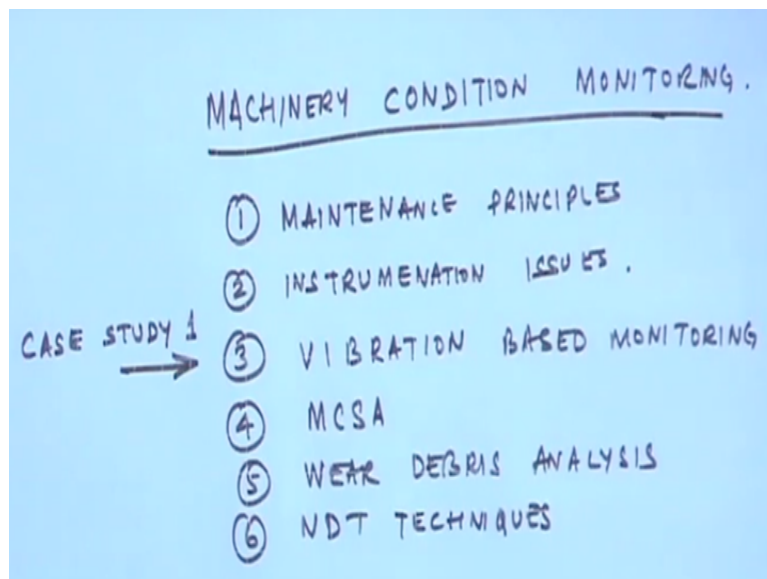


Machinery Fault Diagnosis and Signal Processing
Prof. A. R. Mohanty
Department of Mechanical Engineering
Indian Institute of Technology - Kharagpur

Module No # 08
Lecture No # 40
Case Studies

Hello this is the last class on this course on machinery of fault diagnosis and signal processing, the fortieth lecture.

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Before I get into the case studies few examples of applications of machinery condition monitoring in real life, I would like to just quickly go over the brief overview of the course and the syllabus content. Basically we had this course in few modules. But the main principal was to work on the machinery condition monitoring ok. And then few of the models we talked about was maintenance principles.

Then about the instrumentation issues. And because of this fact that for machinery fault diagnosis throughout the world, few very important practices are followed. Mostly 70% of the cases being vibration based analysis. Followed by about wear debris analysis which for about the remaining 20%. The last ten percent could be the motor current signature analysis and the few of the NDT techniques.

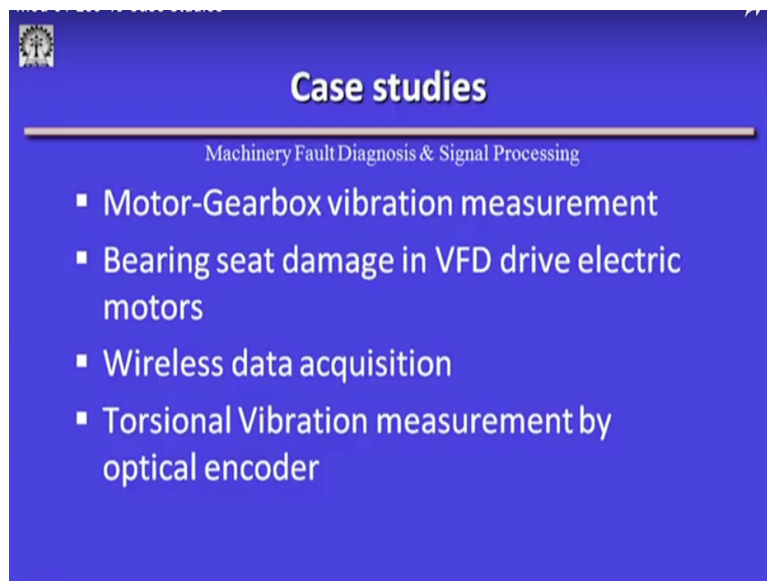
So if I was to see what we have studied in this course the most important aspect was the vibration based monitoring ok. And vibration based monitoring is particularly helpful for finding out faults in rotating machines. Because all the rotating machines can be represented

by a mass spring gas powered systems. And by some and the exceptions could be because of defects in the rotating systems like unbalance, misalignment and looseness, crack and so on. And then we get a response.

Based on this response we try to find out the fault. So in fact one of the very first case study would be the case of vibration monitoring ok. And then we have few other techniques like MCSA, that is the motor and current signature analysis. And wear debris analysis.

And of course the NDT techniques ok. In the past lectures where ever I have discussed about some of these issues, I had tried to bring in few real-life examples into the classroom. So if you look into the lectures of the previous classes you will see some of the examples which could be treated as case studies. So in this class on case studies I will be specifically do about four case studies.

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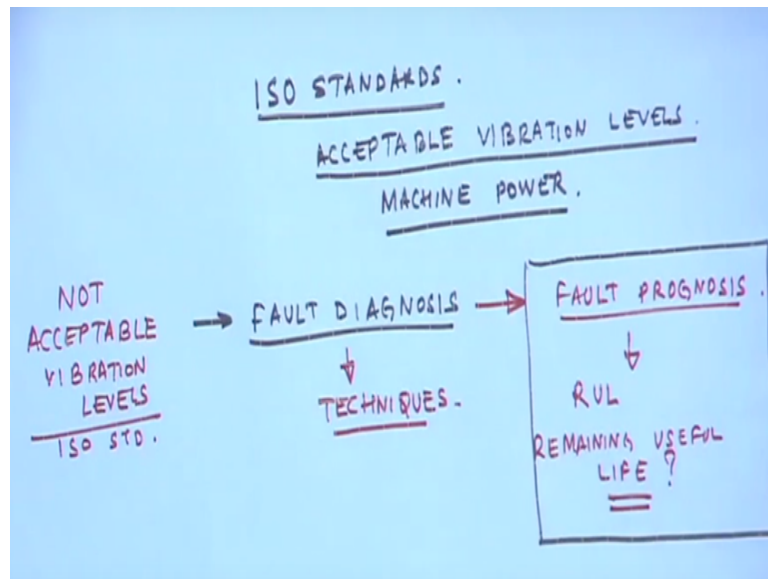


The slide is titled "Case studies" and is part of a presentation on "Machinery Fault Diagnosis & Signal Processing". It lists four case studies:

- Motor-Gearbox vibration measurement
- Bearing seat damage in VFD drive electric motors
- Wireless data acquisition
- Torsional Vibration measurement by optical encoder

And that would be the most general being the motor gearbox vibration measurements. Because of the fact that any plant in the industry is actually driven by a motor. Which could be directly driving a gearbox, a blower, a fan, a compressor, any other crushing unit etc. So this configuration becomes very important you can say as a template for all industries.

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And there are ISO standards available which let us note regarding the acceptable vibration levels before a machine can be considered to be defective because of excessive vibrations. So this is followed. And this is given depends on the machine power. I will refer you to this ISO standard. And for those of you who are practicing engineers in the industry a good idea would be to a good place of reference would be this ISO standard.

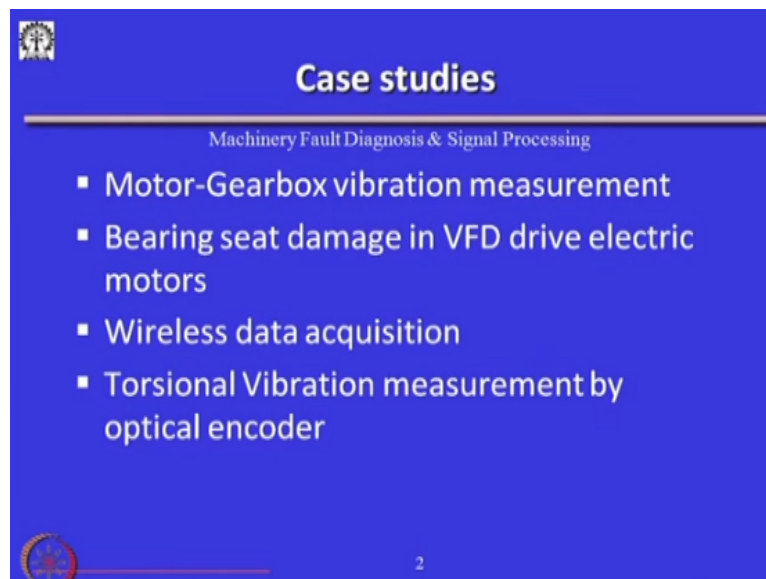
Because it clearly states the machine power and then what is the acceptable vibration levels. So in this first case study I will tell you about what is the acceptable level. And how in a particular plant we did measure such a vibration level and were worried that some of the things were not wrong. So the first level in any condition based health monitoring system is to have an overall idea of the vibration level.

And of course once the vibration levels are higher than an acceptable limit we have to find out the fault. Or what we have to do then is the fault diagnosis. So fault diagnosis is triggered, or the fault diagnosis exercise is triggered if the vibration levels are not acceptable. And this is as per the ISO standard. So once we have such a non acceptable vibration level we will do the fault diagnosis and in this series of 40 lectures we have told you some of the techniques. And which are just told right in the beginning of this lecture.

And of course I will this is beyond the scope of this lecture, people do anyway the fault prognosis thru mathematical models to find out what is in the RUL, remaining useful life. I had talked about one application of the remaining cutting tool life in a machining in one of my early lectures. Remaining useful life of the machinery. And that is what is what we are looking for.

I know there is a fault. But my doing all this exercise is to know whether my machine is going to survive it or machine is going to last how long or machine needs immediate replacement. So these kind of decisions will be only made once I have a fault prognosis. But of course this is not in the preview of this course. Maybe in a second level course on machinery fault diagnosis we can look into this issue issues. And then we will now go to the specific examples of the motor gearbox vibration measurements.

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Another few case study would be the bearing seat damage in VFD drive electric motor. Which I had briefly told while we were talking about motor and current signature analysis. And a new area which is coming up is in condition monitoring is the wireless data acquisition. So you would have seen when we have a machine where all the transmitters are mounted, cables have to be drawn to the data acquisition unit. And then of course the computer based systems does the analysis on the acquired data from such transmitters.

But many a times it becomes cumbersome. It becomes inconvenience to have lot of cables coming from different sensors in the plant. So people are exploring into wireless data acquisition. But earlier I would have mentioned to you how the bandwidth limitation limits us as to what kind of data rates we can acquire the data from the machine with. And how that hampers really to do any meaningful analysis of dynamic signals thru wireless data acquisition.

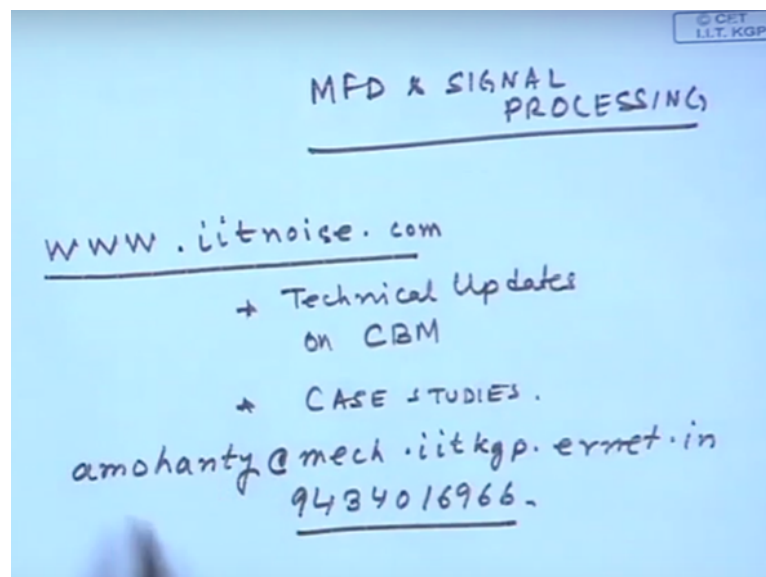
And of course another emerging area is monitoring the healths by torsional vibration. In this ISO standards or mostly in this class we have talked about linear vibration measurements. But recently there have been techniques where people have used torsional vibration measurements to find out faults in machine. And unlike the auxiliary methods which are used to measure the linear vibrations, these torsional vibration measurements by simple optical encoders are very cheap method of finding such analysis.

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So now I will come to the very first case study on vibration measurements.

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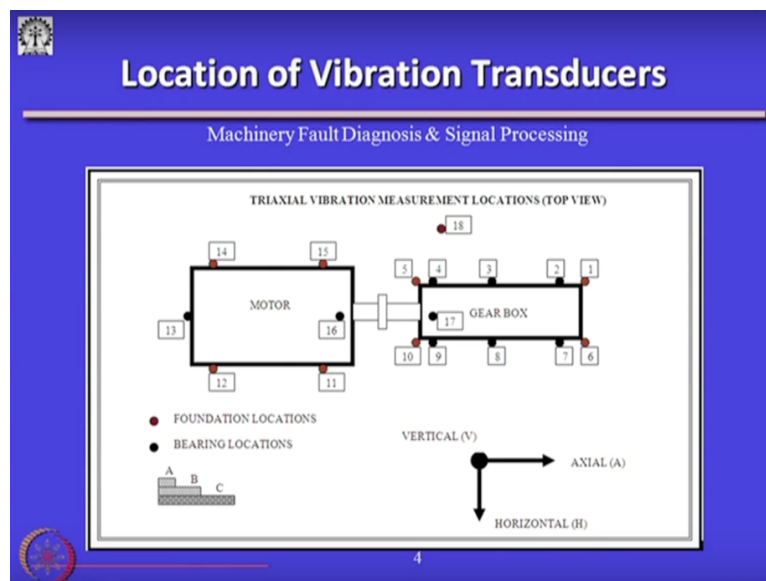


By the way to get more references for this course you can refer to my website. Where time to time I will have a technical updates on condition based maintenance. Case studies uploaded

for anybody to download ok. So this website is openly accessible to everybody so you can know more about this material.

And of course if anybody wants to contact me you can contact me over my email. Of course my mobile number is. So these are my contacts. And if anybody needs more information on this course machinery fault diagnostics and signal processing you can either visit this website or contact me over email or a mobile call.

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So this is a typical configuration in an industry, wherein we have a motor. And then which is driving a gearbox. So motor is the prime over and this is the mechanical unit which is being driving. This gearbox could have been blower or a fan. So in this particular example I will just give you a overview. This is a plant which is used for raw material handling.

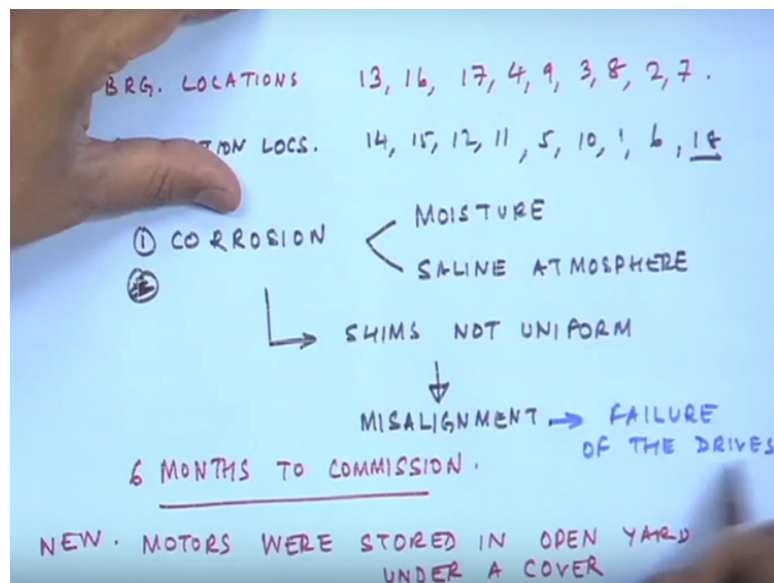
And this gearbox actually drives a conveyer belt system. When raw material at the port is one conveyer system loads them to the ship for export. And there is another conveyer system and then another series of conveyer system which brings in raw materials from the ship haul to the stack yard at the port. And as you know in this port, you know port of course next to the sea, and then this atmosphere is saline. And there is a aggravated corrosion because the harsh environment.

So such a plant we noticed that the vibration levels were alarmingly increasing and there have been failures in the one of the drives. And then we are asked to investigate the cause. So as a very first thing there is no record of any vibration levels in such a system because this was put in a structure which was about 25 meters from the ground. And you only had a narrow

ladder to access to maintain this. You only had a narrow ladder to access the gearbox and motor.

And they were practically not being monitored throughout the life of this plant ok, this raw material handling plant. And once the vibration levels were excessively high we went ahead and instrumented. These locations you see one through 18 are actually the bearing locations. The black ones are the bearing locations. So like 13 would be an NDE bearing location of the motor, that is non drive end. 13 is non-drive, 16 is drive end.

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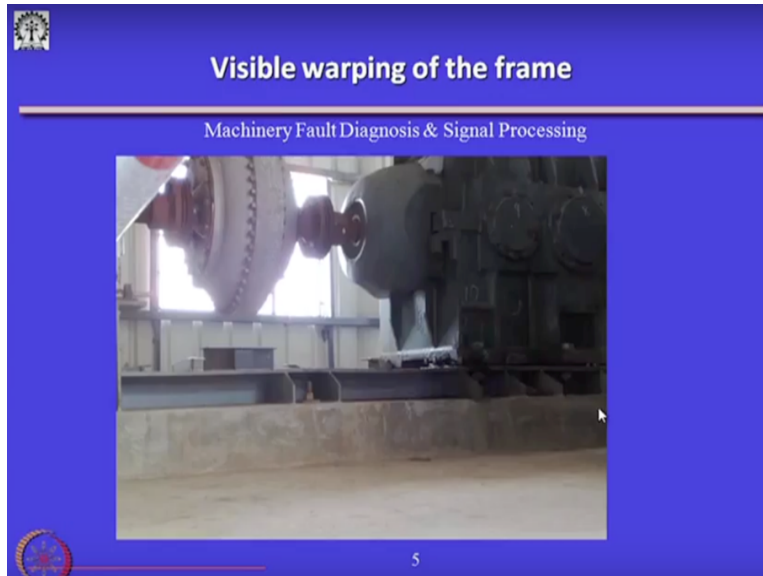


If I was to say all the blacks, so the bearing locations are 13, 16. And this is an intermediate stage gearbox. So there is a three stage gearbox ok. So the shafts are like this. And this is a bevel gear because the direction would be of power transportation is changing.

So 4, 9, 3, 8, 1, 2, 7, 17 ok is the drive end bearing of the gearbox. So all the measurements were done at the bearing locations of the gearbox and that would be 17, 4, 9, 3, 8 and 2 and 7. And then we decided to measure some at the foundation locations. And these were 14, 15, 12, 11, 5, 10, 1, 6.

And another very, for just for reference, because this was at a platform. And while in operation this was vibrating. We meant to measured the structural vibration close to the ground; that was at 18. And they were all measured in different directions, so this is the orientation. And the foundation we had you know different layers of shims. So we measured at A, B and C.

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And I will show you a figure of this plant ok. So this is the motor side end, that is the gear coupling which is driving this motor, this gearbox. And you can see the chalk numbers 9, 8, 10, etc. And you can see pretty well because of poor workmanship this has warped.

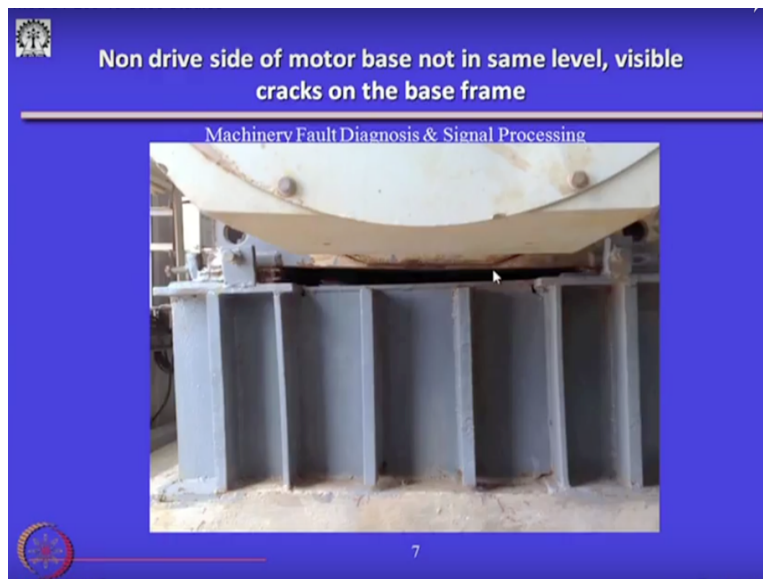
The base has warped. And there is a lot of corrosion in this base because of the harsh saline environment at the port. And because of this corrosion there were lot of play and those were jack bolts which are used to do a local alignment. And eventually this kind of corrosion led to the misalignment ok.

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And this is another view of the shims which were placed underneath the gearbox to arrest to level it. And they also corroded. So misalignment crept into the system. And then excessive vibrations were noticed.

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This is another view of from the non-drive end of the motor. At the base you can see how poor the manufacturing is. And this has led to corrosion, allows to cracking and because this is in a moist environment. And these motors, I was made to understand, while the plant was been commissioned these motors are arrived long before they were put and made to operate. So this motors were actually stored in the yard ok.

And so there was a lot of moisture developed. And this moisture stayed in the motor. And this led to the corrosion of this component. Because if the motor was running, then there would have been lot of heat generation and this problem would not have happened. But since in a yard this motor was stored lot of moisture did come in. And then they corroded. And then that aggravated the entire corrosion of this plant ok. And of course because of these you can see the motor base is also not in the same level.

So many reasons attributed to high vibration level because one is corrosion ok. Next is corrosion was because of moisture, because of saline atmosphere. And this led to shims not uniform which earn in turn led to the misalignment of the system. And mind you in such a plant they never ever were measuring the vibrations or monitoring.

So a new plant it took only 6 months to commission but the motors were stored in open yard under a plastic wrapper, new models. And then they were installed and all those problems happened. And then this led to the misalignment and eventually failure of the drive ok. So once people noticed a failure and then they get worried. What is going wrong with the plant? And then these measurements were done.

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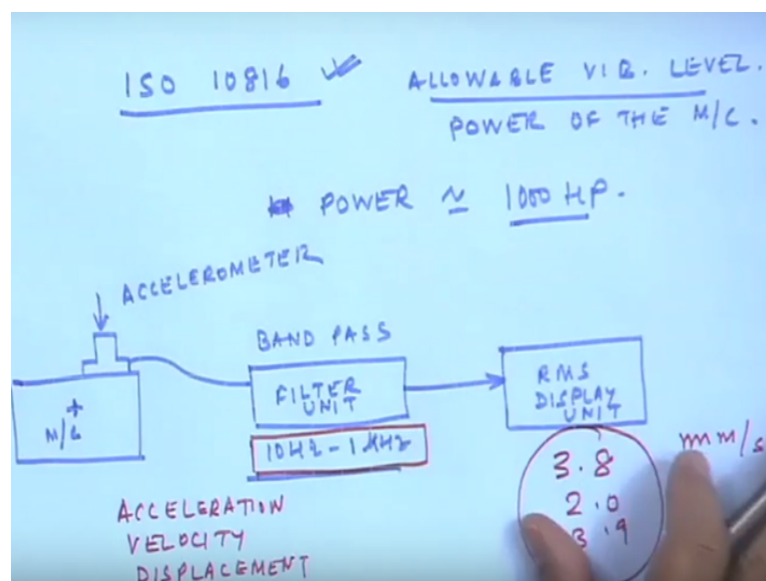
Measured Overall RMS Vibration Level [mm/s] (10-1000 Hz) as per ISO 10816-3

Machinery Fault Diagnosis & Signal Processing

Measurement Location	Location Description	Axial Velocity [mm/s]	Vertical Velocity [mm/s]	Horizontal Velocity [mm/s]
1	Gbox NDE Left Base	0.821	1.96	0.730
2	Gbox Output Left Brg	0.776	1.46	1.78
3	Gbox Intermediate Left Brg	0.502	1.30	1.88
4	Gbox Input Left Brg	2.02	1.15	1.03
5	Gbox DE Left Base	1.44	1.39	1.46
6	Gbox NDE Right Base	0.913	0.821	1.46
7	Gbox Output Right Brg	1.01	0.866	1.10
8	Gbox Intermediate Right Brg	0.684	0.866	2.60
9	Gbox Input Right Brg	1.01	1.15	1.46
10	Gbox DE Right Base	0.577	1.30	0.821
11	Motor DE Right Base	0.548	0.776	1.41
12	Motor NDE Right Base	0.502	0.913	2.46
13	Motor NDE Brg	1.30	3.24	1.42
14	Motor DE Left Base	0.577	2.92	1.14
15	Motor DE Left Base	0.721	2.56	1.69
16	Motor DE Brg	2.10	0.866	2.02
17	Gbox DE Brg	0.866	1.88	1.61
18	Structural Member 2m away from the unit	0.411	1.24	0.721

So this gives you an idea. First of all this is an overall RMS level in millimeters per second from a frequency of 10 to 1000 hertz. And this is as per the ISO 108163 standard.

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There are about different parts of the standard depending on the type of motor or whether it is a flexible system or a overhang system, ridged system, weight of the. This is standard which has to be followed ok. And there are to be earlier a German standard and a higher standard is there. But we would recommend this standard gives us the allowable vibration level in a plant or machinery for a certain power of the machine. Of course if power of the machine is more the vibration level would be more ok.

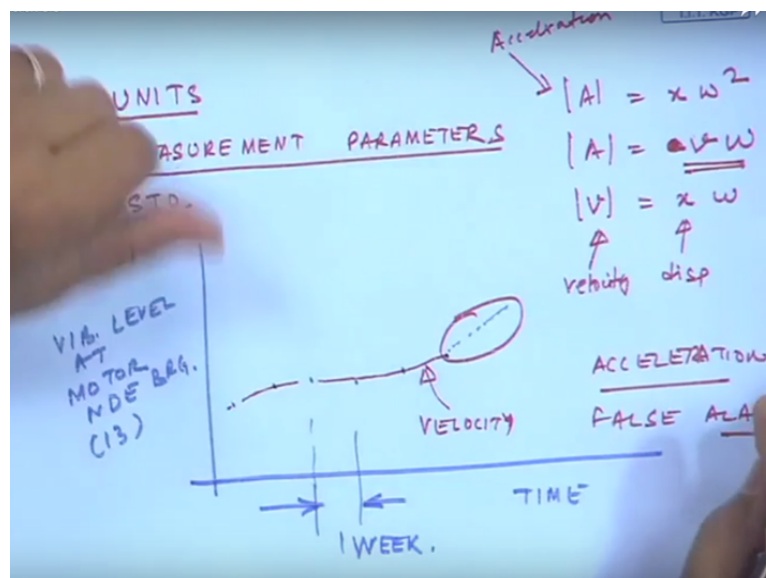
By the way this power of the machine was about you know 1000 horse power is something which can you can keep in mind. The 1000 horse power motor. So you can imagine the size of the system. So these were the eighteen locations and then these are the vibrations measured as velocity in millimeters per second. And they are an single number in the band of 10 hertz to 1000 hertz.

So when you have your measurement system always you know and of course now a days suppose you have this transmitter on a machine. So this is my machine. You can have a filter unit band pass from 10 hertz to 1 kilo hertz and then you can have a RMS display unit. And this is an accelerometer. This is my machine ok.

So one has to keep this in mind that the ISO 10816 standard says that this has to be; this is very important value. It is not any value. And may a times I am telling you when you go to the industry to do troubleshooting of machines the engineers many a times will give you numbers you know. Suppose you know they will say three point eight. Today we are getting 3.8.

Yesterday we got you know 2.0, 3.9. But many of them they see it without assuming that everybody knows that this is in millimeters per second, without making sure whether the filters were on or off ok. Without even knowing whether it was in acceleration mode or velocity mode or displacement mode. So these kind of problems do creep in.

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For example once you are doing a trending because with a simple electronic integrator I can move the measure from acceleration and get the velocity or displacement values. So one has

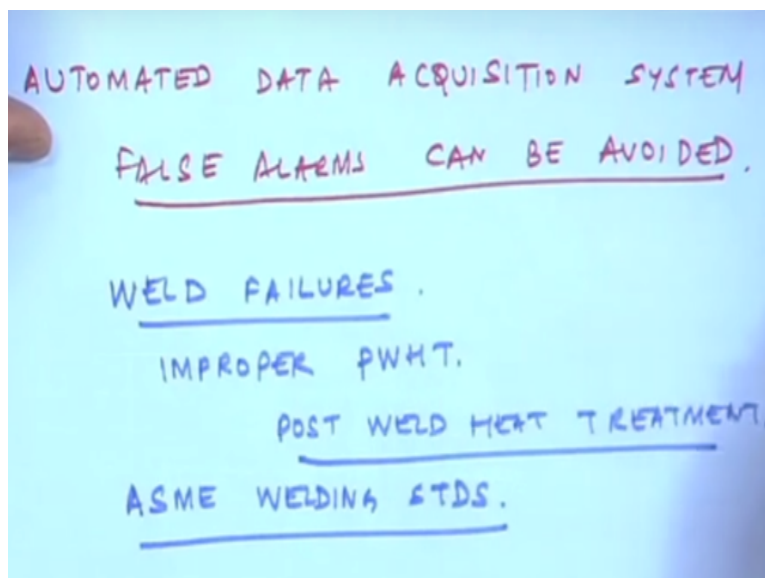
to be careful about the units and the measurement parameters. So if somebody is strictly following the standard, these errors will not creep in. And one has to be careful about it.

Because in such measurements I just showed you for the case of the motor gearbox system, suppose one particular parameter, say vibration level at say motor NDE bearing. In this example point number 13 and with time. In such a plant if somebody was measuring these values at every one week interval ok. Now suddenly unknowingly somebody has changed the parameter units. So for example this was all in displacement velocity ok.

Somebody has suddenly moved it to acceleration ok. It may so happen because see, acceleration amplitude is suppose or suppose velocity V times ω ok. And the velocity amplitude is sometimes X times ω or acceleration is actually X times ω squared. So this is a displacement. This is velocity; this is acceleration. As you will see acceleration is linearly proportional to the frequency.

And what happens? Suddenly you may think that this machine has increased. Its velocity is increased because you have always known it in the velocity. But unknowingly a mistake has happened that the operator instead of monitoring velocity, he has changed it now to acceleration. So this is going to happen; so this is a case of a false alarm ok. So these kind of scenarios are to be avoided.

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Of course now a days in the plants with automated data acquisition system, such false alarms can be avoided. Such false alarms be can be avoided. So in such vibration level monitoring systems any plants now a days you know. 10 years ago there used to be a scenario where

maintenance crew were every day going to different parts of the plant and measuring the vibration by using handheld portable acquisition devices or vibration meters. But just by mistake somebody could change the knob, change the filter settings, change the mode of measurement.

And these kind of errors can creep in. But over the time people have realized the importance of vibration based monitoring for a machinery condition monitoring. And then they have realized the payoff they get out of such measurements. And then they have put in place such automated systems where the accelerometers are permanently mounted. Cables are drawn permanently to the signal analysis unit.

And on the computer screen you can get the current display. You can pull up data which was logged a few months ago while you are doing any troubleshooting to see if there were any serious changes in that machine. There are alarm levels built in the software. When a certain preset level exceeds it will warn the operator or the management that something is wrong with the machine. So good robust vibration monitoring system must have these software driven system in place in a plant ok.

And in this plant we did find out that the vibration levels in the motor NDE bearing were the highest. And they were not what they were supposed to. And this was attributed to corrosion in the bearing and then the lot of high impurities you know. The corroded particles are were getting on the bearing were giving rise to this kind of vibration levels in the motor. So now I will come to another related problems with bearings.

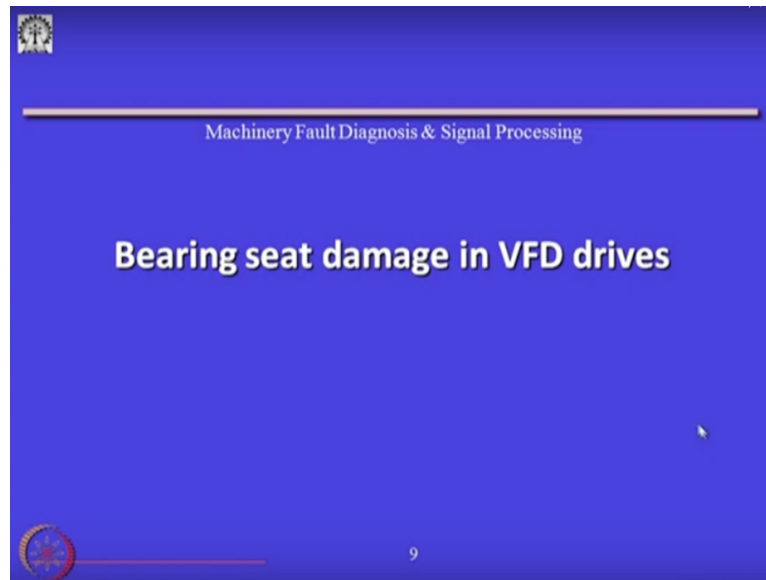
Because let me tell you many of the times you know these reasons could be very simple. Like in the previous example I just told you. Storing the motor in the yard for 6 months, a new motor on a sea coast. Where the port was coming up the motors came in before the structures were there, were built. And then they were stored so moisture got into it and saline environment.

Corrosion was aggravated and eventually people installed this machine without noticing these corroded parts. And once the plant started, few months after the new plant started, components started to fail. And this is because of sheer negligence of people ignoring the fact that corrosions can be a such harmful. And you also saw the poor workmanship of the foundation base because of the fact that this was done at a platform which was twenty-five

meters from the ground. So all the crews and equipment were not easily accessible at that location.

And whatever we have done and there was no post weld heat treatment. You know many a times failures; weld failures happen because improper post weld heat treatment. And this is something which is not to be ignored. So when welding is done there are many ASME welding standards to be followed so that this kind of problems do not happen. Material become do not become weak and then they fail because of excessive loads.

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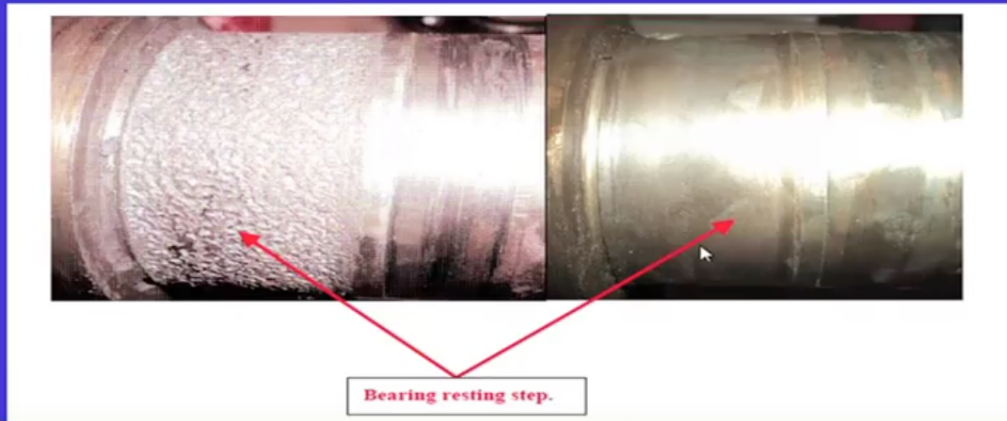


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Motor shaft damage

Machinery Fault Diagnosis & Signal Processing



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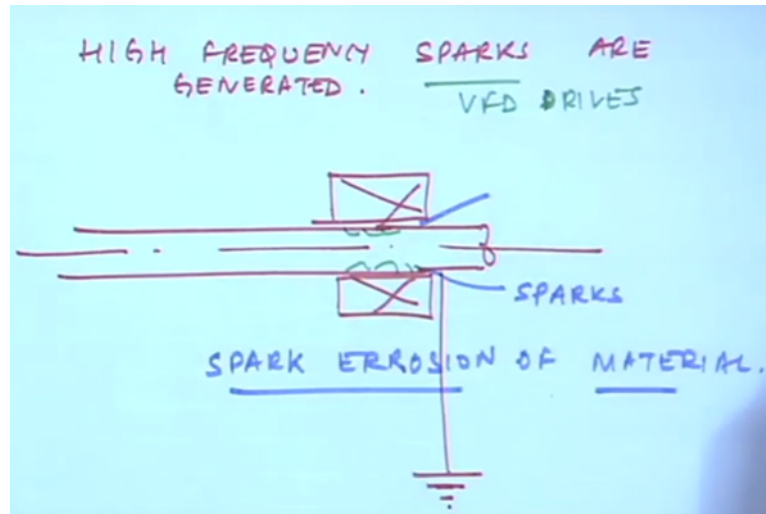
Module 40

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www.iitnoise.com

Now I will come to the second case study, bearing seat damage in VFD drives. So this is just a figure. I had explained this in one of the earlier lectures. But I will just tell you.

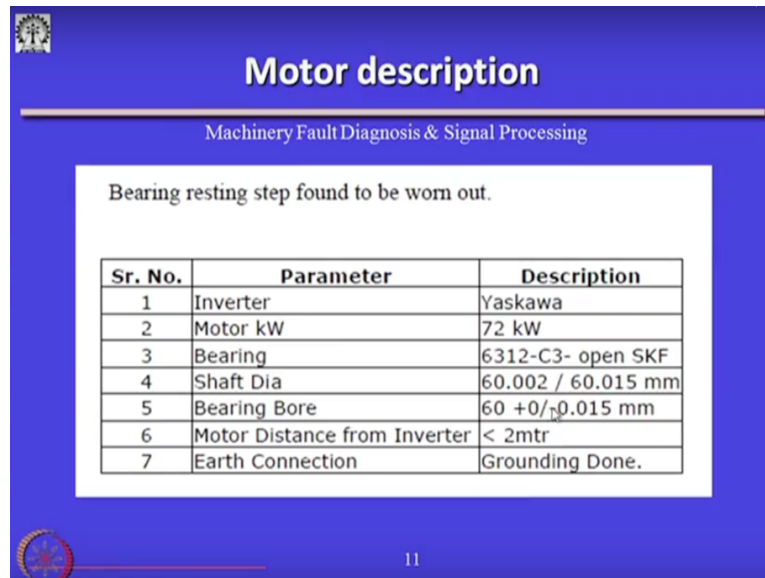
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In a VFD drive in a motor because lot of high frequency sparks are generated between the motor shaft and the bearing ok. So lot of high frequency sparks are generated in this gap. So this sparks are responsible for the spark erosion of material. So this again leads to another problem. If the materials get worn out on the shaft ok like you see here. This is the normal rust set up and this is because of the materials removed because of such sparks erosion. And this sparks are generated because of the VFD drives.

So to protect such VFD drives you know such sparking not to occur these are actually there is a brush. And which is responsible for which are is which is ground; haft is ground thru a carbon brush. So the sparks never occur because it will be at the ground potential, and this can be avoided. But the consequence of this is the bearings there will be lot of clearances. And there will be looseness and the bearings will get damaged while rotating at high speeds ok.

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Motor description

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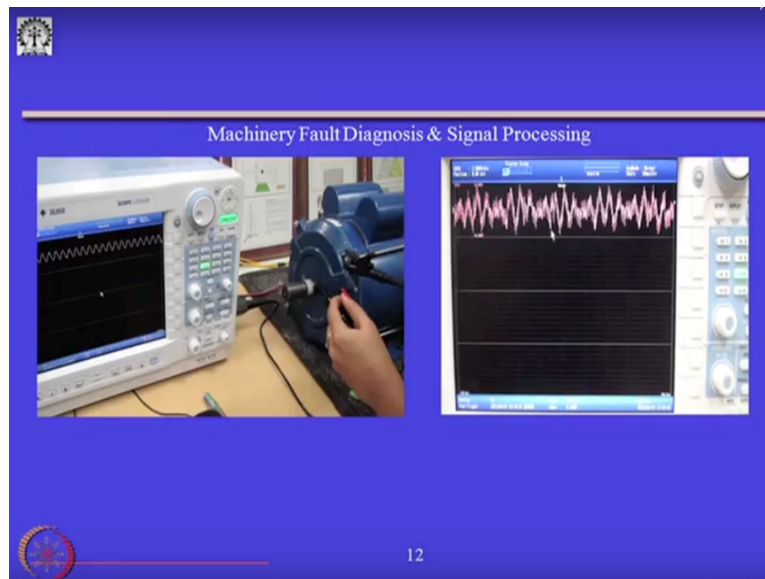
Bearing resting step found to be worn out.

Sr. No.	Parameter	Description
1	Inverter	Yaskawa
2	Motor kW	72 kW
3	Bearing	6312-C3- open SKF
4	Shaft Dia	60.002 / 60.015 mm
5	Bearing Bore	60 +0/-0.015 mm
6	Motor Distance from Inverter	< 2mtr
7	Earth Connection	Grounding Done.

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And this was the case of a motor which had a power of 72 kilowatt. And these are the typical bearing ok. And the shaft was now or thin connection was there. But the shaft motor shaft was not rounded because of the VFD drive ok. So the VFD drive when so whenever we use VFD drive, variable frequency drives we have to be careful about the sparks which are generated. So we should not allow them to erode the particles ok.

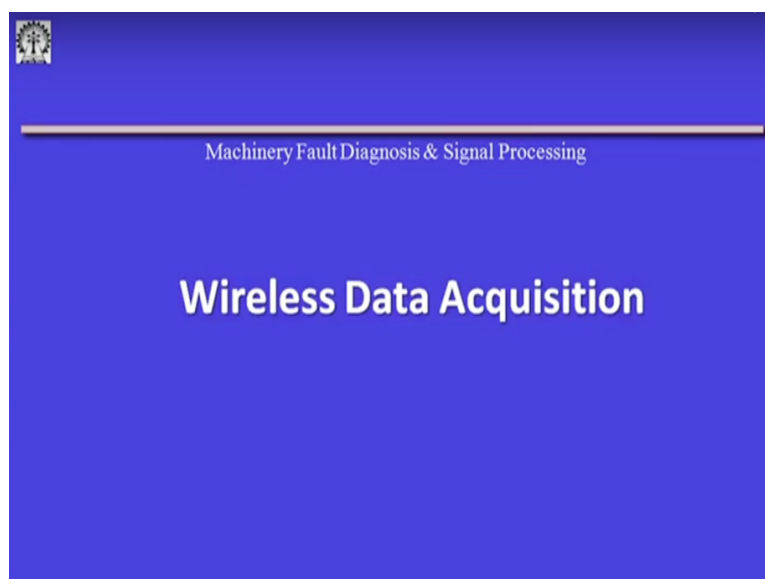
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This was an example which I am showing you in the laboratory what we did. This is a motor. In one case which was not driven by VFD drive but a normal power supply. So you can see a nice low amplitude voltage at fifty hertz. That is the running supply frequency.

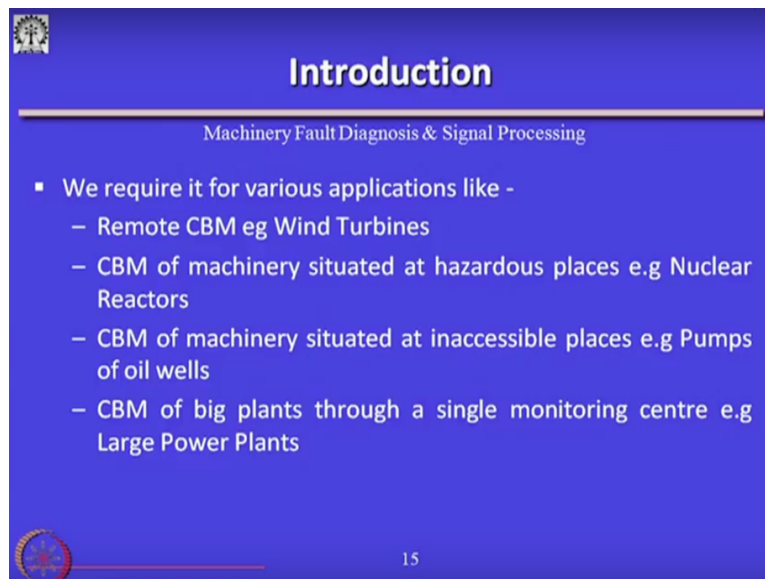
But whenever we change the power supply thru a VFD we can see high levels of peaks occurring because of such VFD drives ok. And this is what we are measuring between the shaft and the ground. These kind of peaks do happen ok, so this has to be avoided. And these are responsible. These are high frequency peaks signals and these are responsible for spark erosion of the bearing seats.

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And now we will come to another technique which is wireless data acquisition system. Which is to be used in machineries where we can avoid long cables.

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Introduction

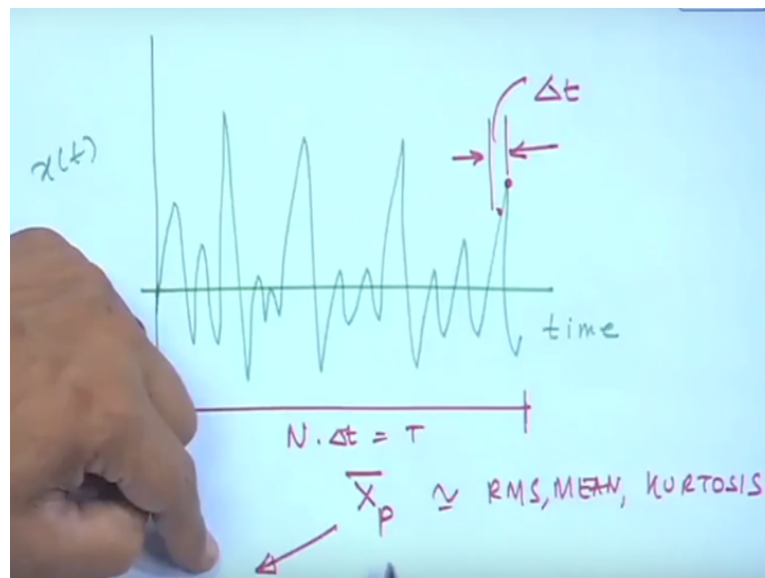
Machinery Fault Diagnosis & Signal Processing

- We require it for various applications like -
 - Remote CBM eg Wind Turbines
 - CBM of machinery situated at hazardous places e.g Nuclear Reactors
 - CBM of machinery situated at inaccessible places e.g Pumps of oil wells
 - CBM of big plants through a single monitoring centre e.g Large Power Plants

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And these are I will just fill it up. We require various applications by remote monitoring of wind turbines, nuclear reactors, pumps of oil wells, large power plants. So imagine it in all these locations. It is not possible for anybody to draw wires ok. Though of course the present standard is at least we have to monitor these parameters in a routine manner, their RMS levels. But there is to do diagnosis I require not just the RMS level but the entire time history.

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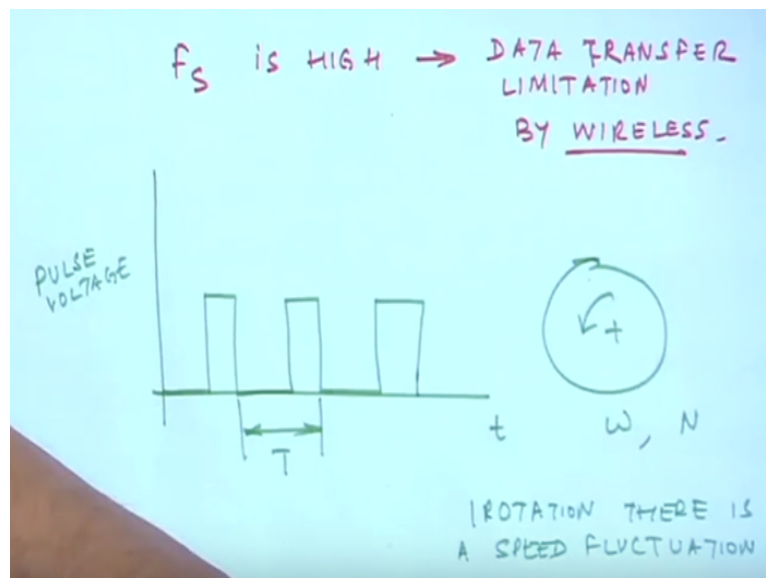


Of some signal $x(t)$, it could be vibration or anything. So this signal has to be acquired. The present day technology is that they send this information in packets. So they will take a certain time window. So this is N times Δt is the total time. Where the successive points are sampled at an interval of Δt ok.

And they will take the sample do at that location do an overall RMS value some parameter. Some overall parameter, some parameter XP ok; which could be its RMS value, mean value, kurtosis value. And this XP is transmitted through wireless. This is the present state of the art. So every machines XP is known to me, like sending and information in a thru SMS on your mobile is one way.

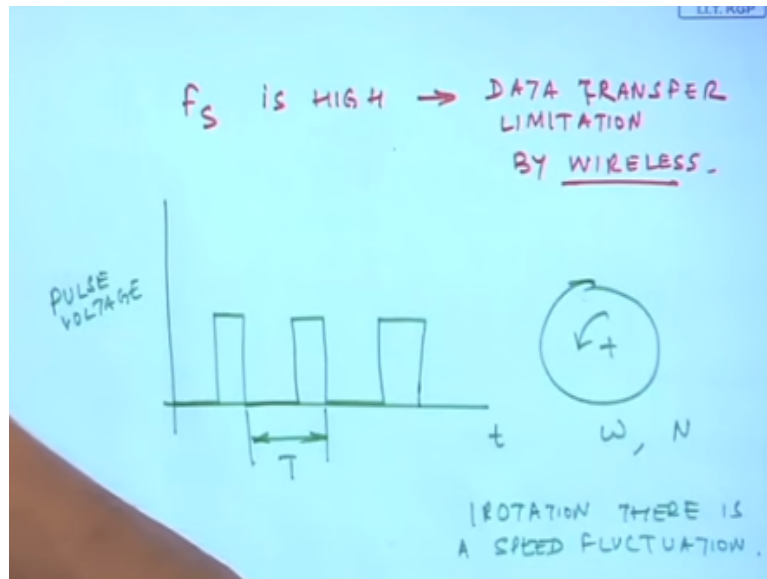
I will just a machine it has an transmitter. And it sends some information of XP to another receiver. That is the present state of the art like we use our mobile phones over the wireless networks, we can have. But the problem happens when we have to access the data at high speeds.

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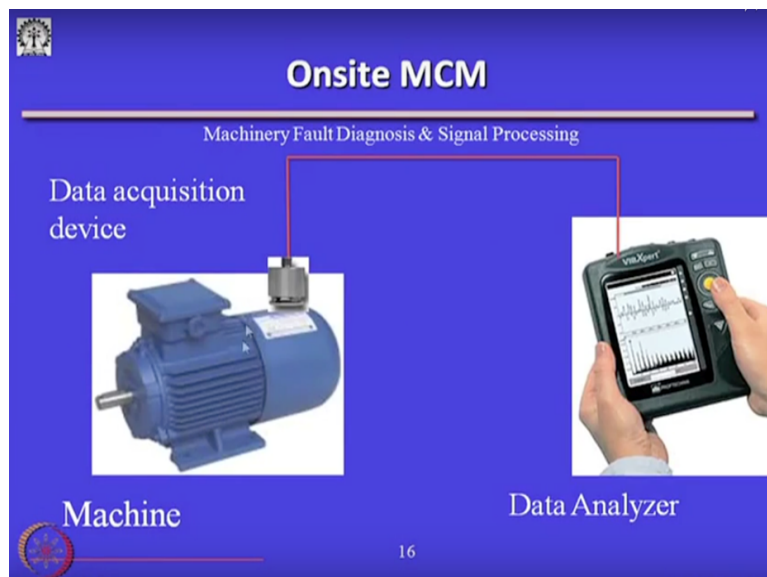


When the sampling frequency is high data transfer limitation by wireless ok.

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So this is one device wherein we can have an data acquisition device right on the machine. And then we can analyze the data.

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Various terms used in Wi-Fi

- **Frequency Band**- Frequency Bandwidth of signal. Frequency used for data transfer
- **Data rate**- Measurement of volume of data getting transferred per second (generally given in Mbps)

$$\text{Data Rate} = n * \text{Acquisition rate (in sample/sec)} * \text{Resolution (in Bits/Sample)}$$

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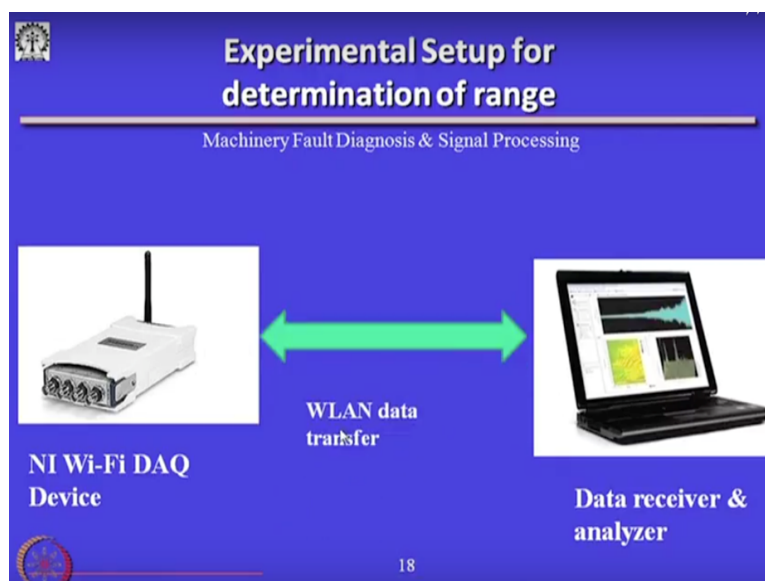
Where n = Total number of data input channels

- **Encoding**- Method of attaching input data with carrier frequency
- **Range** - This is the maximum distance at which two radios can operate and maintain a connection
- **Throughput**- It is average rate of successful message delivery through a communication channel

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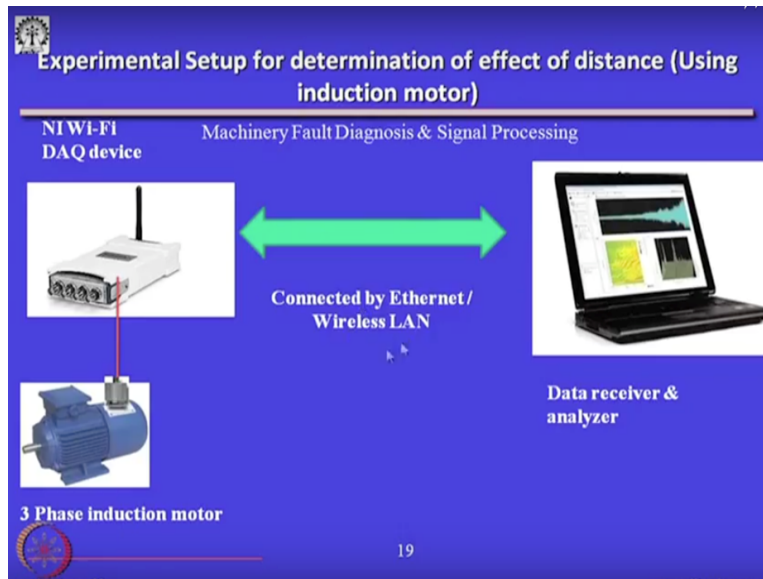
So these are certain terms which are used in WiFi. The data rate is nothing but acquisition rate, resolution. And then we can find the total rate, encoding, range, etc.

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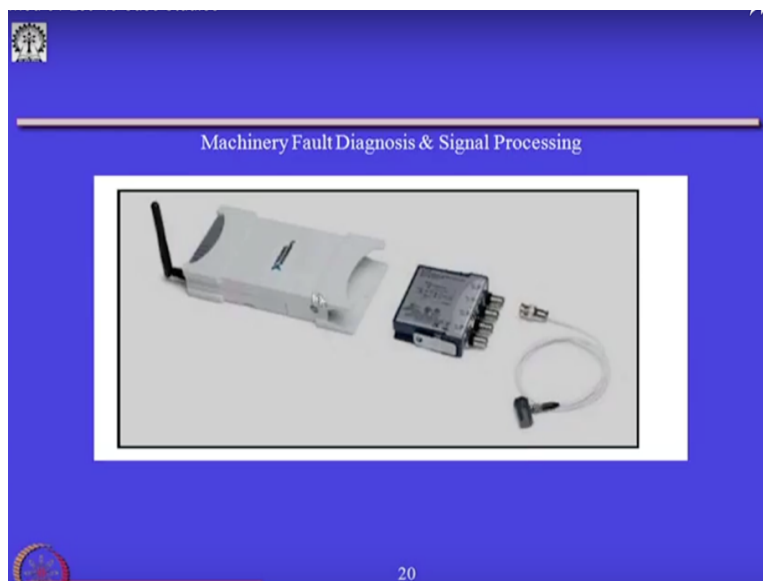
So in the laboratory what we did is we had an device and WiFi DAQ device. And then we have a receiver. And then we did data transfer over the LAN ok.

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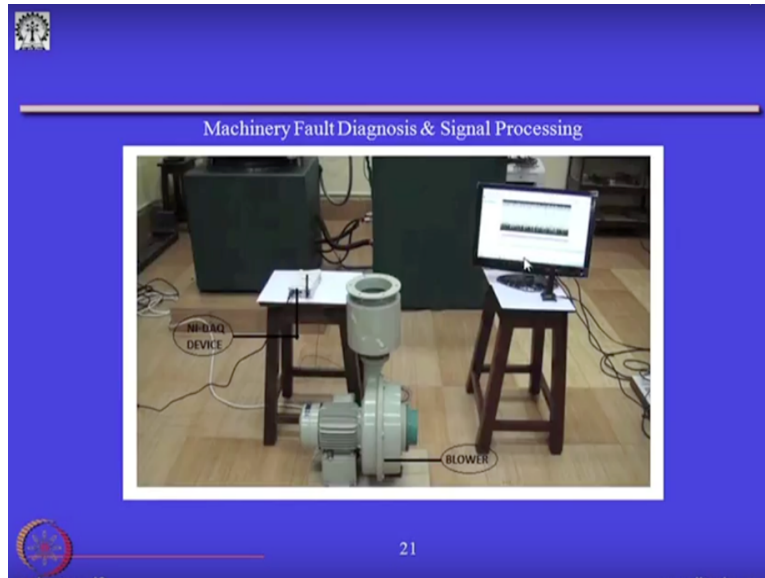
And in the same lab we tried to move this through, by increasing this distance ok. And there were limitations to this.

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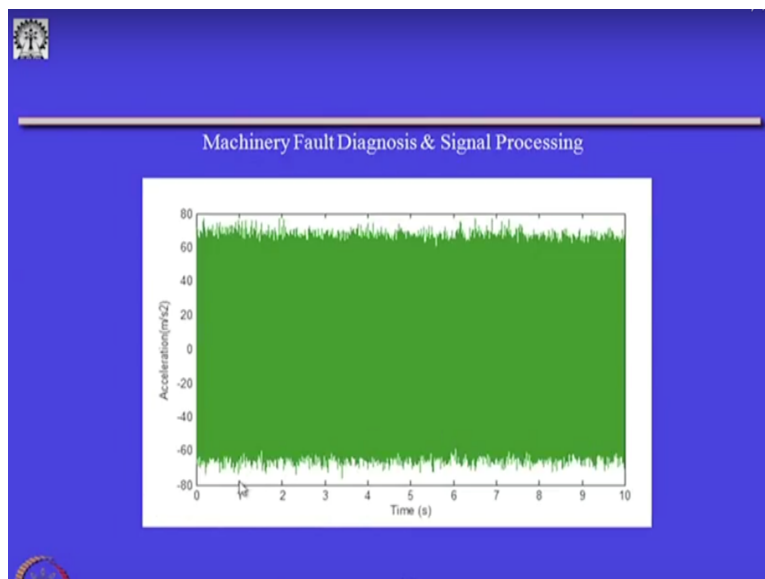
And this is how the system looks like. This is an accelerometer which is connected to an wireless data acquisition unit. And then we have the wireless transmitter ok. And you can capture the other end thru a wireless receiver.

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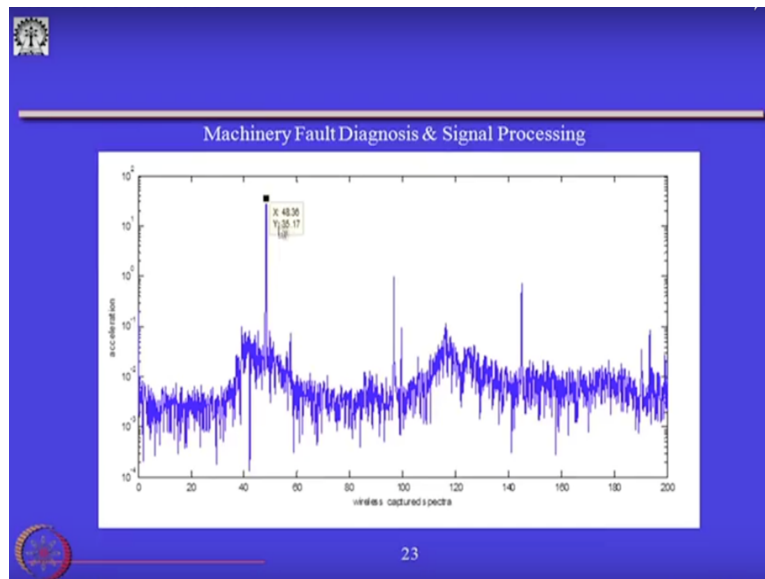
This is one example in the laboratory wherein we have a blower. Whose vibration is being measured by an NI DAQ device. And this transmits. And there is another laptop. You will notice that there is no cable coming from the accelerometer at this end to the analysis unit here. And then we can calculate this data.

(Refer Slide Time: 41:22)



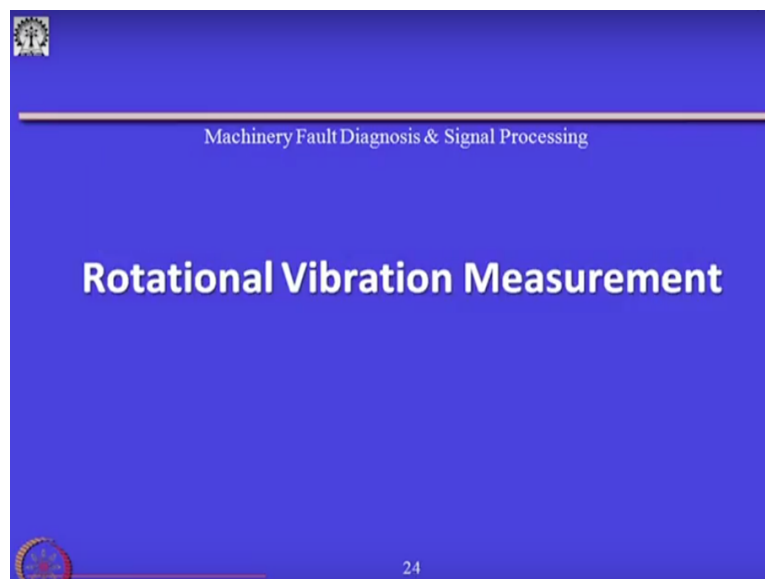
So this is the time signal of the data captured over the wireless. And then we can analyze it.

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And then we could find out the supply frequency a little as in 48.36 hertz. So these kind of captured wireless data can be analyzed thru such systems.

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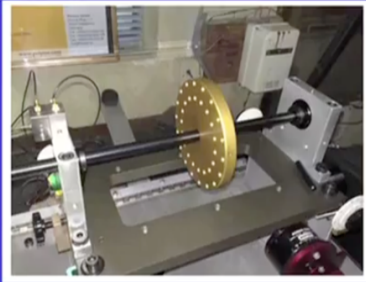


I will come to the last case study wherein we can do the rotational speed measurements or the rotational vibration measurements.

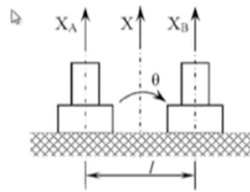
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Two Accelerometer

Machinery Fault Diagnosis & Signal Processing



$$X = 0.5(X_A + X_B)$$

$$\theta = (X_A - X_B)/l$$


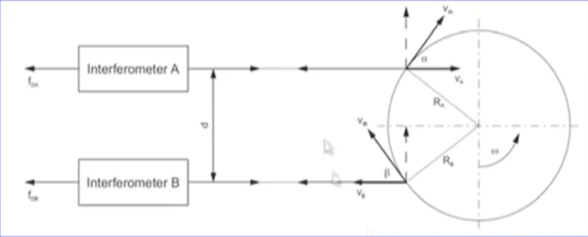
25

See many a times this rotational vibration measurements if you look at the two accelerometers which are kept side by side in a rig, I can measure the angular vibration. You call it angular displacement theta as the difference between these two vibrations X_A , X_B and the length. If these are known we can find out the rotational vibration arc in the system. But this is cumbersome. This is contact type.

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Two Channel Doppler effect

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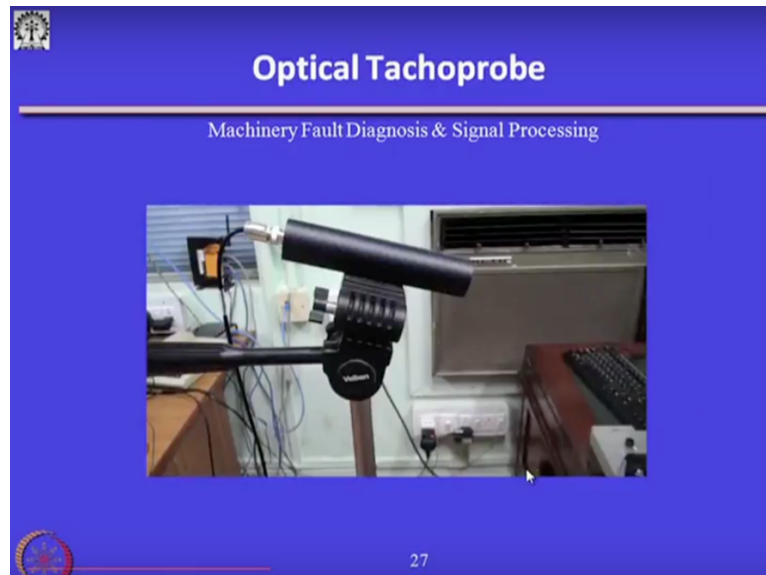
$$f_D = f_{DA} + f_{DB} = \frac{2d \cdot \omega}{\lambda}$$

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So now a days people use the two channel doppler effect laser vibrometers. Wherein we have two laser beams incident at two different points ok on the rotating shaft. And then from the mathematics, from the geometry, you can find out the doppler shift between these two frequencies as this. And then this omega can be known if you know the D.

Because the two channel doppler effect rotational laser vibrometer come with this two lasers fixed at a particular distance. It could be about you know 25 MM, 10 MM etc. And depending on the wavelength, the λ , we can find out the frequency shift. And then we can know the rotational speed or the rotational vibration ok.

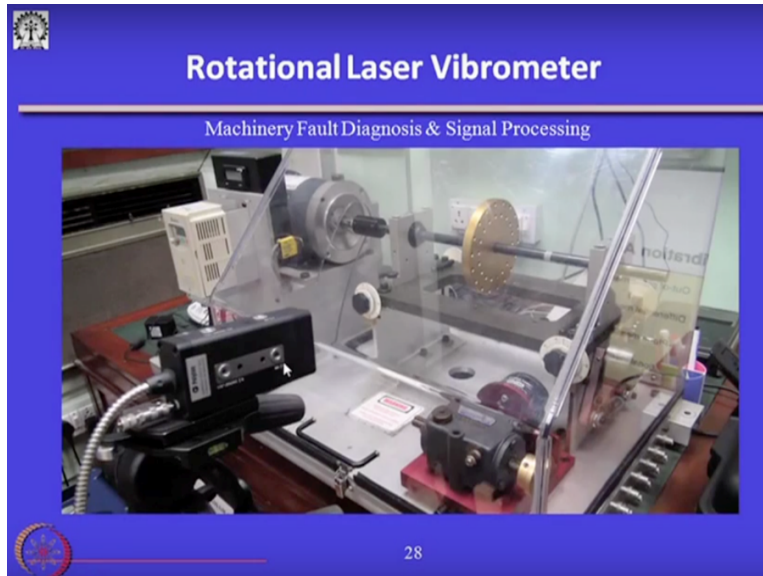
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This is one optical photoetch which is being used to measure the rotational speed of a device which is right here. But the photoetch does not work on the principle of the laser vibrometer. Here only it sends a pulse of light. And it has a transmitter and a receiver on a photo cell.

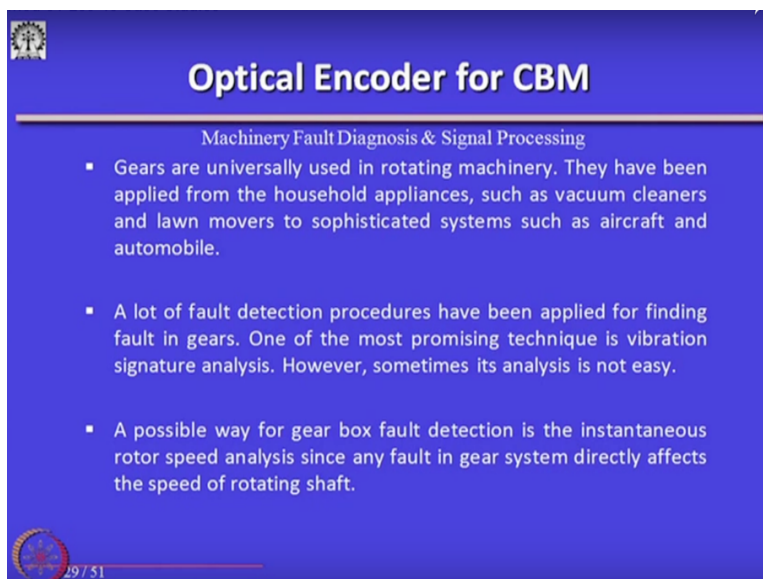
So depending on the time period between these two pulsars, you can find out the rotational speed. But these rotational speeds are very gross. In the sense, suppose a shaft is rotating at a certain RPM. I can know over the period over the time ok what is the mean ω or N . However, because of a defect in a system if the shaft within one rotation there is a speed fluctuation, how does one capture that?

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And that is where I mean this is another view of the rotational laser vibrometer which is focused on a rotating shaft.

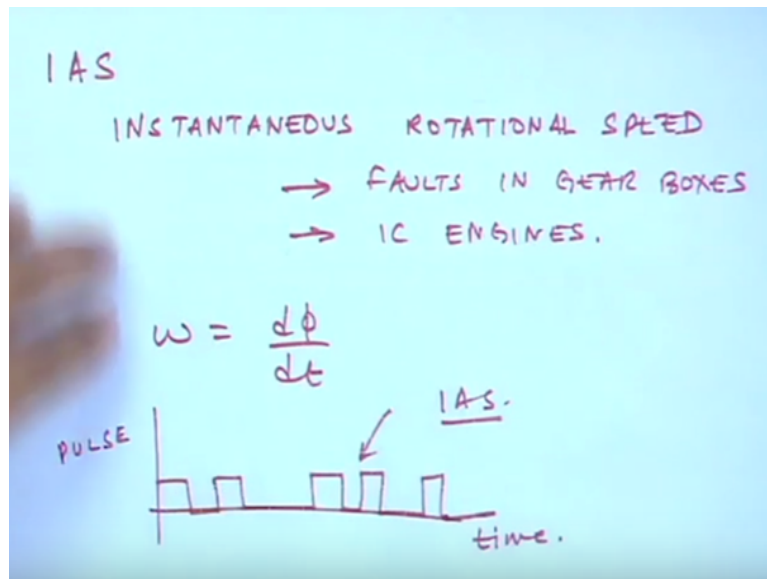
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A presentation slide with a blue background. At the top left is a small circular logo. The title "Optical Encoder for CBM" is centered at the top in white. Below it, the subtitle "Machinery Fault Diagnosis & Signal Processing" is also centered in white. The main content is a list of three bullet points in white. The slide number "29 / 51" is at the bottom left.

- Gears are universally used in rotating machinery. They have been applied from the household appliances, such as vacuum cleaners and lawn movers to sophisticated systems such as aircraft and automobile.
- A lot of fault detection procedures have been applied for finding fault in gears. One of the most promising technique is vibration signature analysis. However, sometimes its analysis is not easy.
- A possible way for gear box fault detection is the instantaneous rotor speed analysis since any fault in gear system directly affects the speed of rotating shaft.

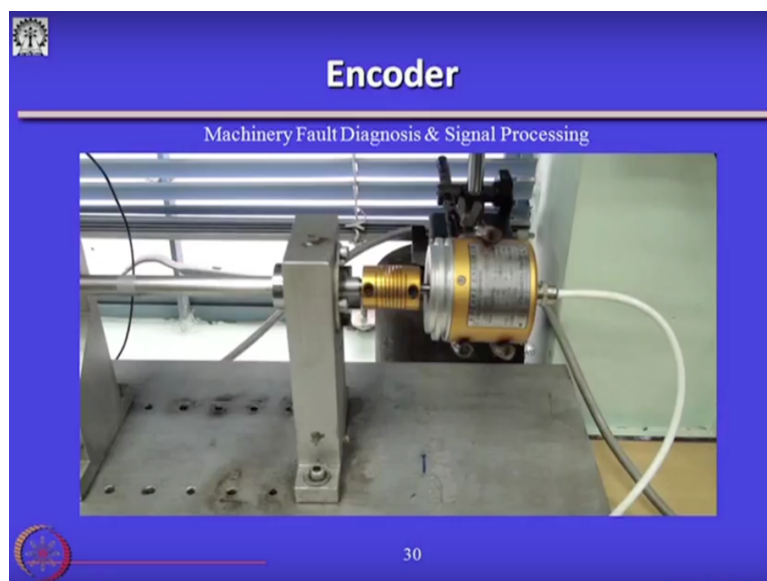
So coming back to the measurement of the rotational speed fluctuation we can use what is known as an optical encoder for condition based monitoring. Where gears are universally used in rotating machinery. they have been applied from household appliances such as vacuum cleaners, lawn mowers ok. A lot of fault detection procedures have been done in finding out faults in gear. But a possible way for a gearbox fault detection is the instantaneous rotor speed.

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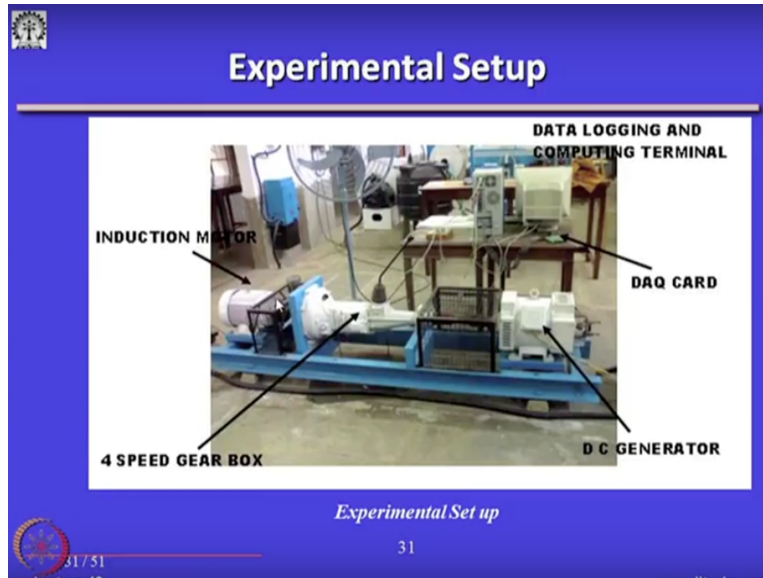
So this is known as IAS. This has been used to find out faults in gearboxes, faults in IC engines and so on. I will not go into details of these much here. The details can be found in my website and some of our papers.

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This is how an optical encoder looks like ok. It is held to the end of the shaft.

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And this is on that same gearbox which I have used quiet often in this class. That is the setup which we have in our laboratory. And then this is driven by a motor. We use this for motor current signature analysis. Now we are doing it for the optical rotational speed measurements ok.

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Experimental Study

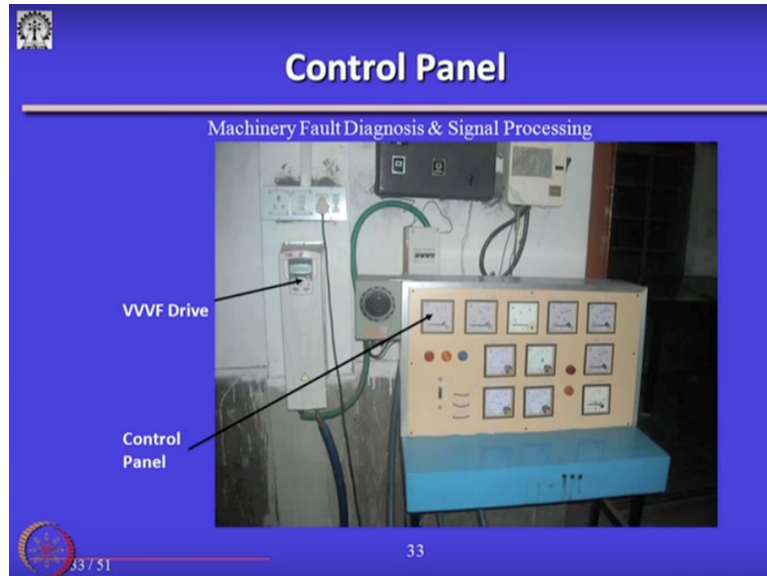
Machinery Fault Diagnosis & Signal Processing

- Experimental setup consist of :
 - 7.5kW, two-pole, three-phase induction motor
 - 7.5 HP D.C. motor acting as a generator
 - 5.625 kW variable resistor load bank
 - Variable-Voltage-Variable-Frequency Drive (VVVFD)
 - 4- speed automobile gearbox

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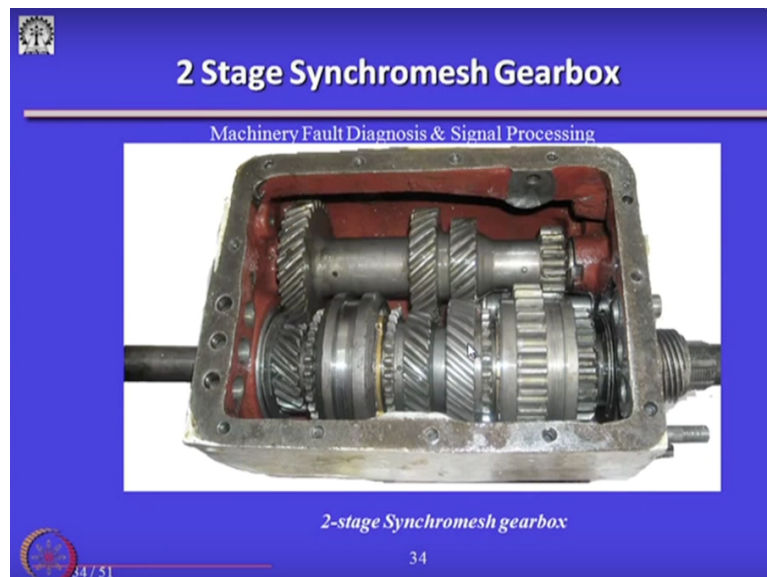
And this is the setup of the gearbox and which I had told earlier in many of my classes.

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This is the control panel for the same.

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This is the gearbox which I had shown earlier.

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Experimental set-up

Machinery Fault Diagnosis & Signal Processing



Gearbox setup, IAS Measuring Equipment



Encoder mounted on the output shaft



Shielded Connector Block Device (BNC 2110)



The ENC 58-10H-1000AB Encoder

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This is how this optical encoder is put at the end of the generator which is loading the gearbox right here. This is the gearbox. And this is the optical generator. And the optical encoder is mounted here. This is how this optical encoder looks like.

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Sensors

Machinery Fault Diagnosis & Signal Processing

- Measuring instruments used are :
 - Incremental Optical Encoder
ENC-58-1000AB-5V
 - B&K 4370 Accelerometer
 - B&K 2632 NEXUS Charge Amplifier
 - NI PCI 6110 DAQ
 - BNC 2110





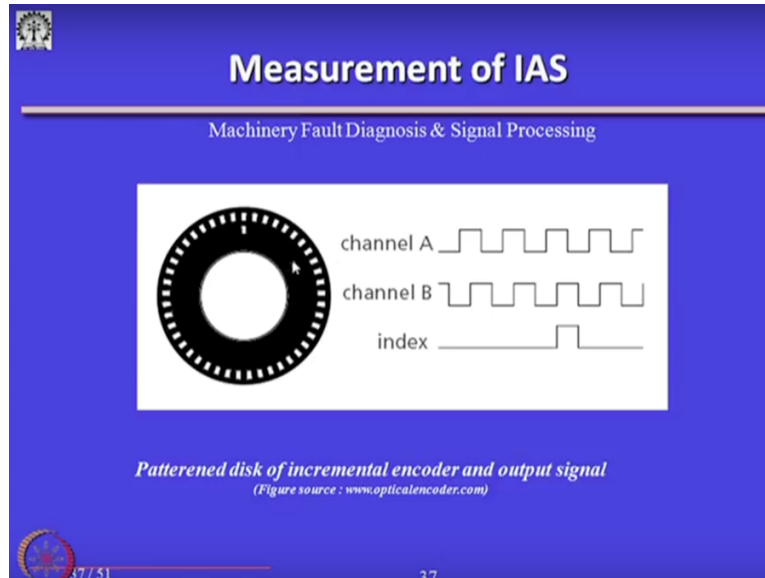




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Ok this is another view of the optical encoder. And then parallel we also measured the vibration ok.

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So a typical optical encoder actually has a slots on the periphery ok. And when a light beam passes through them it will generate a pulse ok. And the spacing of the pulse is a measure of the instantaneous speed.

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Principle

Machinery Fault Diagnosis & Signal Processing

- The instantaneous angular speed can be given by the formula

$$\omega = \lim_{\Delta t \rightarrow 0} \frac{\Delta \phi}{\Delta t} = \frac{d\phi}{dt} \quad \dots \quad (1)$$
- For a pulse generator, if
 - M=resolution
 - tp = time period of each pulse
 Then IAS (RPM) can be given by :

$$IAS = \frac{60}{tp \times M} \quad \dots \quad (2)$$

And this is that is not clear in this slide. This omega is nothing but D phi / DT ok. So we can measure the instantaneous angular speed ok.

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Selection of sensor

Machinery Fault Diagnosis & Signal Processing

- Sensor Resolution
- Maximum measurable speed can be given by : [3]

$$N_{\max}(RPM) = \frac{60 f_c}{M} \quad \dots \quad (3)$$

For the encoder used, $f_c = 20 \text{ MHz}$, $M=1000$
 So $N_{\max} = 12 \times 10^5 \text{ RPM}$,

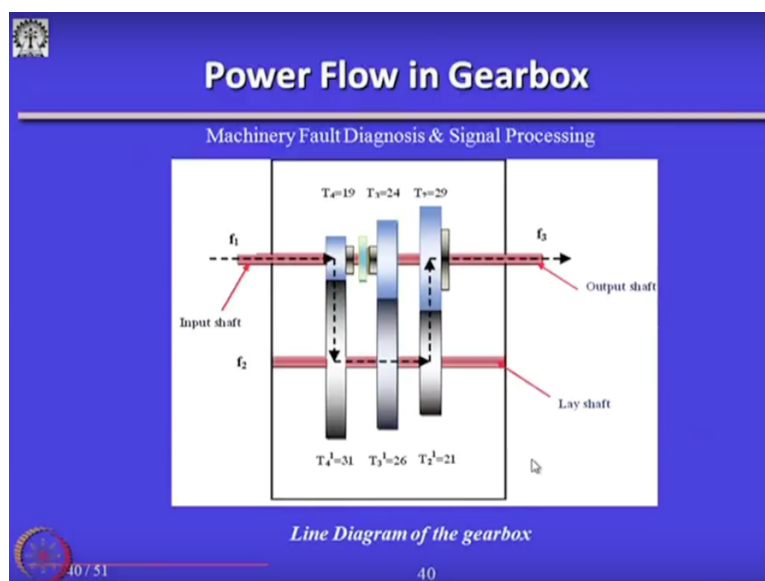
- Minimum measurable speed can be given by : [3]

$$N_{\min}(RPM) = \frac{60 f_c}{RM} \quad \dots \quad (4)$$

So, the minimum measurable speed with the 24-bit register used in DAQ device = 0.0715 RPM

So this encoder has to be captured. The data from the encoder has to be captured at very high frequency, about twenty megahertz. And then we can measure the rotational speed ok. And this is the minimum measurable speed. And these are given in some of the references.

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And this is the power flow from the gearbox.

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Gearbox Frequencies

Machinery Fault Diagnosis & Signal Processing

- If f_1 = input shaft frequency
 f_2 = lay shaft frequency
 f_3 = output shaft frequency
- For second gear :

$$\frac{f_1}{f_3} = \frac{T_3 \times T_4'}{T_4 \times T_3'} = \frac{29 \times 31}{19 \times 21} = 2.25 \quad \dots \quad (7)$$
- Gear Mesh Frequencies can be calculated by :

$$f_{m2} = 29 f_3 \quad \dots \quad (8)$$

$$f_{m4} = 19 f_1$$

where f_{m2} = Second Gear Mesh Frequency
 f_{m4} = Fourth Gear Mesh Frequency

And we could capture the different frequencies of the gearbox. This were known to us beforehand.

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Gearbox Frequencies

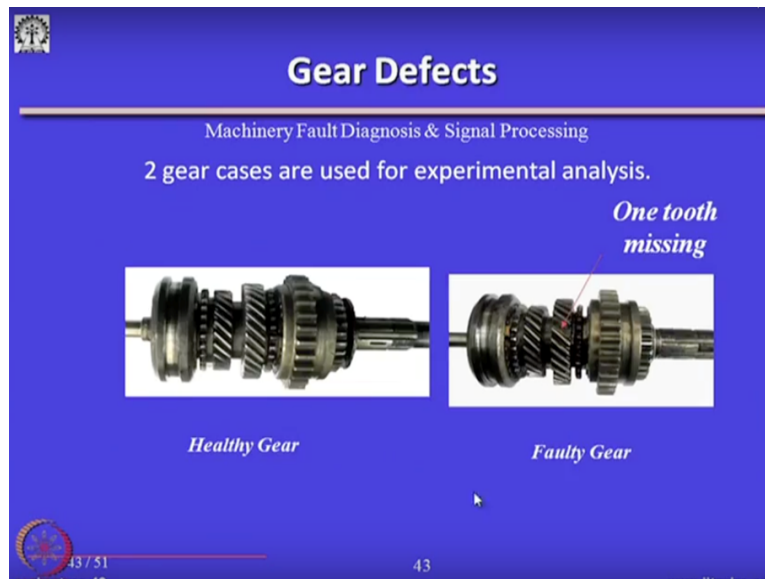
Machinery Fault Diagnosis & Signal Processing

Calculated Lay shaft, output shaft and gear meshing frequencies

S. No.	Input shaft frequency (f_1) (Hz)	Lay shaft frequency (f_2) (Hz)	Output shaft frequency (f_3) (Hz)	Gear mesh frequency (f_{m2}) (Hz)	Gear mesh frequency (f_{m4}) (Hz)
1.	43	26.35	19.08	553.35	816.85
2.	37	22.68	16.42	476.28	703.08
3.	29	17.77	12.87	373.17	550.87

So in a multi stage gearbox these were the input shaft speeds. And this is the lay shaft. And this is the gear mesh frequencies.

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And the interesting part was you know we had the healthy gear, the one tooth missing case.
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Data Acquisition Methodology

Machinery Fault Diagnosis & Signal Processing

1. Record the time period (t_p) of each square pulse in the pulse train generated by the encoder. 10 data sets were recorded, where each data set consisted of data for 60000 pulses, corresponding to 60 complete shaft revolution.
2. The time base is generated by cumulatively adding up the time periods.
3. Calculate Instantaneous Angular Speed for each pulse (corresponding to 0.36° on the encoder disk) by the formula ... (9)

$$IAS = \frac{60}{t_p \times 1000}$$

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And the data were acquired over the entire pulse duration and this pulse spacing would change ok. And these are indications of the IAS ok, that the speed is changing ok.
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Data Acquisition Methodology (Cont'd)

Machinery Fault Diagnosis & Signal Processing

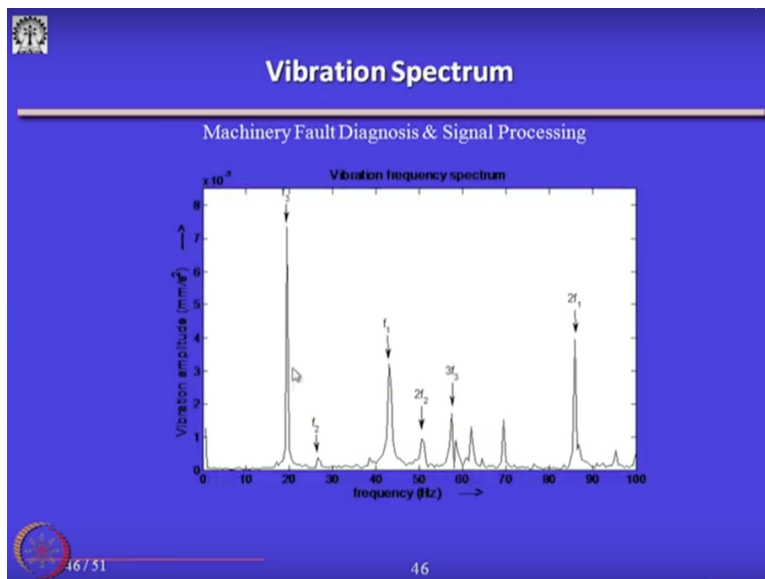
4. Apply interpolation to generate uniformly sampled data from above non-uniformly sampled data. Sampling frequency can be given by the formula :

$$f_s = \frac{1}{\Delta t} \text{ where } \Delta t = \frac{\sum_{i=1}^N p_i}{N} \quad \dots \quad (10)$$

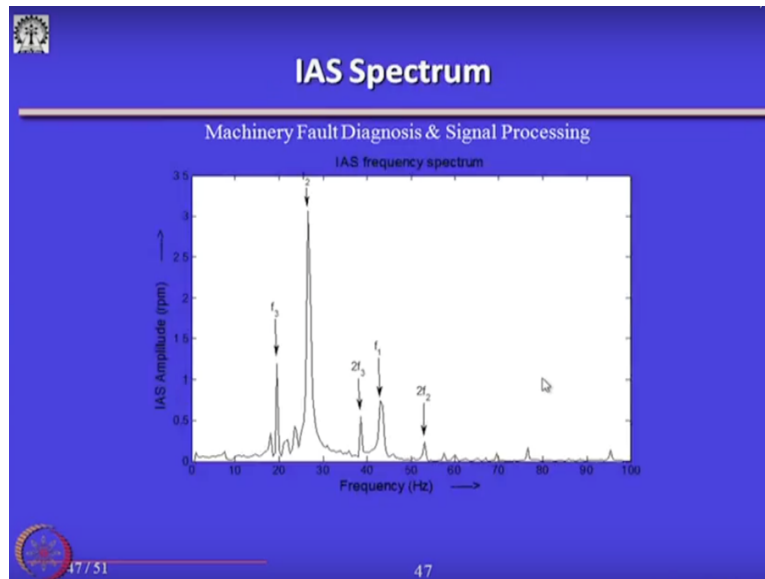
where N is the number of IAS data points (=60000)
5. Perform Time Synchronous Averaging taking 30 averages.
6. Apply different frequency and joint time frequency analysis techniques in uniformly sampled IAS data.

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And then this data is you can see a lot of signal processing is required ok.
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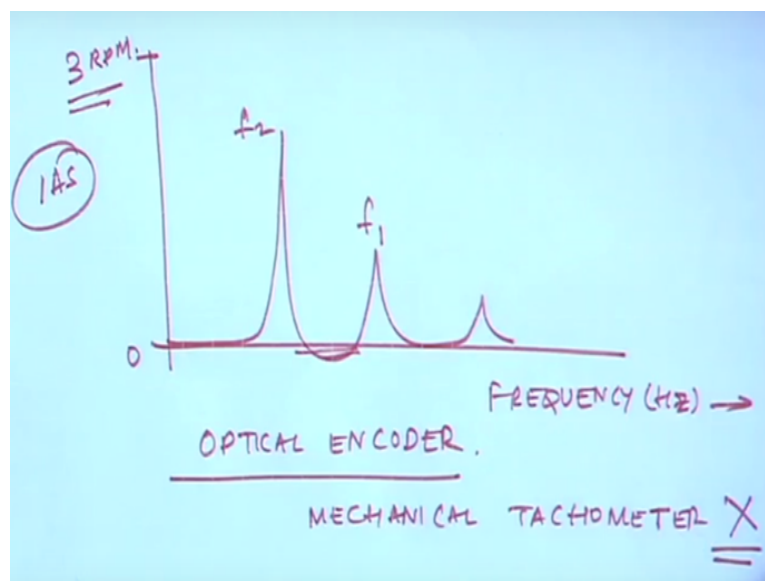


And this is the vibration spectrum of that same gearbox as measured by the transmitter.
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And the most important thing here is to notice that the IAS amplitude in RPM which are measured from the pulses in the optical encoder. See the variations is not much only to 0 to 3.5 RPM ok.

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If I, this is the IAS and this variation is only zero to three RPM. However this small f_2 , f_1 etc. However, this small fluctuations are captured by this optical encoder ok. And which is not possible with a normal mechanical tachometer. It is not possible ok.

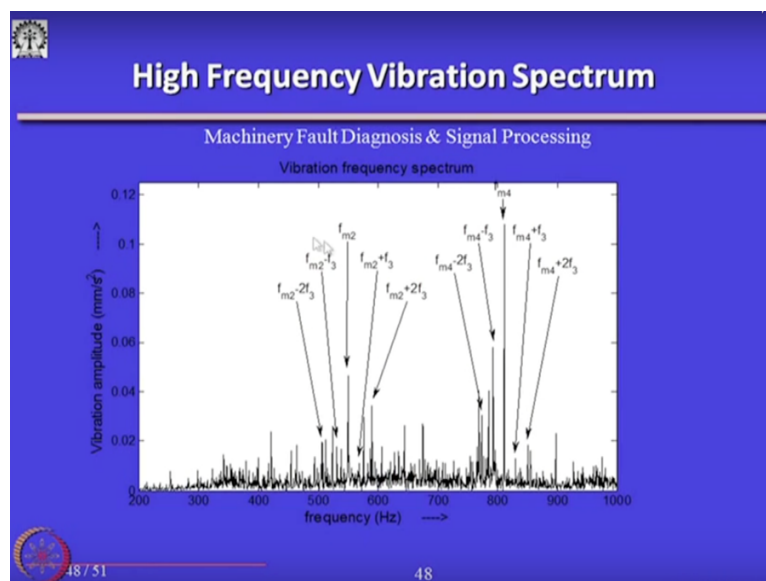
So by IAS we can capture this phenomenon. And the best part about this optical encoders is that they are relatively very very cheap. And all they require is a high frequency data acquisition unit so that the signal are captured at a higher rate. They can be analyzed with the signal processing unit and then we can find out the fault in the system. Because we are able to

detect the gearbox defect frequencies just by monitoring the IAS or the instantaneous angular speed.

Which is measured by from the pulses recorded by the optical encoder. So by signal processing of the pulses, we have to capture them at a very very high frequencies. And then just by doing a derivate of the pulse strain we can find out the instantaneous angular speed. And these speeds are not varying much. Even 0 to 3 RPM. Or in even some machine is running at say 14, 40 RPM, for a fraction of a second if the small variations is there because of a load, because of a fault.

And if that can be captured that gives us a telltale sign as to what is defective in the system. And this has been very popular with IC engines. And at our laboratory at IIT Kharagpur we have been using them to find out faults in gearbox systems. And they are cheap replacement to normal vibration measurements. By additional laser vibrometers, laser vibrometers cost us in millions of rupees. Whereas this is very few thousands of rupees ok.

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And these are the high frequency gearbox vibrations which again we could capture through vibrations. And with this I would like to conclude this course on machinery fault diagnosis and signal processing. Hope you had an enjoyable teaching and learning lesson in this class. And if there are any issues you can contact me over email or at my website or my phone numbers. Thank you.