + f_m$ okay. Now there could be sometimes you know $f_c - \text{twice of } f_m$, $f_c + \text{twice } f_m$. So, basically there will be a group of side bands around a carrier frequency. It would suffice right now to say particularly this kind of signals occurs in speech signals.

Occur in gear boxes, now these are very ideally represented signals if you go to the real world machines again there will be a lot of noise okay and on top of it there will be many carrier frequencies. On top of it the frequencies could be smearing because of the effect of the load or the speed fluctuations. So, and then once you do an FFT you may not be getting a sharp frequency because of the frequency spreading.

So, because our objective is to identify frequencies I mean we should why are we studying signal processing? Our primary objective is to identify frequencies so that we can do fault detection okay this is our primary objective we should never forget that no matter what amount of signal processing we do it may be a mathematical exercise altogether.

But end of the day unless I detect defaults my signal processing is no good okay. But so what are the tools available? Excuse me so what are the tools available to do this kind of signal processor. We will come to this in the later classes regarding substructure analysis we can identify the sidebands etcetera.

But it would suffice to say that in a frequency spectrum I will be seeing side bands as well as harmonics okay or I may see none of them also at times. So, now let us see why and how these side bands are generated in the first place and harmonics are generated in the first place ok.

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Signal Beating

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- Summation of signals which are independent of each other
- The independent frequencies are close to each other

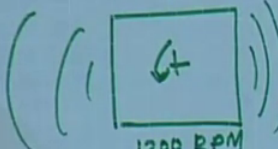
Lecture 12
3
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To begin with let us talk about signal beating okay.

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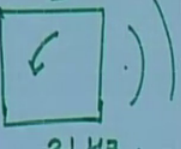
SIGNAL BEATING.

A



1200 RPM

B



21 Hz

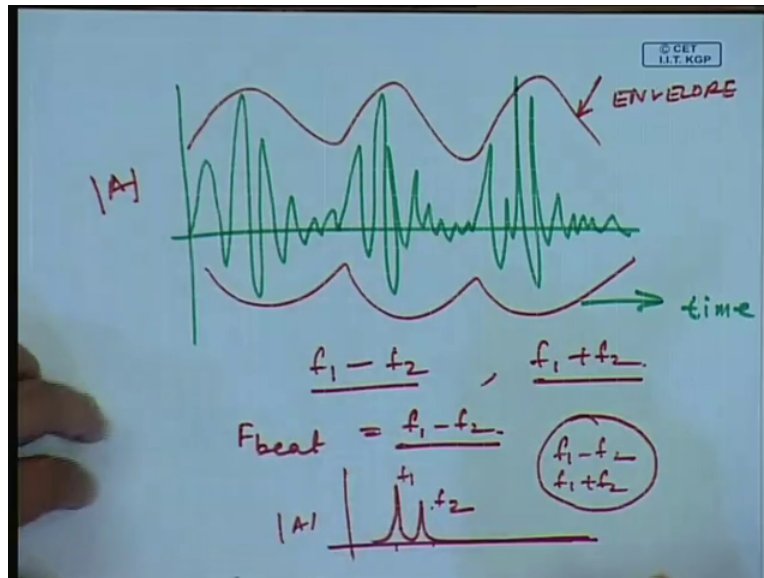
$\omega_1 = 2\pi f_1$
 $f_1 = 20 \text{ Hz} \Rightarrow \frac{1200}{60} = 20 \text{ Hz}$
 $f_2 = 21 \text{ Hz}$
 $\rightarrow 20 \text{ Hz} + 21 \text{ Hz}$
 $A = A_1 \sin \omega_1 t + A_2 \sin \omega_2 t$

For example I have a machine A running at say 1200 RPM that corresponds to 1200 by 60 that is 20 Hertz okay. Some machine is there it is operating and running. I have another machine B which is for some reason it had a defective supply or something it is running at 21 Hertz okay. Of course I am standing here now because it is running at 20 Hertz on this heavy mechanical machinery it is also going to generate noise at these frequencies.

To my ear I am beating 20 Hertz and also I am getting 21 Hertz okay. And then you know if I have two signals say $A_1 = \sin \Omega_1 t + A_2 = \sin \Omega_2 t$ where $\Omega_1 = 2\pi f_1$, so in

one case $f_1 = 20$ Hertz in another case $f_2 = 21$ Hertz okay. So, once I see this or hear the signal in fact if you mathematically;

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Some of the signal they are going to look like this because I am not being accurate and while drawing in by my hand this is how it will look in the time domain. And if I can draw waveform this is the envelope it is known as and this is the resultant signal A. So, you see this resultant signal which I hear is no longer constant in amplitude it is changing with frequency and this resultant frequency will be because if $f_1 - f_2$ and $f_1 + f_2$ okay.

So, two independent frequencies because the relationship between machine A and machine B they are totally independent. But the net effect produces a resultant signal something like this wherein the frequency; then this signal will sound like as if you must have gone to a factory where in two machines are running, you will get this kind of howling noise you know.

Suddenly noise increasing, decreasing, increasing, decreasing and that is because two machines are running side by side at very similar very close by frequencies. So, frequency of this beating is nothing but $f_1 - f_2$ and this is a very small quantity and the time period of this beating is the inverse of this. So, in the frequency domain all I will have is two frequencies close by one is maybe f_2 one is f_1 , some amplitudes.

I will not know whether they are beating unless I see the resultant wave form in the time domain okay. But I will see two distinct frequencies and I will also see if frequencies of $f_1 - f_2$, $f_1 + f_2$, if I see this I will know the signals are beating.

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SIGNAL MODULATION

$$x(t) = A \sin \omega_c t$$

↓

$$A_m \sin \omega_m t$$

$$x(t) = \frac{A_m \sin \omega_m t \cdot \sin \omega_c t}{(\omega_c + \omega_m) \text{ and } (\omega_c - \omega_m)}$$

CEILING FAN — NRPM [HUB]

No. of Blades = 3
BLADE PASS FREQUENCY = $\frac{3N}{60} \text{ Hz}$

But another very important characteristics of signal or types of signal that the signal modulation okay. Now suppose I have a signal $x(t) = A \sin \Omega_c t$, now this A itself in this case is a constant. But suppose A was also varying with A frequency is given by $A_m \sin \Omega_m t$ and this is Ω_c okay. So, my $x(t)$ will be $A_m \sin \Omega_m t \sin \Omega_c t$ okay.

So, product of two sine functions will be a summation or you will have components in the result and as two frequencies one with $\Omega_c + \Omega_m$ and another with $\Omega_c - \Omega_m$. So, the product of two sine waves one is modulating the other like I give an example of a very common example is a ceiling fan. Ceiling fan the hub rotates at a particular RPM say N RPM, the rotation of the hub.

And then I have say number of blades equal to three I will have the blade pass frequency as $3N$ by 60. So, you see the rotational speed of the ceiling at the blade pass frequency and the rotational frequency they are related one is affecting the other and then we can have modulation to begin with.

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DEFFECTS IN BALL BEARINGS.
GEARS.

$$x(t) = A_m \sin \omega_m t \cdot \sin \omega_c t$$

$(\omega_c \pm \omega_m)$
 CARRIER FREQUENCY MODULATING FREQUENCY.

But more lessons you will see in details when we talk about defects in ball bearings and gears and so on. So, but the fact that $x(t) = A_m \sin \Omega_m t \times \sin \Omega_c t$ this gives rise to $\Omega_c + \Omega_m$ and this is what is the sidebands. If we look at this FFT of this signal because modulation has occurred the resultant wave form will have signals which will have frequencies of $\Omega_c + \Omega_m$ and $\Omega_c - \Omega_m$ or $f_c + f_m$ and this is known as the carrier frequency and this is one of the modulating frequency.

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Distinguishing Features of Amplitude Modulation

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- Carrier Frequency
- Modulating Frequency
- Sum of the carrier and modulating frequencies
- Difference of the carrier and modulating frequencies

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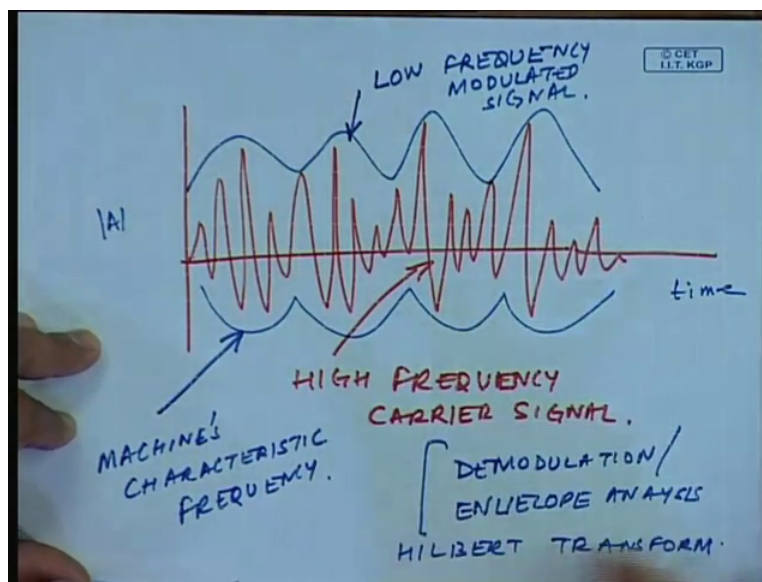
I will; so what are the features of these distinguishing features of amplitude modulation. Suppose I have taken an amplitude modulated signal and I have done a fast Fourier transform of such a signal, one is I will see the carrier frequency f_c , I will see the modulating frequency, but most

important is I will see the sum of the carrier and modulating frequencies, difference of the carrier and modulating frequencies okay.

In the case of the beating these frequencies may not be visible carrier and modulating frequencies it will be two independent frequencies showing up it could be f_1 and f_2 very close by. And usually in amplitude modulation one is pretty high compared to the other and then this sum and difference frequencies plus these two frequencies will be seen then you can know for sure that amplitude modulation has occurred okay.

And once we go to gear, but because our objective again is you know how do I find out my carrier frequency and modulated frequencies.

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Because once you do the; say for example this is a typical modulating signal I will show you how this becomes modulating because if you look at this signal this in time domain is the signal A. So, this is my high frequency carrier signal, so the transducer has collected the signal it is sending the receiver or the analyzer.

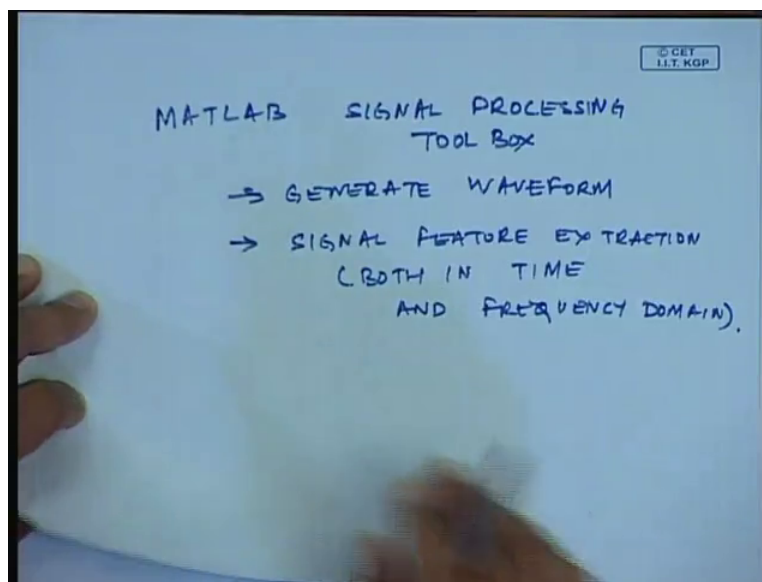
And the information is actually this one here, this is the low frequency model related the machines defect or machines features are actually there in the blue signal machines characteristic okay. If I do; so I have to find out a mathematical technique by which I can only obtain this low

frequency modulated signal because otherwise what happens once you go to the frequency domain there will be so many frequencies.

You will be kind of getting lost which one is a modulating frequency which one is your carrier frequency, which are the multiples of carrier frequency etcetera. They will be side bands, so there are mathematical techniques which we will cover subsequently how do we de modulated de modulate demodulation or sometimes known as envelop analysis okay.

There are many ways to do demodulation and an envelope analysis like using a Hilbert transform and that is something we will discuss later on. And then and this can be used to obtain this blue signal envelope of this modulated signal and thus know more about the machinery okay.

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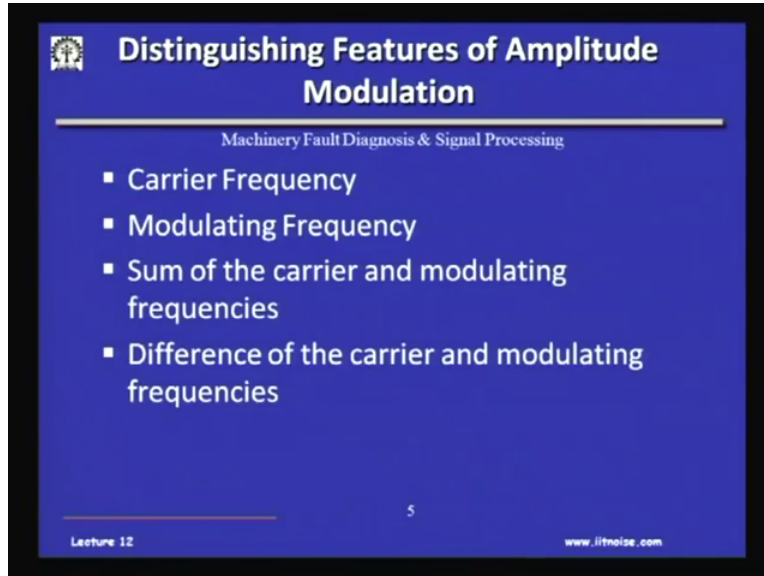


I should again tell you one thing other than this virtual lab I would also recommend that all of you use the MATLAB signal processing toolbox to generate waveform signal feature extraction both in time and frequency domain. And MATLAB is a software which is freely available in educational institutes as a floating open license students are you can use them or you can buy them and then use them.

But some of the examples which I will be subsequently showing you could be from our virtual labs website on signal processing and also some examples done on MATLAB. So in MATLAB if

you use the help menu you can know how to do signal rigid modulation, frequency modulation how to figure out find out the side bands etc. All these functions are level in the MATLAB.

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Distinguishing Features of Amplitude Modulation

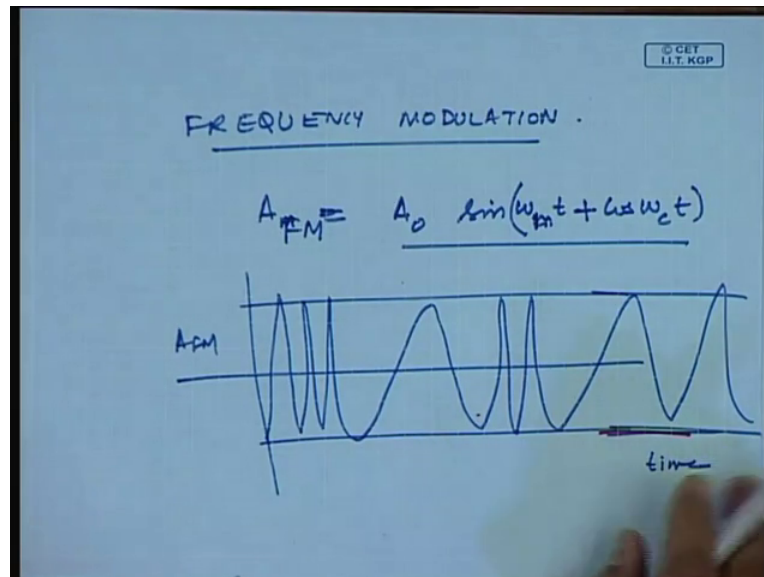
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- Carrier Frequency
- Modulating Frequency
- Sum of the carrier and modulating frequencies
- Difference of the carrier and modulating frequencies

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Now another type of signal modulation is what is known as the frequency modulation.

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In frequency modulation what happens FM I am writing AFM A naught sine Omega mt + cosine Omega ct okay. Now in such a case what happens if I was to draw the signal in time domain the distinguishing features of frequency domain signal in the time domain is the amplitudes are constant but the frequencies vary.

So, there when increase and decrease of the frequency about the same amplitudes okay. Because you can see these are the high-frequency signals, these are the low frequency signal because the time period has changed and then amplitudes are constant. Such signals also, we will come across in machinery and then we will see some of the features of this in the single Posse.

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Distinguishing Features of Frequency Modulation

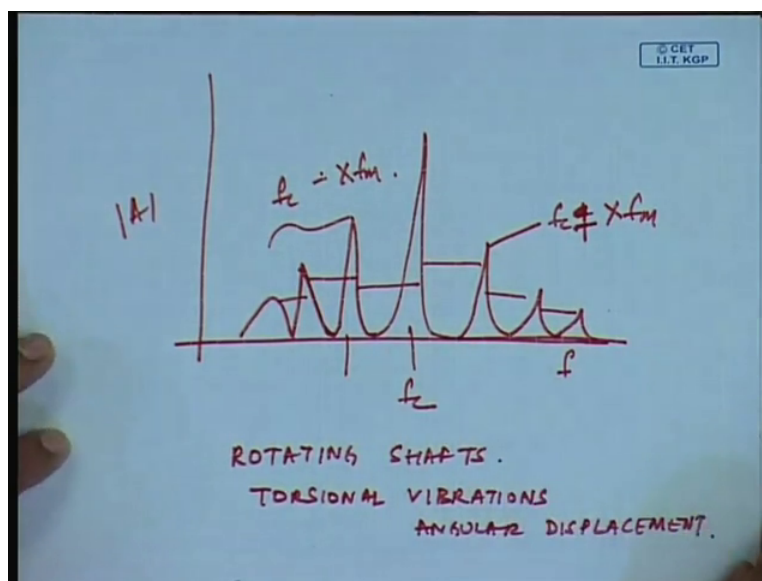
Machinery Fault Diagnosis & Signal Processing

- Carrier Frequency at the center of component array
- Multiple sidebands at the carrier frequency minus orders of the modulator
- Multiple sidebands at the carrier frequency plus orders of the modulator
- Constant signal amplitude when viewed in time domain
- No distinct component occurring specifically at the modulating frequency

Lecture 12
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Now what are the distinguishing features of the frequency modulated signals? Carrier frequency at the centre of component array;

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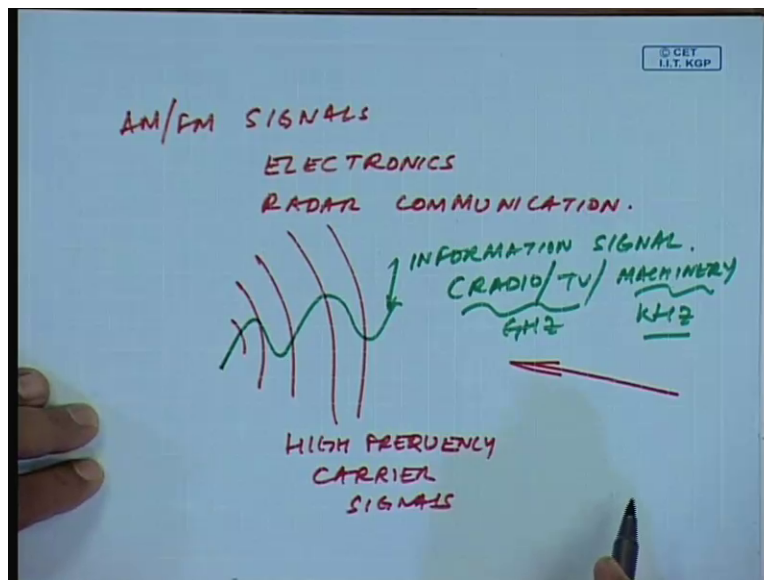


You will see a lot of sidebands okay and it presents of a multiple side bands with a spacing of f_c , $f_c - f_m$ or $f_c + f_m$, some X times f_m this is plus and this is again $f_c \pm$ some multiple of f_m and

this actually occurred in rotating shafts and particularly when we are monitoring torsional vibrations as a function of the angular displacement. So, there will be multiple sideburns at carrier frequency in minus orders of the modulator and multiple side bands at the carrier frequency plus orders of the modulator.

And constant signal amplitude when viewed in the time domain which would have been seen but there is no distinct component occurring specifically at the modulating frequencies which was present in the case of amplitude modulated signals. So, you will not see this happening in the case of the frequency domain fm signals.

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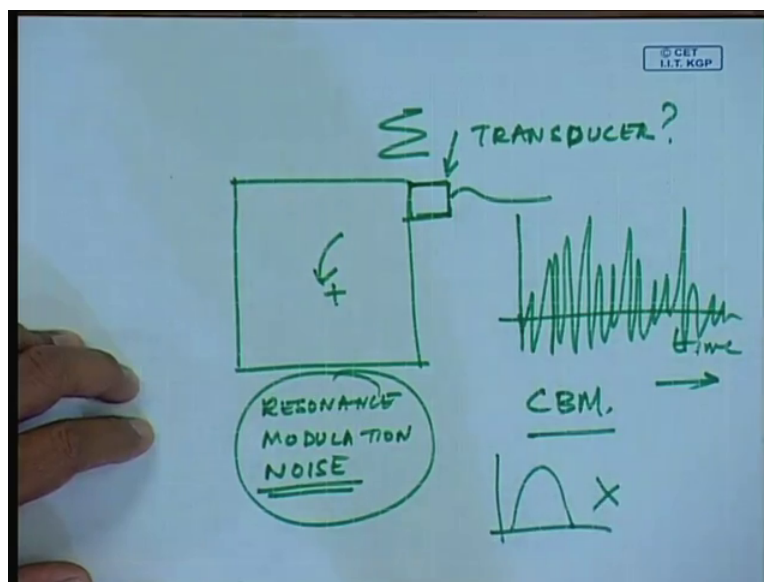
Now this Am and fm signals have traditionally been used in electronics mostly for radar communication. Wherein the; because you know the carrier frequencies are usually high frequency signals and high frequency signals are very directive ok. For example the radio signal, the TV signals they are very, very high frequency signals gigahertz and very directional.

So, if you have an antenna now you must have observed that when an antenna particularly with your shortwave radios or AM radio is you have to point the antenna towards the source and because the high frequencies they are very directional and on this carrier high frequency carrier signals. My information signal is the information signal, it could be a radio station signal, TV.

It could be machinery; okay these people talk in the order of Giga Hertz. I am talking in the order of only Hertz or kilo Hertz okay. Our signals are much, much lower bandwidth than the radio signals but nevertheless the physics of data communication is the same, laws are the same. But objective again from a machinery condition monitoring point of view is, how do, I get this information.

Whether it is frequency do not modulated or amplitude modulated is immaterial to me as long as by some signal processing algorithm I can find out this information green information signal okay. And that is what we will discuss in the subsequent classes regarding how do I find out the harmonics, how do I find out the sidebands most importantly how do I find out the modulated signals from such composite signals.

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And mind you once you go to the frequency spectrum of a signal because see my machine is there, my machine is an inanimate object and many things are happening in it simultaneously. All I have is put this poor transducer okay, so everything depends on what my transducer is capturing. So, the phenomena of the resonance could be occurring, the phenomena of modulation could be occurring okay.

Everything and of course our good friend noise is always present okay. So, all, everything is happening together in this system and I only captured this by a transducer and transducer is no

matter what you see in an oscilloscope will always give me a signal which is you know, I can make nothing out of it okay.

Our starting point in CBM is this I will not get a signal a transducer will never tell this is your modulated signal, this is your resonance signal this is your noise know everything is there built in, summation, some effect of all signals are there. So, we have to now, use our skills mathematical power how do, I analyze our signals. First of all is, whether it is a stationary signal where there is a non stationary signal.

Whether I can find out features in the time domain which are repeating, repeatability of the signals or whether it is one of a kind then we have to go into the frequency domain see if my FFT, I can see the frequencies as sharp peaks or there are no frequency smearing this is to be avoided. On top of it if signals are getting modulated there are presence of lot of side bands and end of the day I will land up with the signal where in a lot of these components are there.

So, then we will see how we can analyze the signals to get the different frequency content of the signal okay. So, I think with this I will stop here, thank you.