

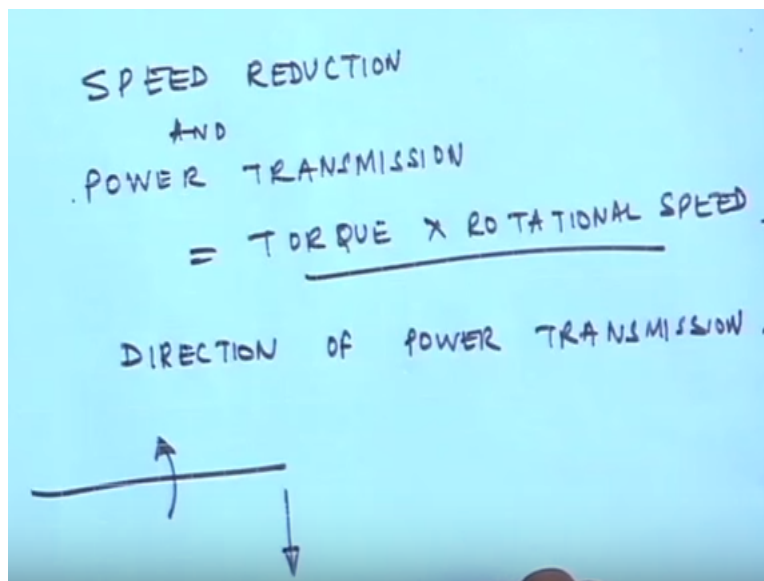
Machinery fault diagnosis and signal processing
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Module No # 06
Lecture No # 29
Gear Fault Detection

In this lecture today am going to discuss on gear box fault detection as you know gear box is a very important machinery component which is there in all most all plants. Particular gear boxes are used for a speed reduction of course power transmission with the reduce speed many operations in a plant are at very slow speeds and typical the prime movers in any industry are typically the electrical motors you all know.

And electrical motors variably wrong at a constants speed may be at just little less than the internal speed could be around 3000 4 pole around 1500 little less 140 RPM or so on. And but there are many operations where plants needs to run at 3 RPMs gear boxes in lath machines which run at various speeds.

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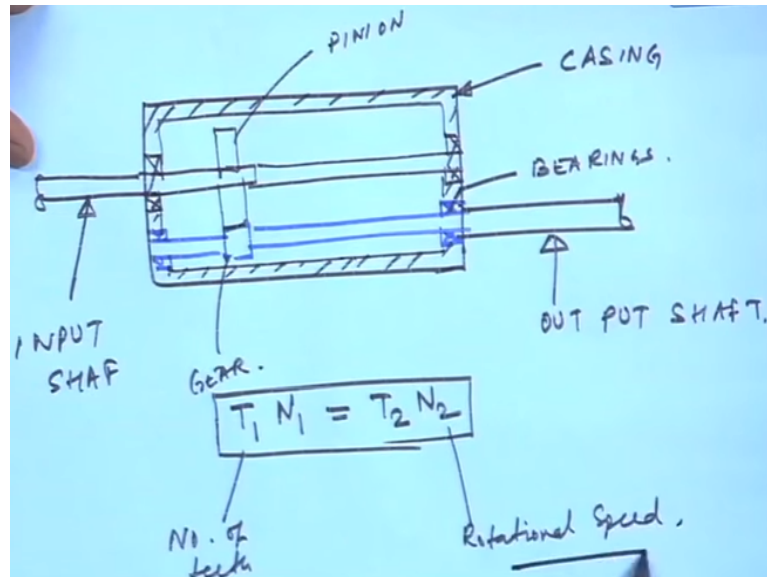


So there is a requirement of speed reduction and power transmission and of course power transmission which is nothing but the torque and the rotational speed. So essentially gear boxes are used to transmit power by playing with parameter changing rotational speed and torque for a

given power. Now another important feature of this gear box feature is the direction of power transmission.

For example we have a shaft okay which is rotating I suddenly want a power in a direction 90 degrees to it. So obviously I have to have some sort of arrangement in the gears so that this power can also be transmitted in an angle of 90 degrees to the incoming shaft.

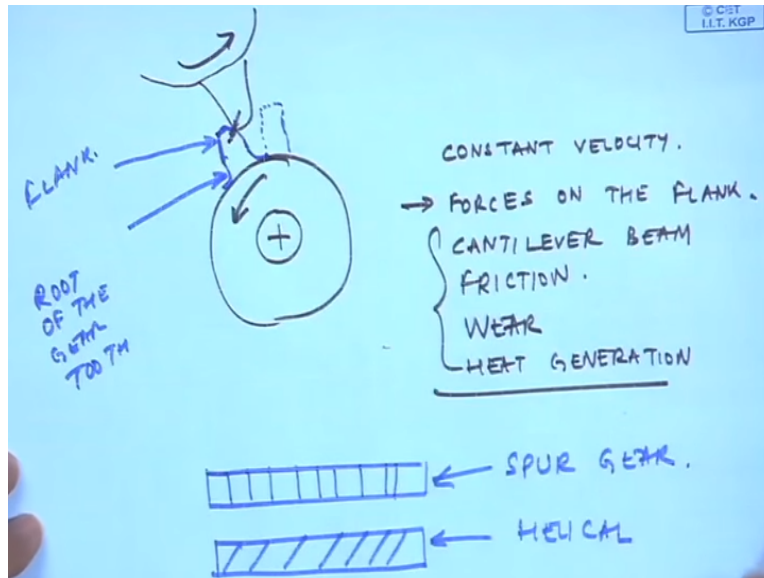
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So if you look at a gear I have an input shaft and then I have an output shaft. And there are on the shafts there are gear mounted the shaft of course not in the air so there will be monitored on bearings and there put on a casing this shaft also this will have a gear and this is also I have a shaft and which is put on a bearing here I just demonstrate to you how a simple gear box looks like.

This is the casing this are the bearings and this is known as the pin in gear and another gear. One fundamental principle in gearing is the number of T should be times this T should be equation to nothing T in another. So this always obeyed and as a rotation speed okay this now this gear are basically as to draw here.

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Of course I am not going to give a lecture on gears but essentially some of the important features if I just draw 1, 2 gear okay and then there will be such to all round the circumference and this is the root of the gear tooth this is flank as if I am this is going to mess with another gear this is on the pin and so on and one gear go this way and another gear this way. So lot of things happen on this gear so there as to be a constant velocity other as will be getting a jerky motion and so on.

And there will be forces coming on to the flank forces on the flank so there are lot of metal to metal contact between the gear tooth. So for a gear to strong so this tooth is also behaving like a cantilever beam obviously it is going to reflect each time it messes with a gear tooth from another gear. So along the gear box this pinion is there gear there each time they are rotating one tooth messes with the corresponding tooth from the other gear and so on this kind of gear mess happens.

My question is even the gear tooth are in contact with the other tooth there will be forces and because of the contact the friction and so there will be where there will be heat generation. So lot of this things happen in the gear box this kind of mechanism in the gear box so for some reason if this gears are not able to sustain heat generation because of the friction not able to generate the forces they are going to fail.

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Type of gears

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- Spur
- Helical
- Bevel

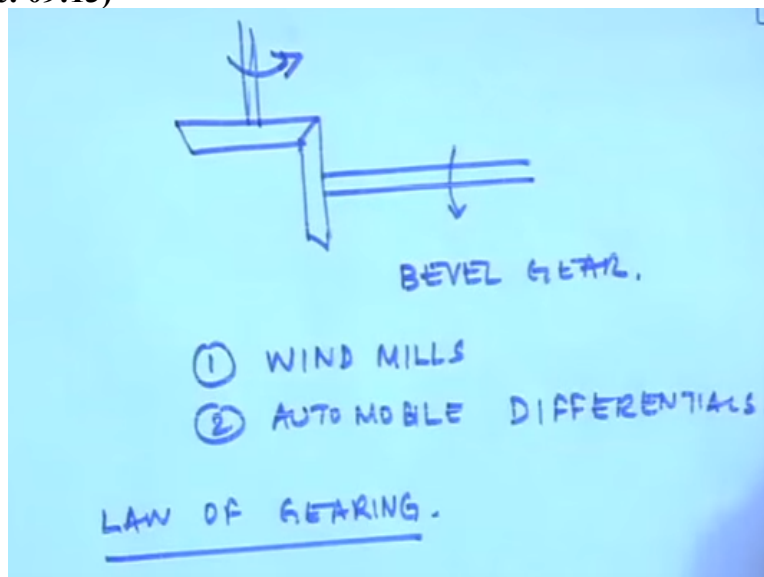


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I will come to this later a little later but now let me tell you what are the difference types of gear available. So this gear depending on if I look at a top view of the gear this gear can be all straight and this are easily known as the spur gear or there would be at angle in this known as the helical.

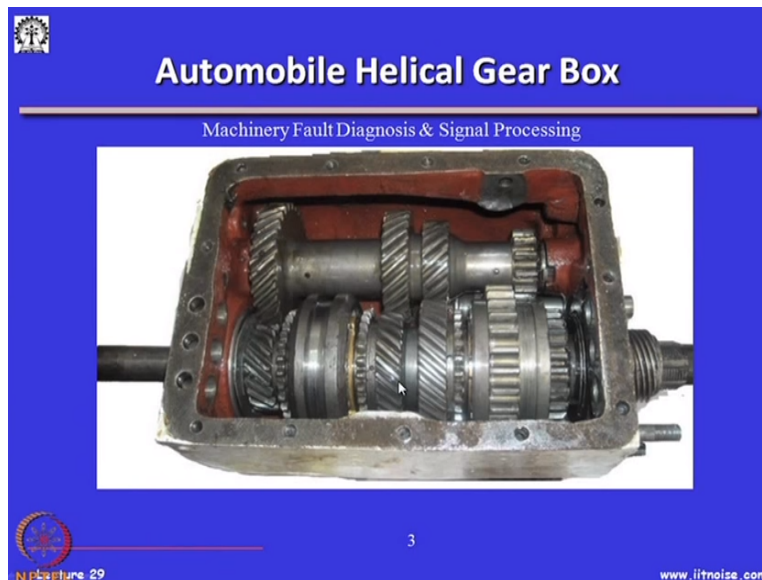
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But spur and helical gear are used to transmit power when one the same direction but whenever there is an power transmission in an 90 degrees we have what is known as an verme and mechanism so gears looks something like this from this is one shaft here and another shaft which is rotating at this direction. So this is bevel gear arrangement and such gear boxes such gears you will find in wind mill and automobile differentials okay.

And of course they all have to obey the law of gearing while they are in motion now these gears are put in a casing. Just mentioned to you these gears are put in a casing as mentioned to you and because we have to remove the heat which is generated from the gear boxes because of the frictions and many things happen in the gears and this will lead to them if you go unnoticed they will lead to the failures of a gear box.

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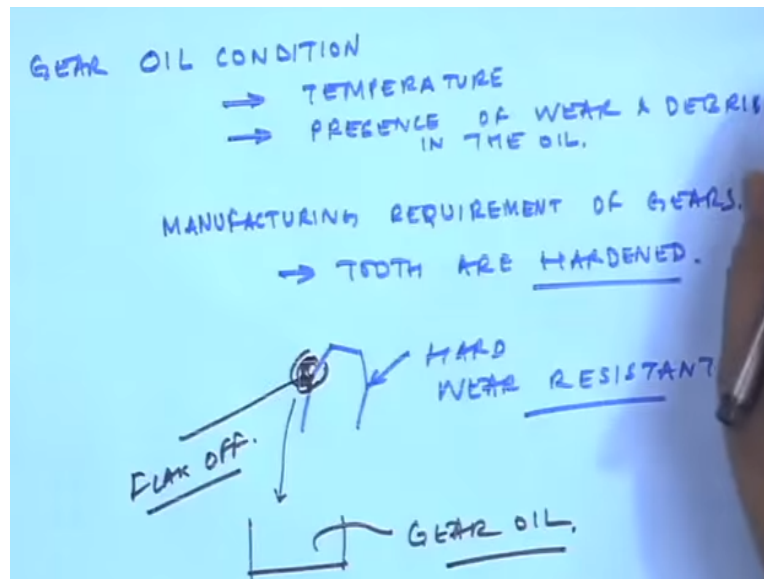


So this is a typical automobile gear box I just wanted to show you what are the things which we have say for example this one of them is the input shaft other is the output shaft and this is an intermediate shaft in an automobile gear box we can bring about different types of speed reduction. So this is the four speed gear box and you see this kind of gears which you are at an angle there are helical gears.

This is one particular gears machine which counter shaft and lathe shaft and this are again the gears and these are what as known as the synchronizers which can be shifted while we shift the automobile gears. So that they will mesh the gears will mesh then we will get a speed reduction and this is another gear okay. So in an automobile gear box you know we have synchronizers and I will show you how these defects can be because each of these gears this tooth will reflect under the load they will get heated up because of friction.

So there is an auto base gear boxes are having and then casing some sort of gear transmission oil or an oil basically used for a lubrication carry over the heat and many of the automobile gear boxes are in gear boxes.

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Say people also monitor the oil condition gear oil condition in terms of its temperature because there should be a case when the temperature of this oil has gone to a level where the chemical and physical oil are lubricating oil are lost the molecule bonds etc., okay. And another is the presence of wear particle or wear and debris in the oil because what happens with time when this two teeth mesh with each other they rub against each other okay.

Once they rub because they may be shaft the proper heat treatment is not done this particles may flake off and can be deposited in the oil. So a very important manufacturing requirement of gear boxes is such that the tooth are hardened okay. They are you know case hardened in the sense that the tooth are very hard to or wear resistance. So many times what I have seen if a proper heat treatment is not done on the gear tooth on the top this particle will flake off.

And this particle will get deposited in the gear oil so to find out the defects in the gear boxes many techniques can be used and which will come one by one.

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Defective Gears

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Healthy condition of 2nd gear



One tooth broken in the 2nd gear



Two teeth broken in the 2nd gear



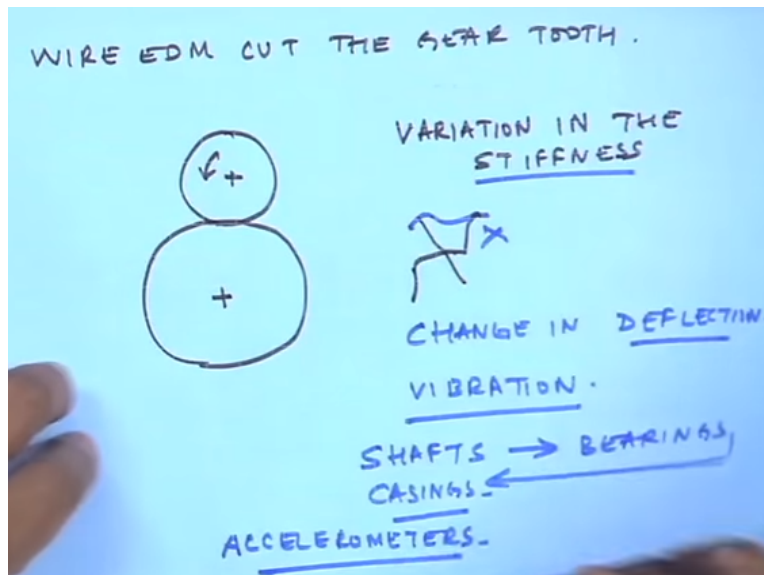
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I will just show you another type of gear box and this are some of the defective gears. For example this is some experiments which are doing in the laboratory wherein we could artificially seed false in the gear by an vary in a machine this is very hard and you know normal milling operations which cannot perhaps occur this and remove the gear tooth. So this is where we are removed tooth because we are find to do some experiments on vibration on the gear boxes because of such defects.

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So we have to do it and of course they are so hard that we had to use wire radium to cut the gear tooth. Now the this kind of false which happen is a I will list them in a next slide so this is how a gear looks like and this is what I meant by flank land root okay. And these are all helical gears

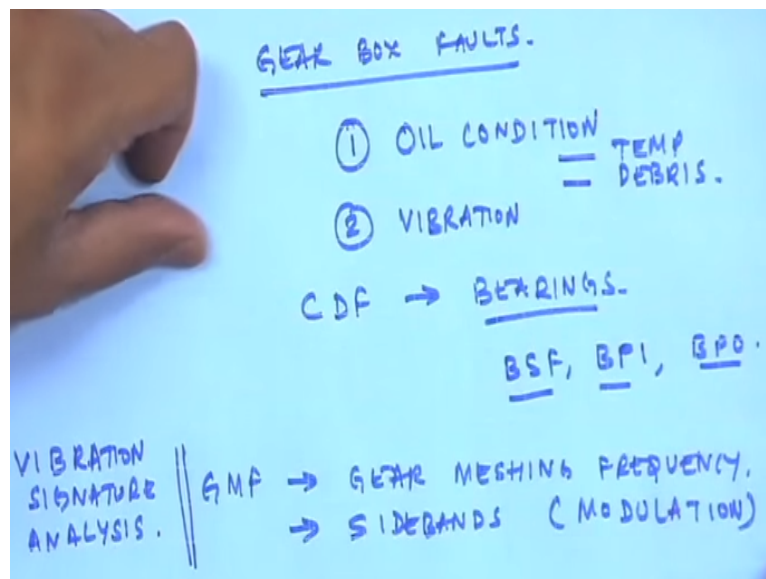
and we have known then what happens because of the change in the gear tooth and two gears are messing against each other okay.

There is always a variation in the stiffness by stiffness I mean you can imagine one gear making contact a one tooth making contact with a one tooth it would have left and then the other tooth will come up but imagine if suddenly one of them is absent what a is going to happen a moment it is not going to with stand that resistance that it is not going to have that resistance on it. So this will lead to a change in stiffness material is not there okay.

So this variation in stiffness leads to certain change in response or reflection change in deflection of the gear. So these deflections will be responsible for creating a vibration okay so because a vibration has been generated because of gear box fault because we will see that the fault as occurred okay. So one is the gear all conditions in terms of its temperature and physical changes become wear every particles and other is the vibration in the gear box.

And this vibration is transmitted to the shafts which are monitored on bearings and then which are convey to the casing and to the casing we can mount out transducer or accelerometers.

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So to detect gear faults we can have so many conditions number one is the oil condition other is the vibration. Same oil conditions have temperature and the debris but interesting thing about vibration is that in a gear box there are bearings there are gears so how do you that vibration is

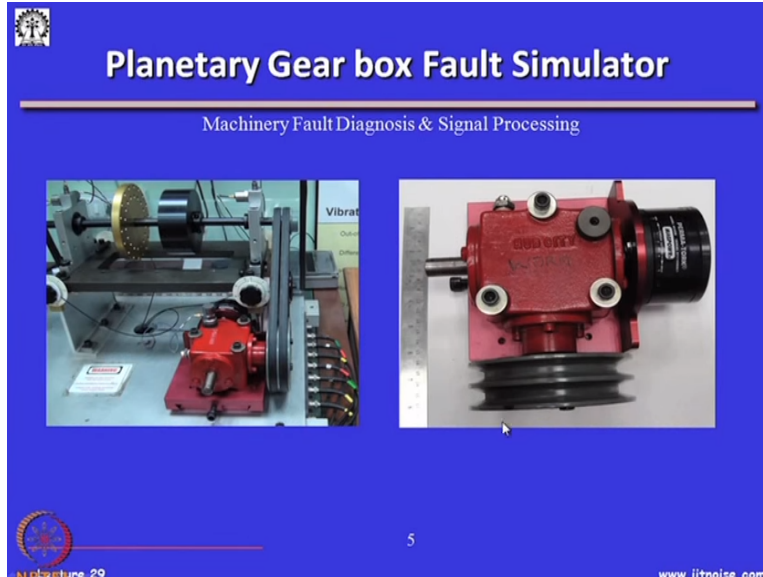
not because of the bearings and it is only because of gears that is the power of vibration signature analysis that is every mechanical components its vibration is manifested at its characteristics frequency.

So what are the characteristic frequency of failure of gear box of course we know the fundamental characteristic defects frequencies of bearings and in the earlier classes I told you how to find out the defects in bearings because of the faults in the bearings and you would have seen the frequencies of ball spin frequency, ball pass inner frequency outer frequencies okay. so these frequencies and then harnet show up in the bearing fault but when there is gear fault something known as the GMF.

It is known as the gear machine frequency will show up and there will be side bands around the gear machine frequency because these gear boxes are subjected to change in load, change in speed okay and there will be momentarily modulation of this gears, gear vibration because of this defects. So they are they will be side bands around the gear machine frequency because of modulation.

So any signal processing technique which can identify this that is the gear machine frequencies that's is side bands around it is good enough to find out the gear box fault. But that calls for a detailed vibration signature analysis okay. So how do we do that we will come to that little later but let me continue on my discussion on the other types of gears.

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This is a planetary gear box okay where inside it we have the gears which are worn and this is how the gear box is used in our fault simulator in the laboratory where there is this is actually a motor driving the shaft and through which we have the pulley which will input shaft and then this is the output shaft at this end you will see a clutch a magnetic clutch which is used to load the gear boxes.

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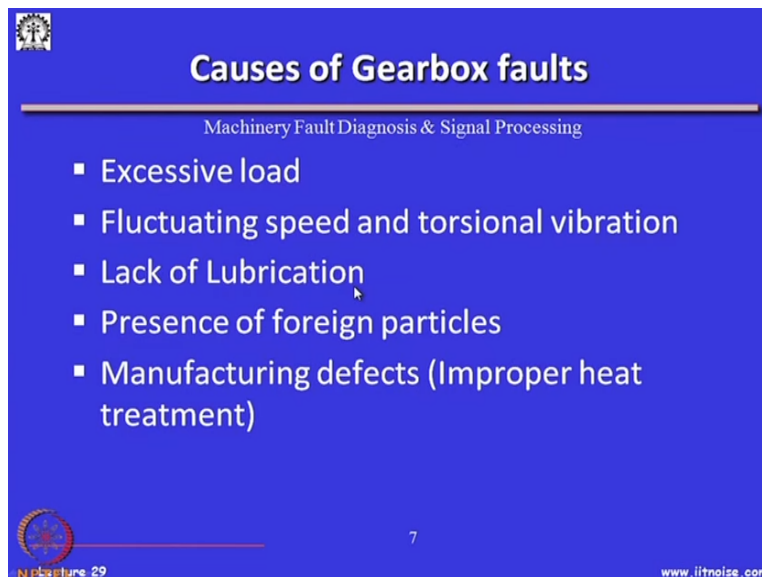
This kind of gear box is used in our lab for the studies and this is actually a gear box in a plant if you can see here the white one is actually a big motor okay which is driving a multi stage gear box is 3 stage gear box and this is an output shaft where we bring about the speed reduction in the

and this actually is used drive a in a raw material and implies and this is you see the side glass they all which is kept inside the gear box.

And you will see some they all actually leaking from one of this drain plants here and this gear boxes are put on the foundation here and on the gear box base okay. And in fact you will see lot of corrosion occurring and many times because of this corrosion there the gear boxes will lose their alignment and then the bearing will get unnecessary loaded because the heady loads and they will be rotating under load.

So you can imagine it is like a domino effects one leads to the other poor manufacturing of the gearbox housing poor foundation hard environment. These all lead to the misalignment of the gear box base which in turn will increase the load because there are heavy bearing here there are usually rolling element bearing at this location and this bearings will be responsible for the loads on the unnecessary loads in the shaft here.

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Causes of Gearbox faults

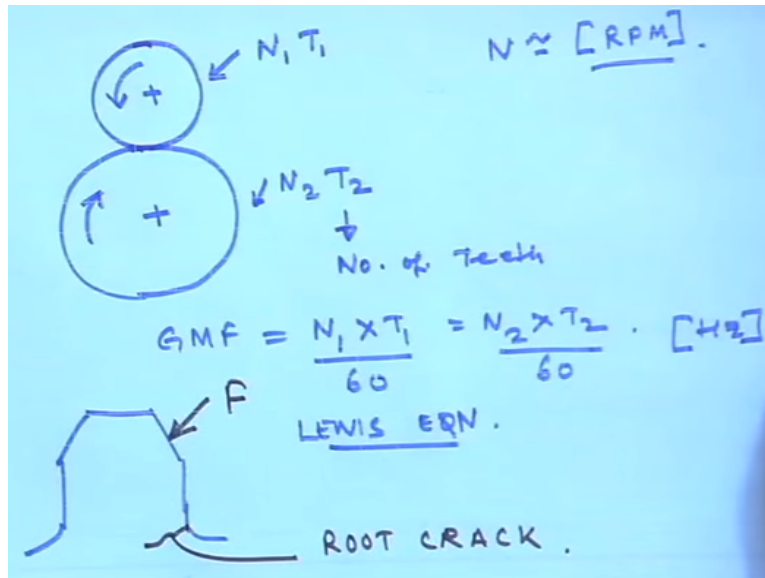
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- Excessive load
- Fluctuating speed and torsional vibration
- Lack of Lubrication
- Presence of foreign particles
- Manufacturing defects (Improper heat treatment)

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And then there will be uneven weight so to find out the causes of gear box faults one is of course the excessive load because these gears are designed to transmit a particular amount of talk okay.

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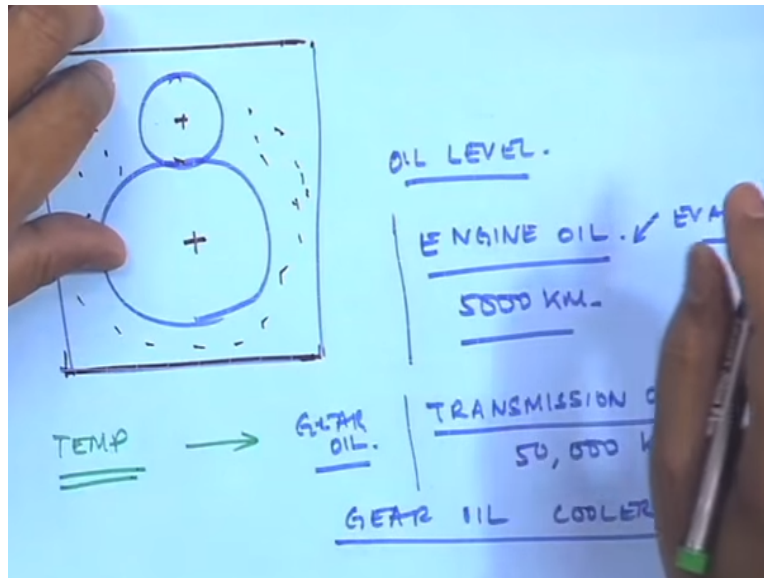


This is 1 and 1 T_1 and 2 T_2 now the torque which is been carried out of course this is the number of teeth not the torque here. So GMF is equal to either N_1 times T_1 or which is also equal to N_2 times T_2 okay. Gear machine frequencies of course they are doing the same units okay. So that we get them in either in hertz or in RPM if it is an hertz if N is in RPM then we have to divided by 60.

Then this will be an hertz okay and N is an RPM rotations per minute so because of excessive loads sometimes when a gear box are designed to carry a maximum load because you know the root the famous LEWIS equation is used to find out the stresses at the root of the gear okay. In a gear box design both of you who do gear design is that and because this is like a cantilever they will be failures and these are usually the root crack and because excessive loads came on the gear boxes.

And then the things is on this gear box we will be having what is known as the fluctuating speed and torsional vibration okay.

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Lack of lubrication if the particles are not lubricated and the heat is not been taken away by the lubricant there will be lot of heat generation and many times there is an minimum oil level which has to be maintained and in industries you know there could be mistakes and people do not have the entire oil of course in automobile you know we have that transmission oil which almost there.

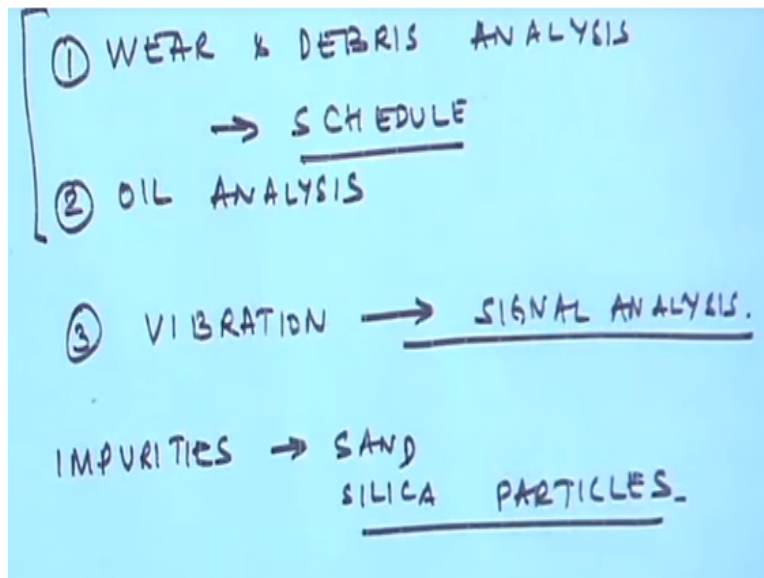
And many times you must have I will just tell you a story see in an automobile there are few types of fluids which is used one particular for the engine lubrication we call it as the oil which is used in engine oil okay. And engine oil is exposed to much higher temperatures because they are very close to the combustion taking place and they lose out because of evaporation we lose them so every maybe 5000 kilometers we top up the lubricating oil that is on.

But another one is the transmission oil are not at a temperature as high as the engine so the evaporation losses is less and maybe we only check them after 50,000 kilometers okay. And this is what is known as the gear oil okay that is of course the purpose of both is the same to lubricate and reduce the friction in the mating engine components in the gear components but because these are at a lower temperature than the engine oil when you not replace them or check their level beyond 50,000 kilometers.

Sometimes in some of the modern cars where the transmission oil goes to the even very very high temperatures they have what is known as the gear oil cooler. A small heat exchanger which

is pointed next to the gear oil so that it is cooled and back in the system. Of course the key idea here is that this temperature has to be monitored in such gear oils. Now I will just tell you about this where debris analysis and in gear boxes and all these oils can be used to find out their particles in them.

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And the normal wear debris routines can be followed and there is a particular schedule which has to be followed. So that the all analysis gear all analysis along with the wear debris is done that is what the gearbox. But of course a much quicker way is to monitor the vibration and do some sort of an analysis and then find out the fault in the gear okay. So we will come how the signal analysis is done.

So the cause of gear box failure are excessive load fluctuating speed and torsional vibration lack of lubrication presence of foreign particles manufacturing defects like improper heat treatment so that they will flank wear we will increase many times in gear box you know I myself have seen like of impurities is there in the gear box and particularly impurities like sand or silica particles will be very detrimental for such system okay.

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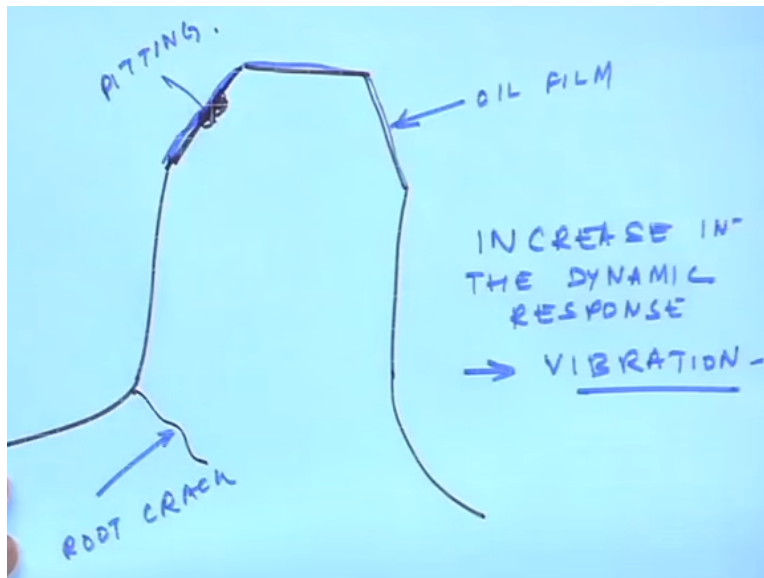
Types of Gearbox Failures

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- Pitting
- Cracks (at the roots)
- Scuffing (breaking of oil film)
- Bearing fault
- Debris detection
- Coupling faults
- Overheating


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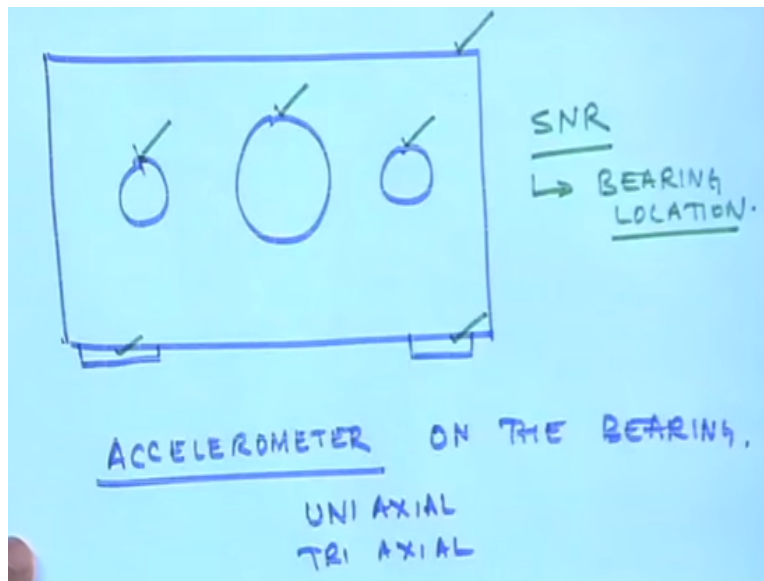
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And how do you detect that so in a gear box type of failures which can occur is a because of pitting of the gear flank this one tooth okay I have a spitting code occur in from this areas there could be cracks there could be the all frame because there is always a thin layer of oil film here the root crack is the pitting. Of course the bearing faults, debris fault, detecting coupling fault or overeating all this can occur.

So all these will lead to increase in the dynamic response or otherwise vibration of the gear box okay. So we can capture the vibration of the gear boxes and then how do we capture the gear box vibrations.

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Suppose I have a multi stage gear box from the outside these are the gearing housing so I can I have option on the these are all the basis of the gear box. Usually the good locations to put the transducers are at the bearing locations. Sometimes are put it on the base just to make sure and just for reference will be return one casing of course the highest signal to know is ratio will be obtained at the bearing location okay.

Highest signal to know at the ratio will be obtained at the bearing locations so we have to be careful that we mount the accelerometer on the bearings and they either could be uni axial or tri axial okay.

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Signal Analysis Techniques

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- Time domain (Kurtosis)
- Frequency domain (Sidebands due to modulation)
- Cepstrum (Sideband detection)
- Wavelets (Time-Frequency analysis to detect impacts)

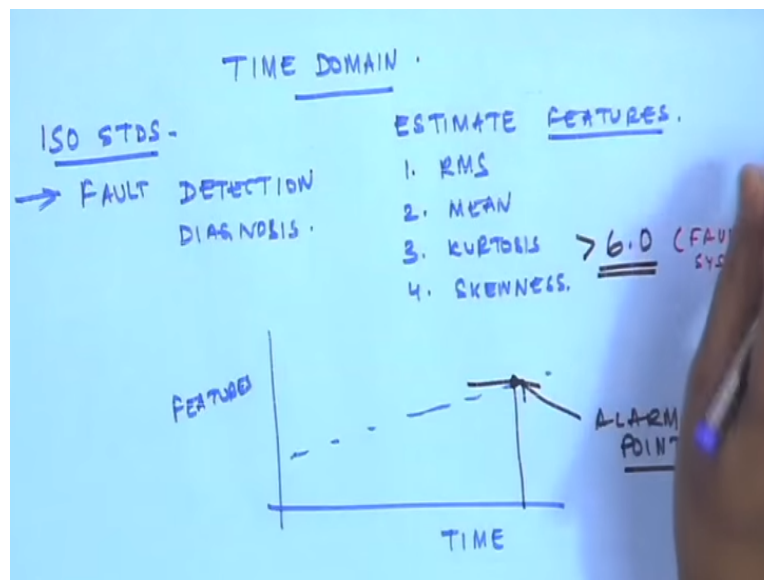


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Now once this vibration from gear box has been captured we can do what is known as the signal analysis. And signal analysis can be done in many types.

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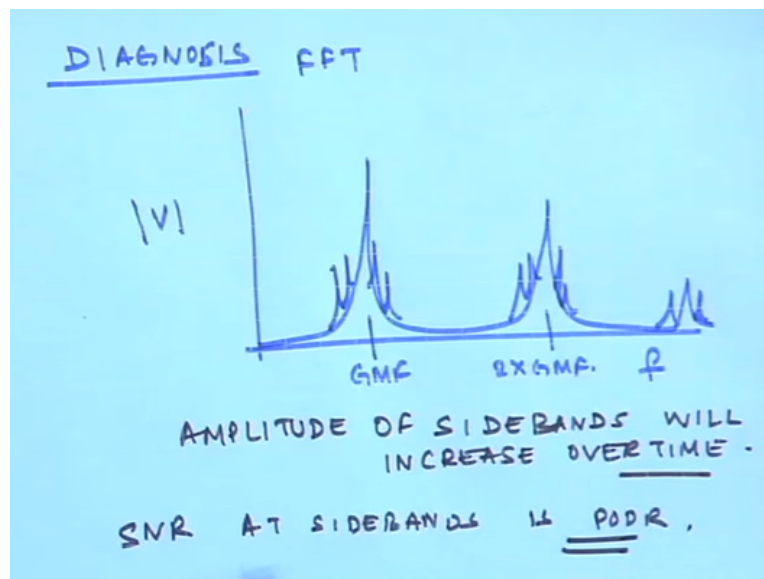


Of course the very basic signal analysis one does the tank domain in time domain we can of course always estimate it parameters or relevant estimate the features. And there are many features we can estimate from the gear box time domain signals one of course the RMS, mean okay the kurtosis, Skewness etc., there is there are rub at you know there are many difference features which we can find out and then of course we can always trend this features called time okay.

And then this may be increase in time and there will be a level at which i will know this an alarm point okay but we do not like to measure a only at such gross levels to only know whether defect as occurred or not. However to diagnosis it we have to do something further beyond just time domain feature estimation of this signals. However it has been found in gear boxes which time domain signals are created then 6 kurtosis we can say for sure there is a fault in the system okay.

Or a faulty system there can be but how about to diagnose there is a difference between fault detection and diagnosis we know grossly this will let us know the fault in the gear box but would like to know which gear how where and so on. And then we have to go more into diagnosis module of the gear boxes and there are ISO standards which I will tell you in the case when we discuss about case studies in general and how such case studies used to measure the vibration of systems.

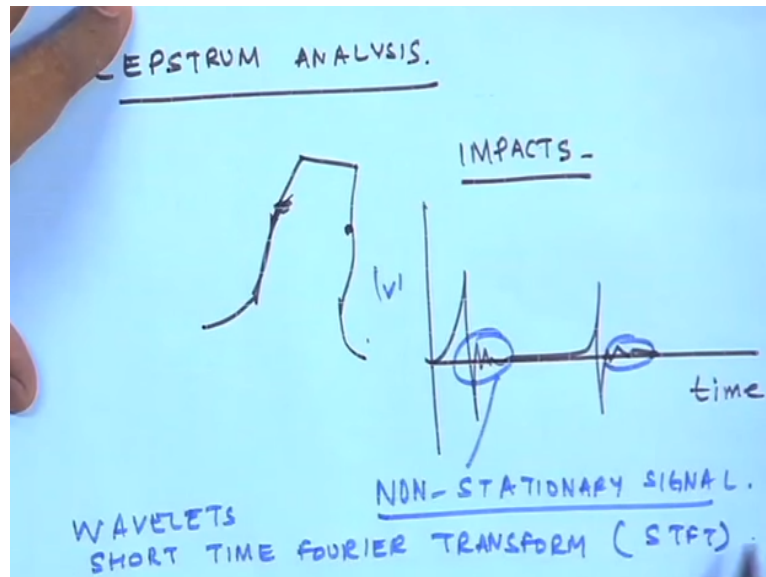
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And of course because we want to go into a fault and diagnosis mode we have to do what is known as the we can go in frequency domain mode by technique of FFT and I will be seeing a certain peaks and then around them there will be side bands and this is the vibration level. So this is the amplitude of side bands will increase over times and this side bands around the gear machine frequencies and it is multiple.

But what happens many times because there are lot of other signals so this side ones are nicely buried in noise so the signal to noise ratio at side bands is poor. So we have to find out an improved signal processing technique to detect such side bands.

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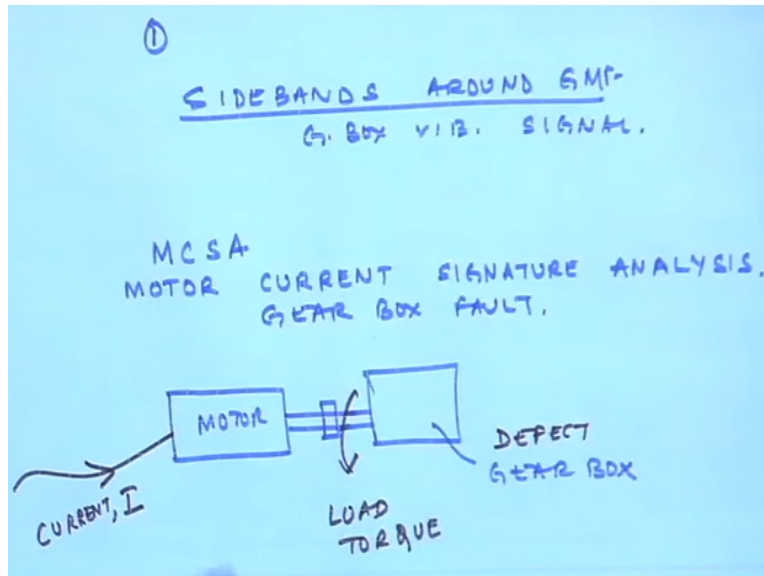


And that is what we known as the Cepstrum analysis we had an entire class on system analysis and there also I believe I have covered about the gear box signal fault detection. I will give some examples but another important things which happens because of these defects in the gear tooth sorry maybe lots of impacts occurring and this impacts in the time domain will looks something like this.

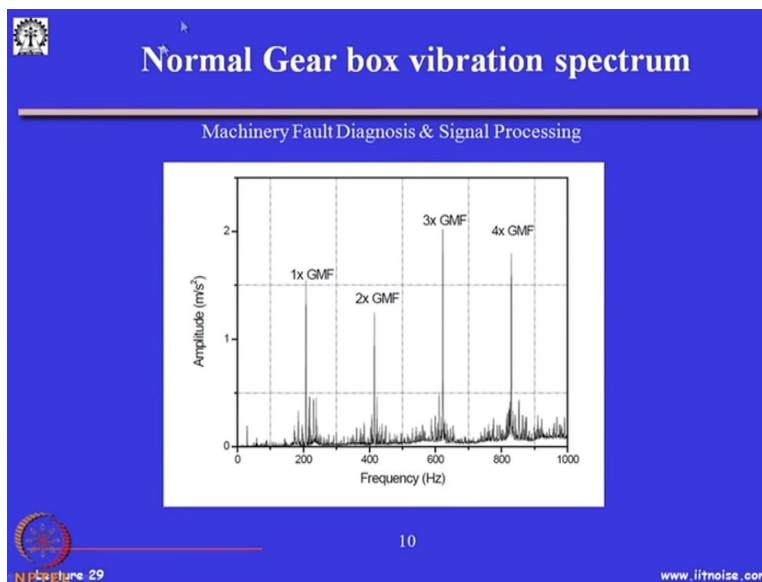
So this kind of they are highly non-stationary signals because they are not definitely existing at all times they are not periodic. So the fundamental signal processing theorem of stationary signals where in the properties of the signal ensemble over a given time change is being violated and thus stationary signal analysis like FFT etc., cannot be done on such signals.

So we have to do signal analysis using certain non-stationary signals like the wavelets okay and then things like short time four years transform or STFT. So some of the advanced diagnostic software which are available have this features by which we can do such signal analysis okay.

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Now I will give you a case study for a signal which we have done in the signal analysis in the laboratory. I will just give you relative feel of the this is a normal gear box frequency okay and then you will see about 0 to 1000 in the gear box which I showed you in the laboratory is similar to and this is the amplitude of the vibration measured at the bearing location or sometime in the gear box casing you will see this gear box side burns around the gear box frequencies.

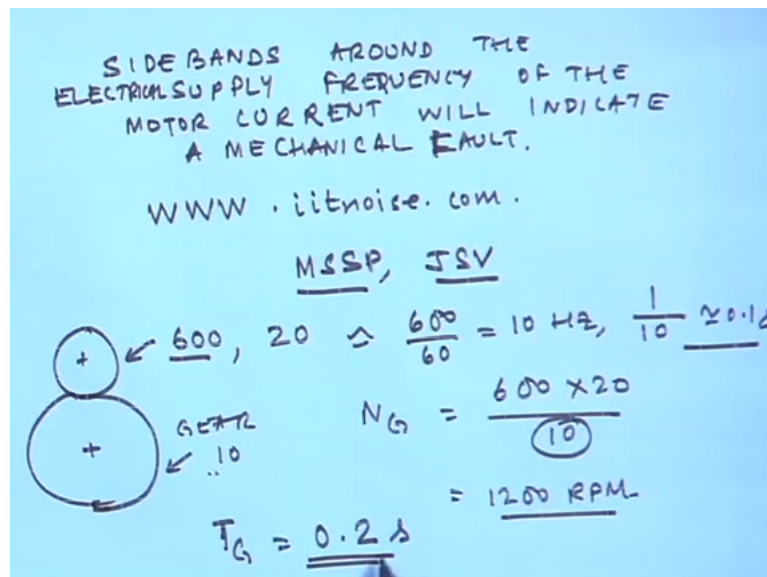
And these are characteristics of the gear box signals I will you will realize that whenever we have seen the signals of the other mechanical system we will see such side bands around GMF. And that is the characteristics of the gear box vibration signal and to find out more about the side

bands we have to use to technique of system analysis. So this to quickly recap you know I did tell you about the gear box debris analysis, debris and oil analysis I mean the gear box oil will lose its properties the debris will be deposited looking at debris as we can get some clue.

Next is vibration of course another technique which we in our group at IIT Kharagpur have successfully this MCSA a motor current signature analysis okay. And this has been used to find out this gear box fault I will tell you briefly what is there in suppose I have motor here my electrical motor through a coupling it is driving a gearbox and this motor there are current which is been drawn by the motor.

So what happens is there is a defect in the gear box this gives rise to some rise of load addition load work on the motor. So if this motor is been subjected to additional load torque the current itself get modulated at the frequency of the occurrence of this defects and so these side bands in the current will also indicate some presence of the mechanical defects.

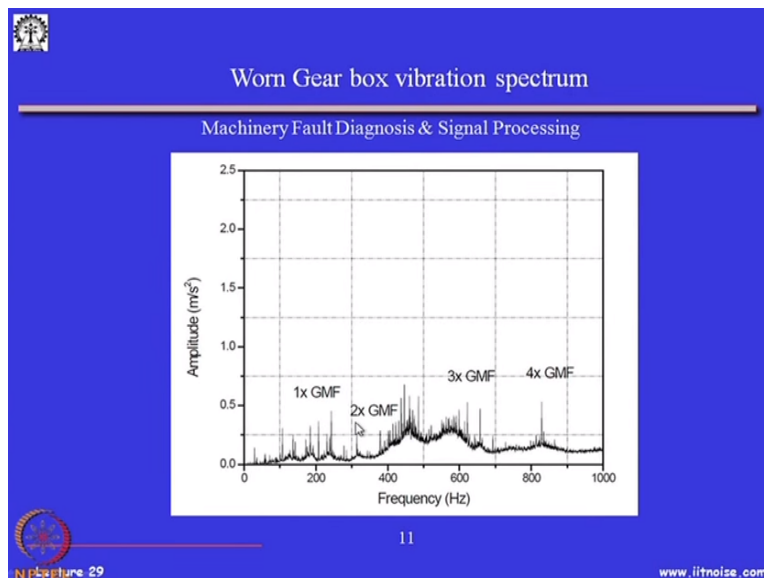
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So side bands where on the supply I mean the electrical supply frequency of the motor current will indicate all mechanical fault. So this we have successfully used to demonstrate gear box fault and more details about this can be found again at my website and you can refer to some papers in journals like MSSP or JSV again the system and signal processing or journal of journal of side band vibration are my publication.

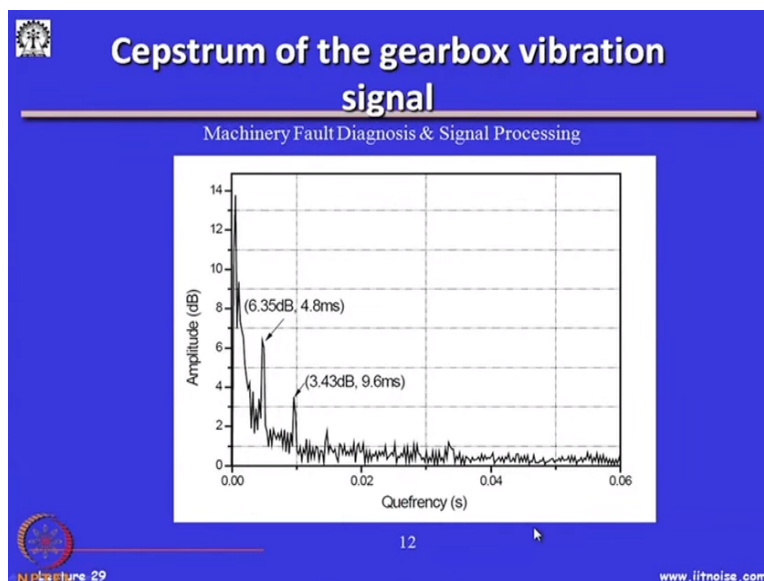
And then you will see that how these motor current analysis has been used to found out a gear box fault in the laboratory.

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Now when we had a one gear case okay amplitude there is a change in amplitude in this case I will show you a comparison actually the amplitudes are from a different gear box though so that is why it is not fair to compare between the first graph and this graph but then there is a difference in the spectrum but what I want to do show you here is that the gear box side band around the GMF have to be found out by this system analysis.

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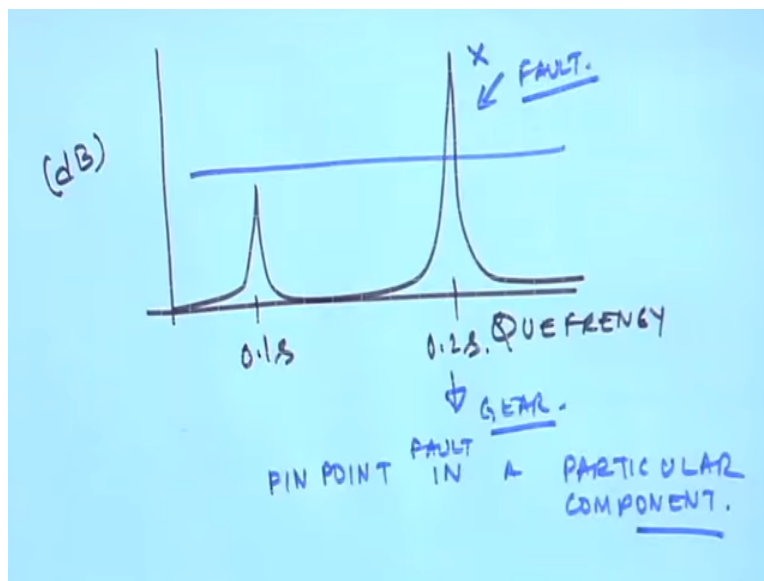


And the system analysis of this gear box signals this is an DB they will give certain Quefreny is so the inverse quefreny will be related to rotational speed of the pinion or the gear or the multiple in this case there is a strong multiple so you will see which one is more at fault. Just for the sake of discussion suppose this is running at 600 RPM and this has a 20 teeth and this as a 10 teeth the speed at which the gear and gear will nothing about 600 time 20 by 10 is about 1200 RPM okay.

So one rotates at 600 RPM other rotates at 1200 RPM and in the inverse time period would be so this is 600 RPM will corresponds to $600 / 60$ that is 10 hertz so the time period is $1 / 10$ that is 0.1 second is for this one. For this one it will be just twice so this will be time period of G will be 0.12 seconds okay this is going at a much slower speed is that right I do not mistake here I believe this will be at slower speed is not it okay.

I have taken the cases at 10 mega drawing it and drawn it wrong this or the other way but if the number of teeth here is time is that ok so this is a rotating at 0.2 seconds.

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So in the quefreny and some DP amplitude because this is a log scale if I see a quefreny at 0.1 seconds or 0.2 seconds. I know at a particular and with time if I monitor the quefreny is I will know that there is a fault in the device which is running at with a time period of .2 seconds of fault in a the component which is running at 0.2 seconds in this case it is my gear okay.

So we can use such a technique system analysis to find out pinpoint the fault in a particular component oaky. So a just to summarize in gear box it is a very important mechanical component and this component or this device is used almost in every industry so two broad ways of this fault detection in gear box is one is doing the either the over analysis and where debris analysis and other being the vibration analysis.

And vibration analysis itself can be done in many ways in time domain signal analysis frequency domain, time frequency or in system analysis and then we can not only know the gear box fault conditions but also actually diagnose and find out the real cost of fault in a gearbox thank you.