بسم الله الرحمن الرحيم

Training Course
on
Vibration Analysis Level-1

Centre for Vibration Analysis & Condition Monitoring (CVCM)
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Vibration Analysis &
Machine Fault Diagnostics

Contents

Vibration Analysis

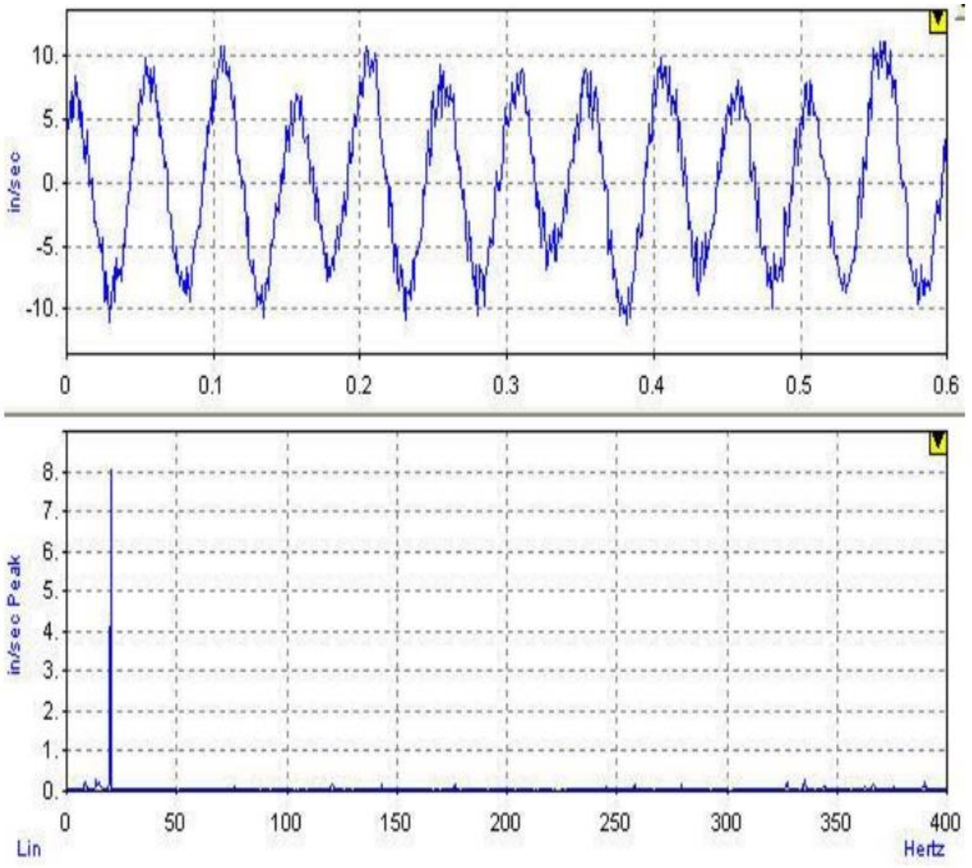
Rules of Vibration

Rule one: Sine wave

A mass bounces up and down on a spring and creates a sine wave with its motion

A sine wave creates a single peak in the vibration spectrum, with a frequency and an amplitude.

But what happens when the waveform is not a sine wave?



Rules of Vibration

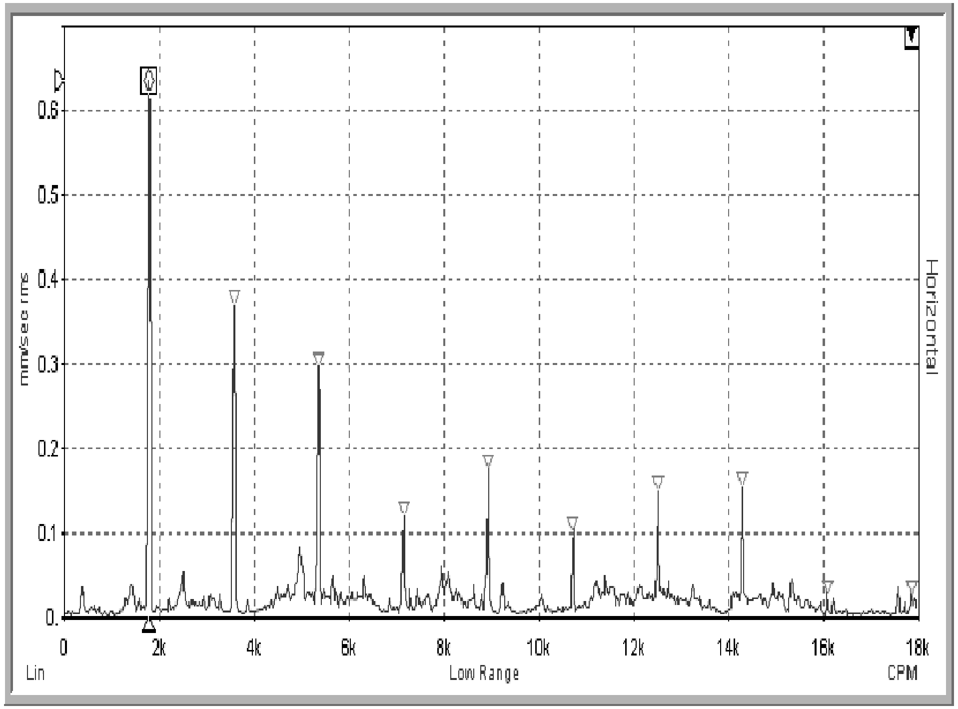
Rule two: Harmonics

Harmonics are a series of evenly spaced peaks that are multiples of the first peak in the series.

The first peak is called the fundamental frequency.

Harmonics can be multiples of any frequency

Harmonics are generated when there is clipping, transients, or random impacting in the waveform

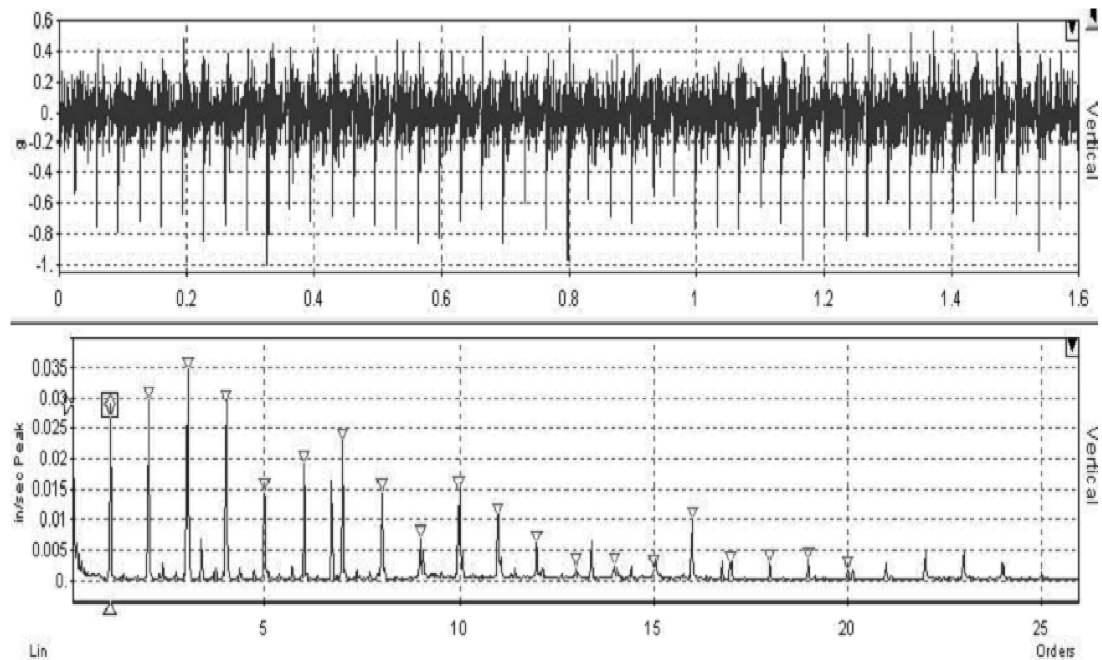


Rules of Vibration

The impacting, transients, and clipping in the waveform produce harmonics

Conditions that can produce harmonics:

- Looseness
- Misalignment
- Bearing Wear
- Gear Faults



Rules of Vibration

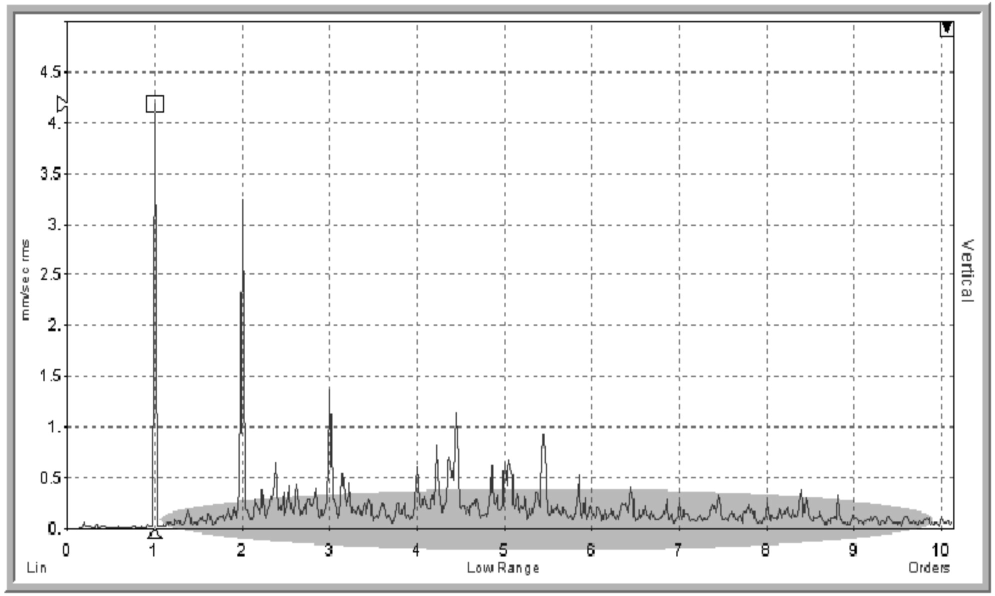
Rule three: Noise Floor

Noise is generated by either:

A single event in the waveform (like an impact) or

Random vibration – a waveform that does not repeat itself

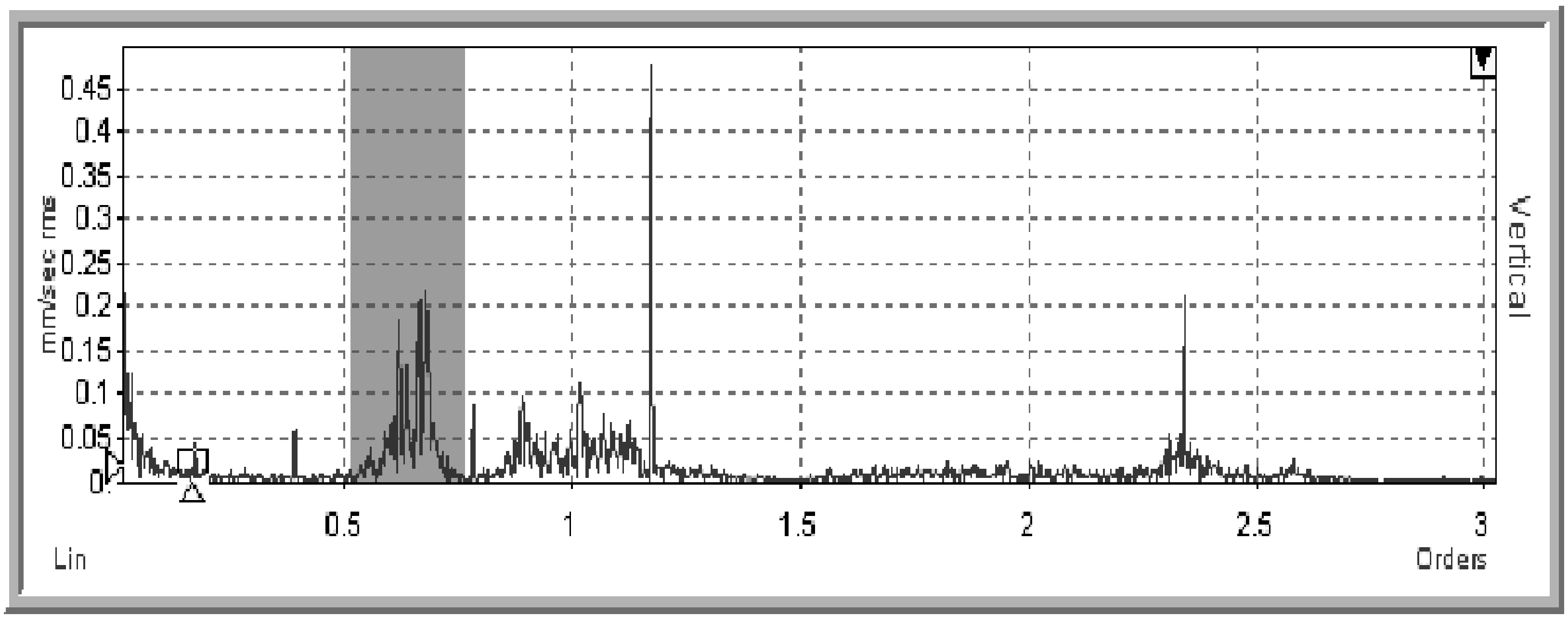
However, for a variety of reasons, there will often be cases where the noise floor seems to lift up, either across the entire spectrum or in certain areas.



Rules of Vibration

Noise floor appears to be high in specific areas due to:

1. There may be serious bearing wear, when problem become worse.
2. The second possibility is that there is a resonance and spectrum appear as humps



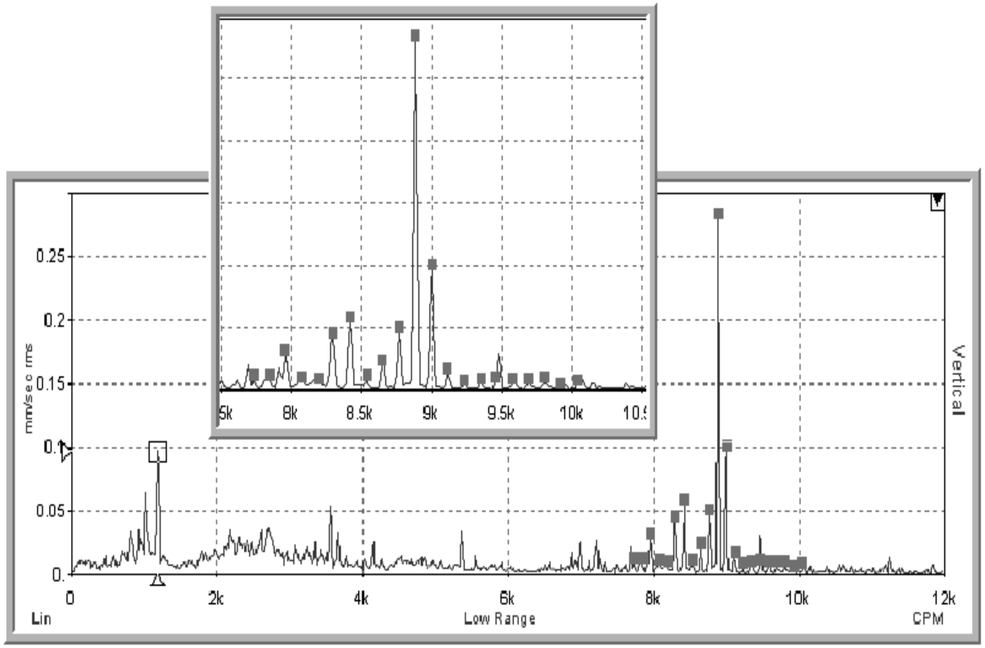
Rules of Vibration

Rule Four: Sidebands

Sidebands are a very important phenomenon to look for (and understand) in machinery analysis.

Sidebands are a result of amplitude modulation between two signals.

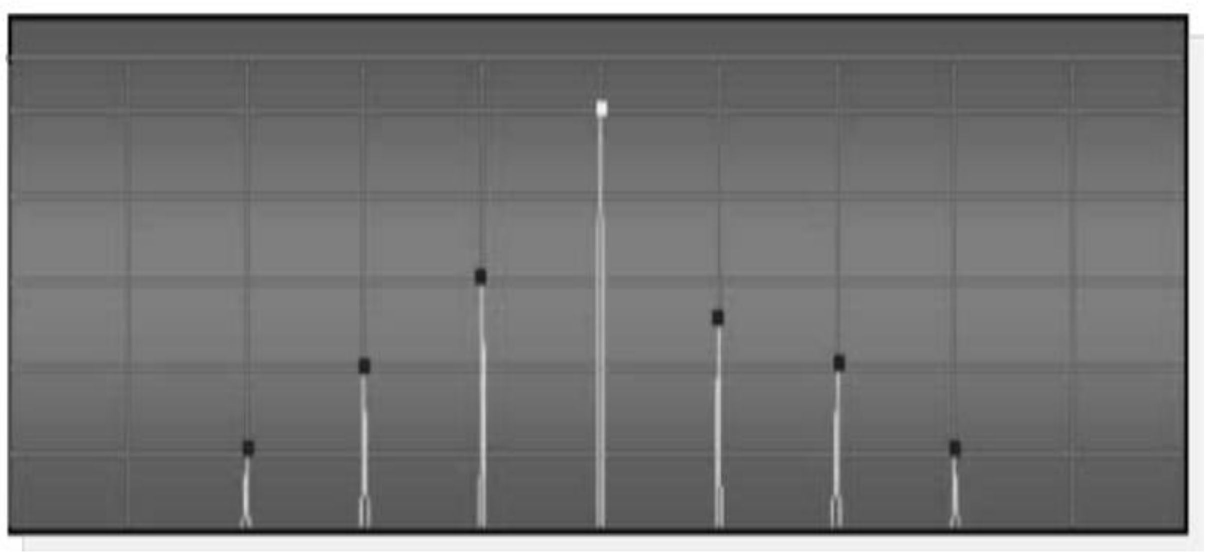
Sidebands are common when studying rolling element bearing, gearbox, electrical, and certain other fault conditions.



Rules of Vibration

Sidebands look like evenly spaced peaks, centered on another peak called the "**center frequency**".

The center frequency is the "**carrier**" frequency and the sidebands are the "**modulation**" frequency.



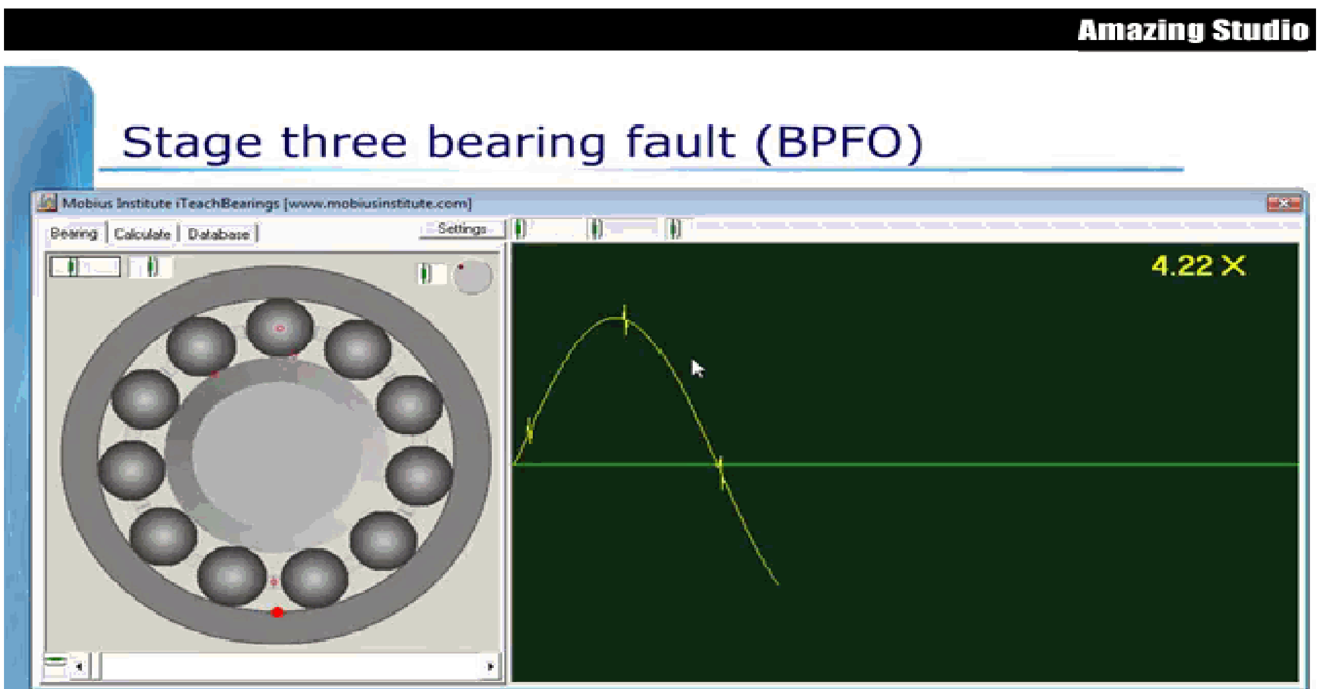
Rules of Vibration

Examples of Carrier Frequencies:

- Gear mesh Frequency
- Bearing inner race frequency
- Rotor bar pass frequency

Examples of the Sideband Frequencies:

- Running speed
- Fundamental train frequency (cage frequency)
- Pole pass frequency



Analysis Process

Here is a general procedure that describes the analysis process:

- Validate the data
- Find the running speed / normalize data
- Look for harmonics
- Identify forcing frequencies
- Compare data to a baseline
- Look for and identify faults the machine can have

Data Presentation

- Spectral comparison to reference data
- Overlay graphs
- Trending
- Staked plot
- Waterfall plots
- Logarithmic display

1. Spectral comparison to reference data

Condition monitoring relies heavily on comparisons between current data and older data.

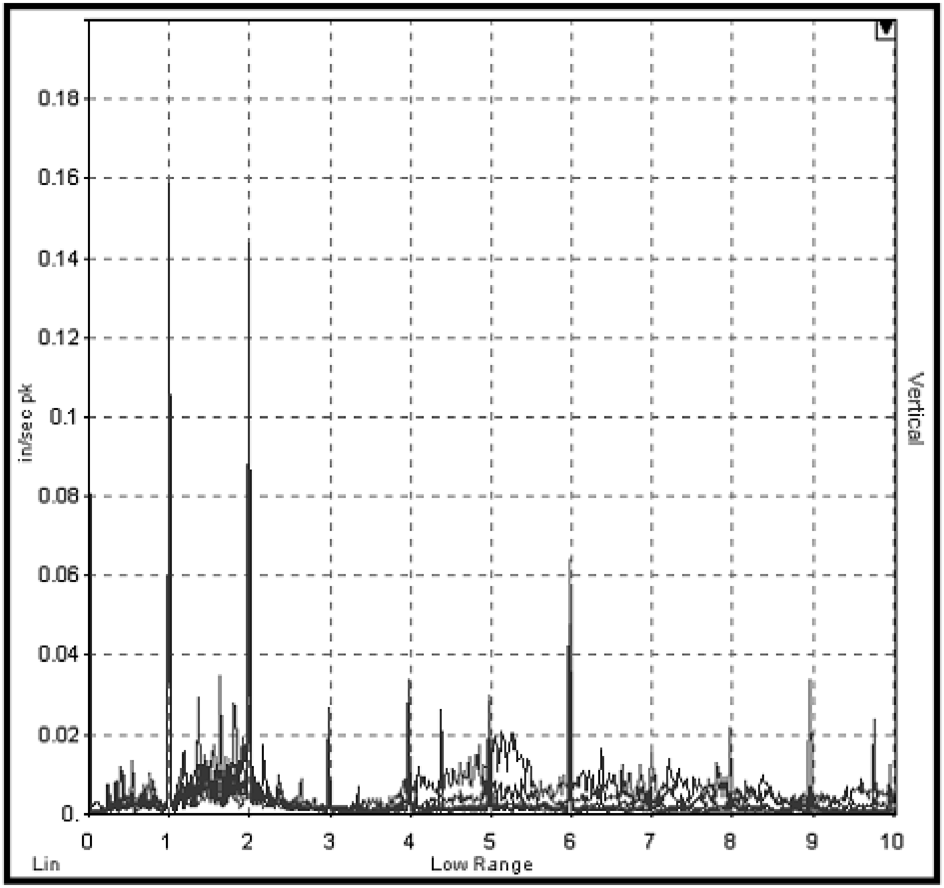
If it is possible to know how much the data has changed, and where it has changed (what frequencies) then that is a real help.

2. Overlay Graphs

View the data is to overlay the graphs one atop the other.

To see exactly how the data has changed at each spectral peak.

If all of the spectra overlay closely, then there is really nothing to worry about

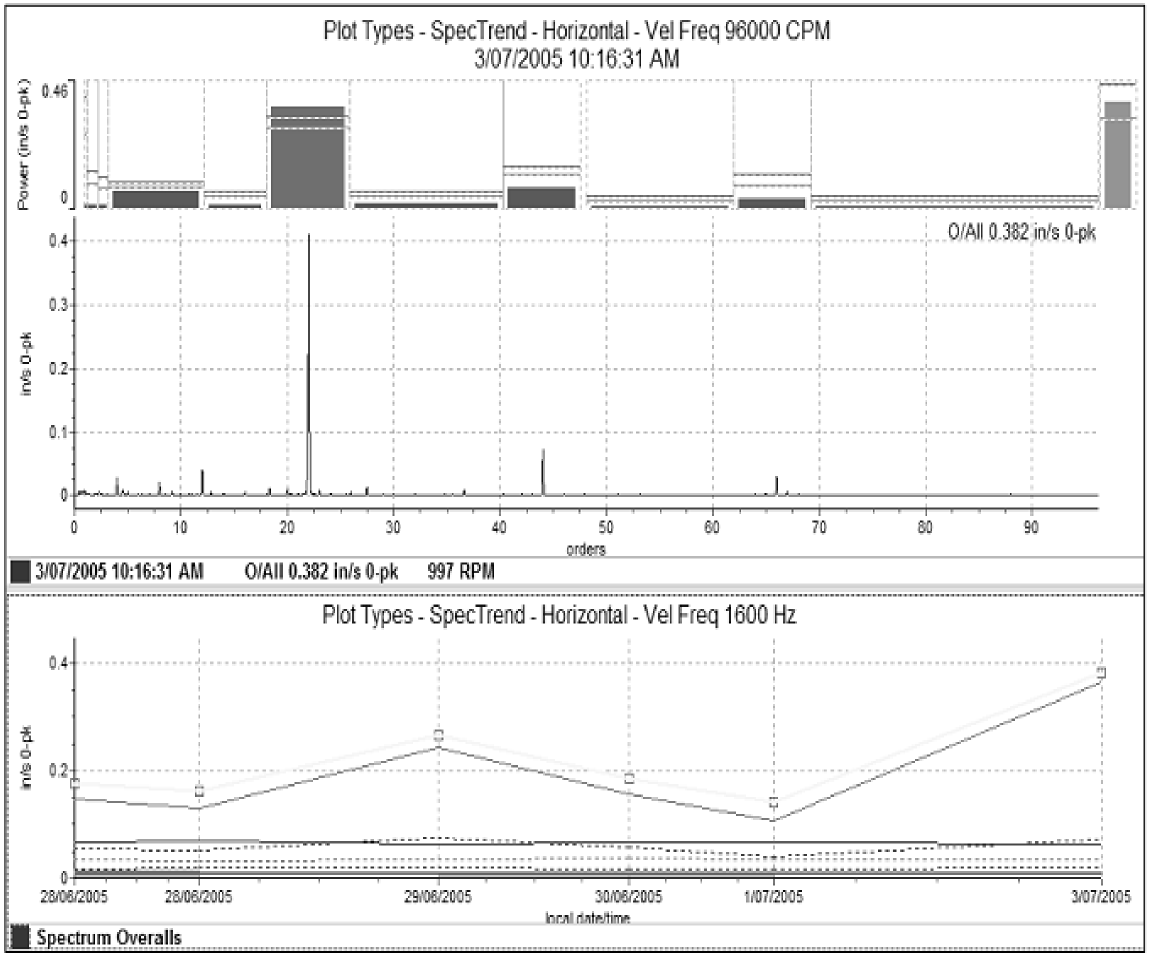


3. Trending

Trend graphs provide a quick visual view to the changes that are occurring.

Figure shows trend of vibration levels at particular frequencies and in frequency bands.

Trending is probably the most important part of analysis, whether it is temperature, pressure, vibration, oil analysis, or any other process.

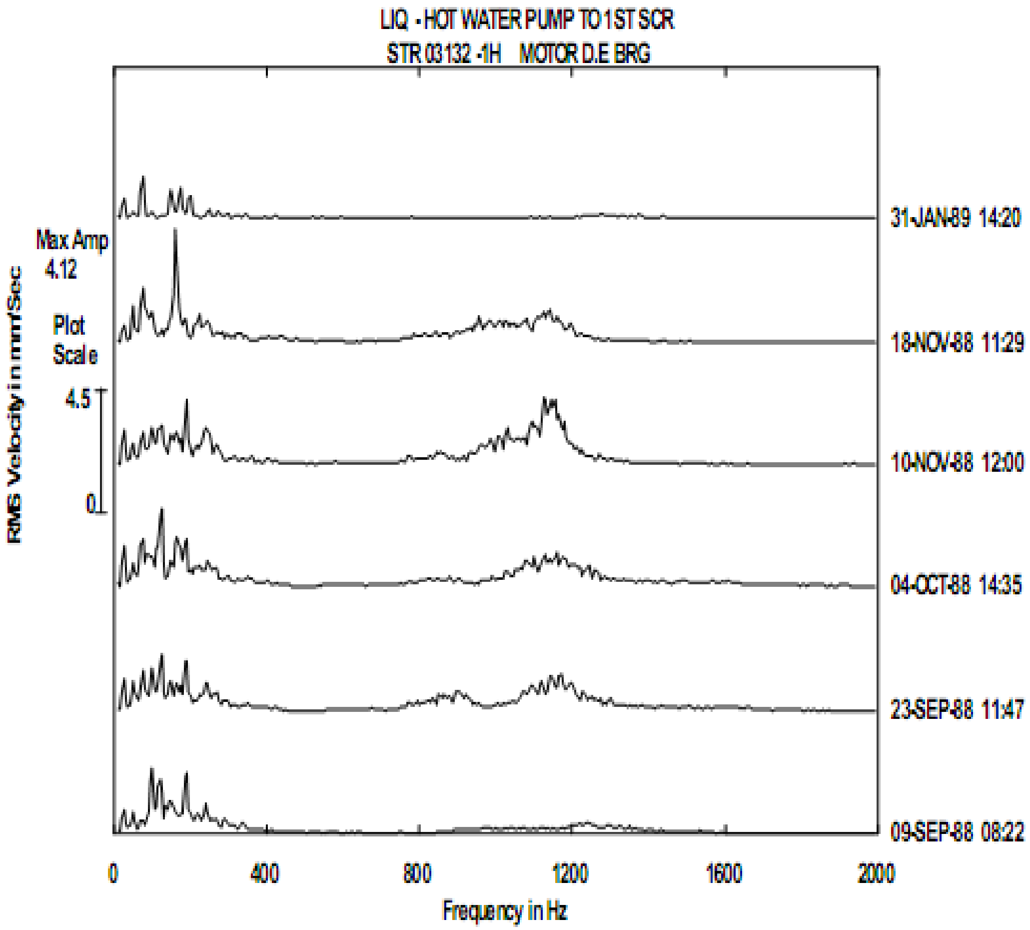


4. Stacked Plot

Spectral graphs to be stacked vertically.

With larger data sets there is insufficient room available for each graph; they become cramped

The waterfall plot can solve this problem

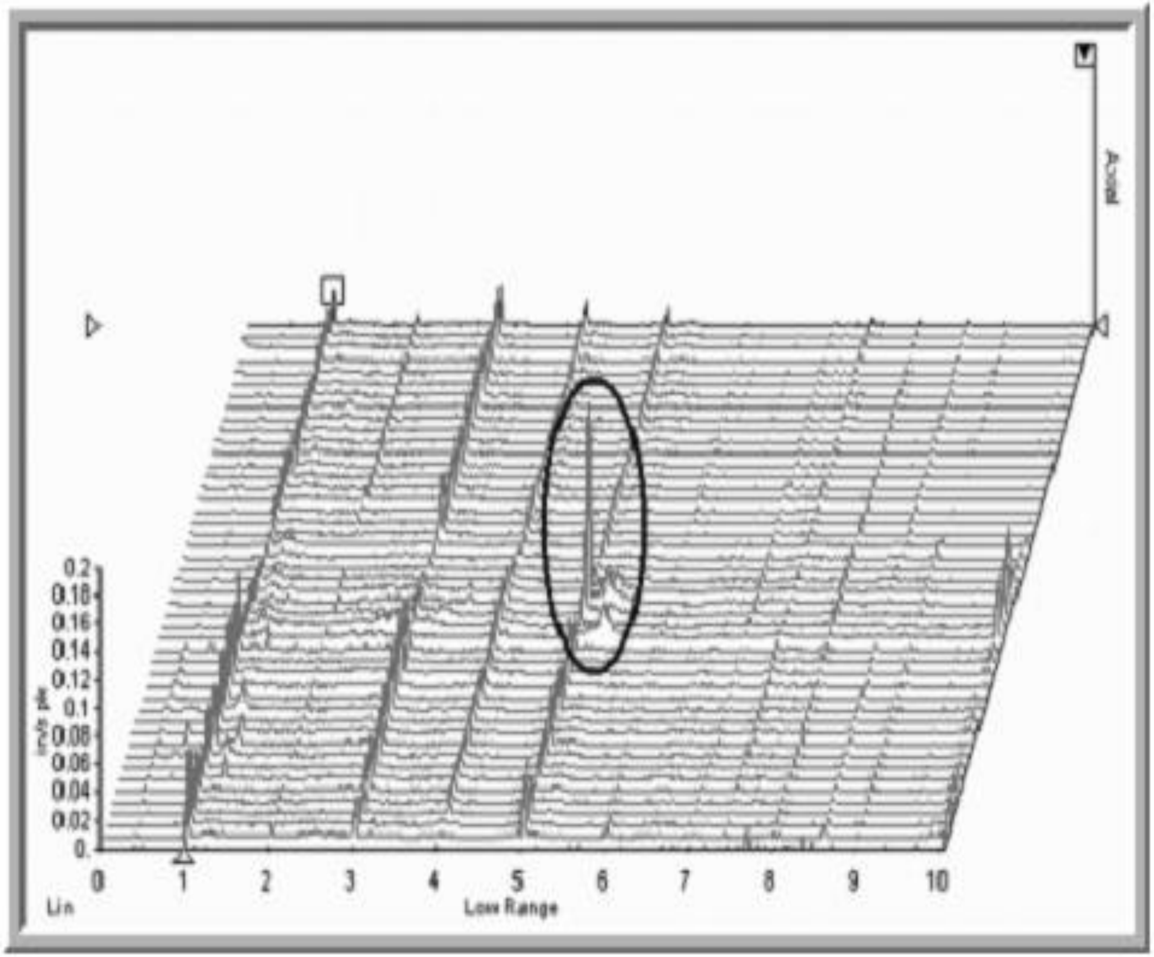


5. Waterfall Plots

A very popular way to study a larger sample of spectra.

This plot is used to show how the peaks and patterns have changed over a period of time.

After a few years of data it is easy to see where faults have begun to develop and then disappear after the fault was dealt with.

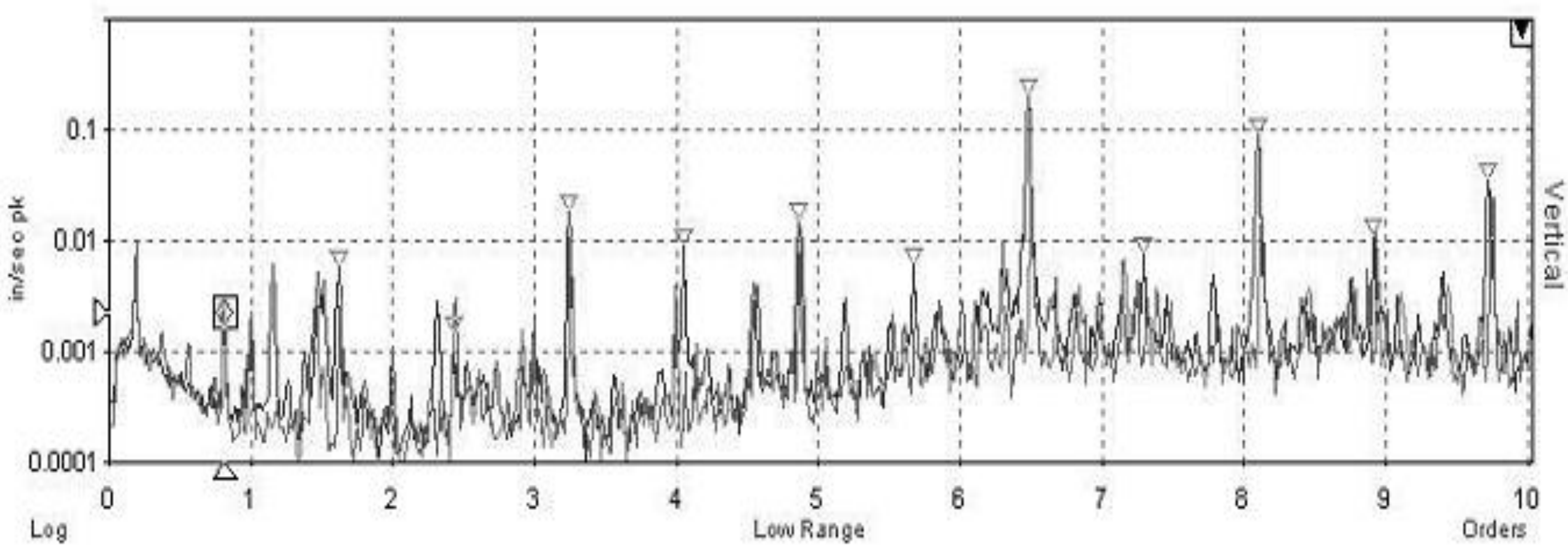


6. Logarithmic Displays

Logarithmic graph scale is often used to highlight harmonics, sidebands, and other patterns in the data.

logarithmic scale displays small amplitudes in the presence of large amplitudes.

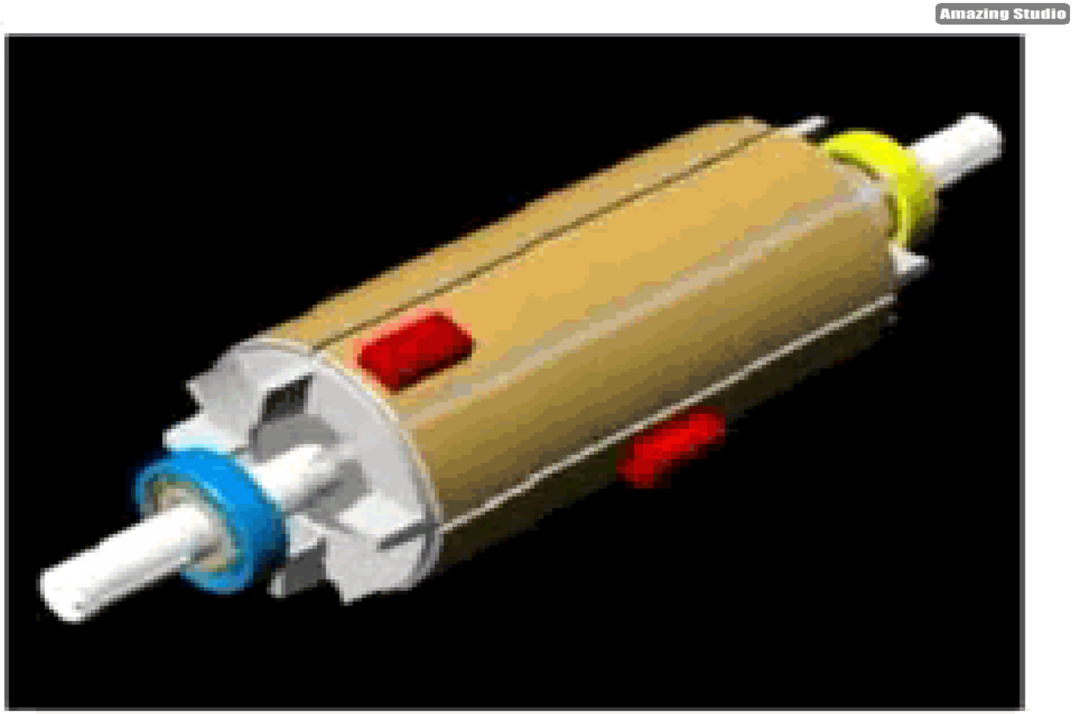
logarithmic scaling is also useful when performing graphical comparisons between two sets of data.



Machine Fault Diagnostics

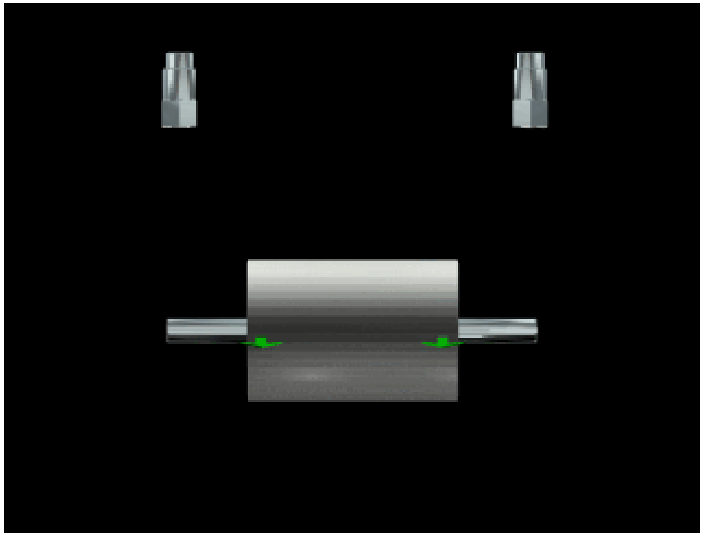
Imbalance

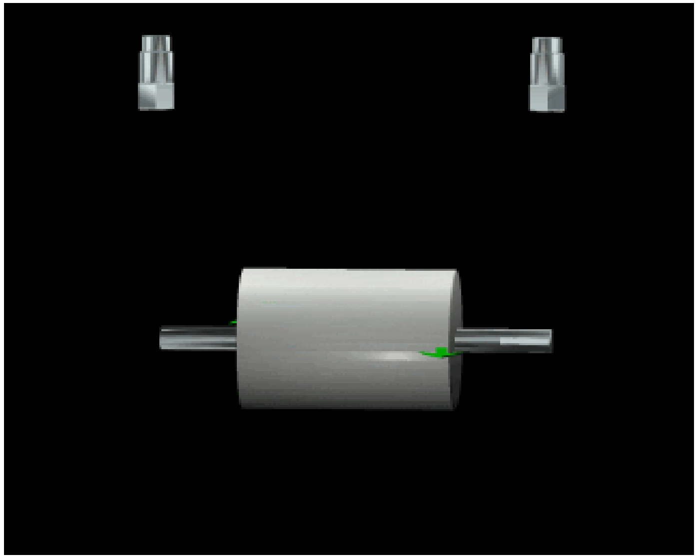
- **Unbalance is a condition where a shaft's geometric centerline and mass centerline do not coincide.**
  - Another way to describe it is that the center of mass does not lie on the axis of rotation.

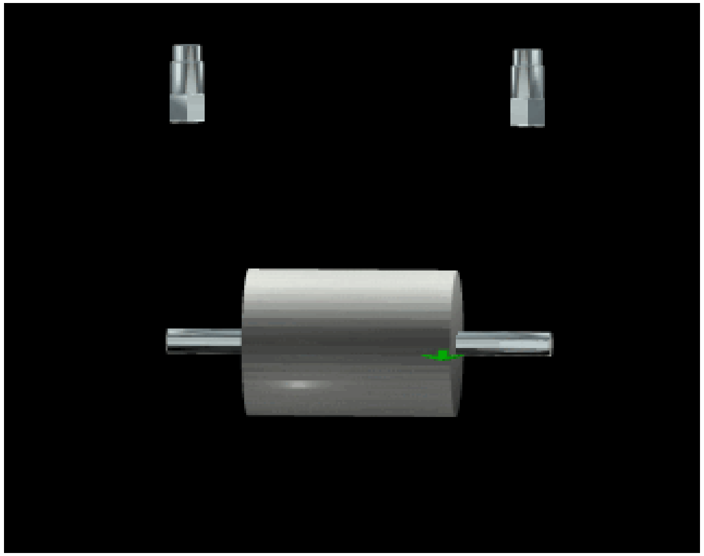


Imbalance (Types)

- **Types of Unbalance**
  - Static Unbalance
  - Couple Unbalance
  - Dynamic Unbalance







Imbalance

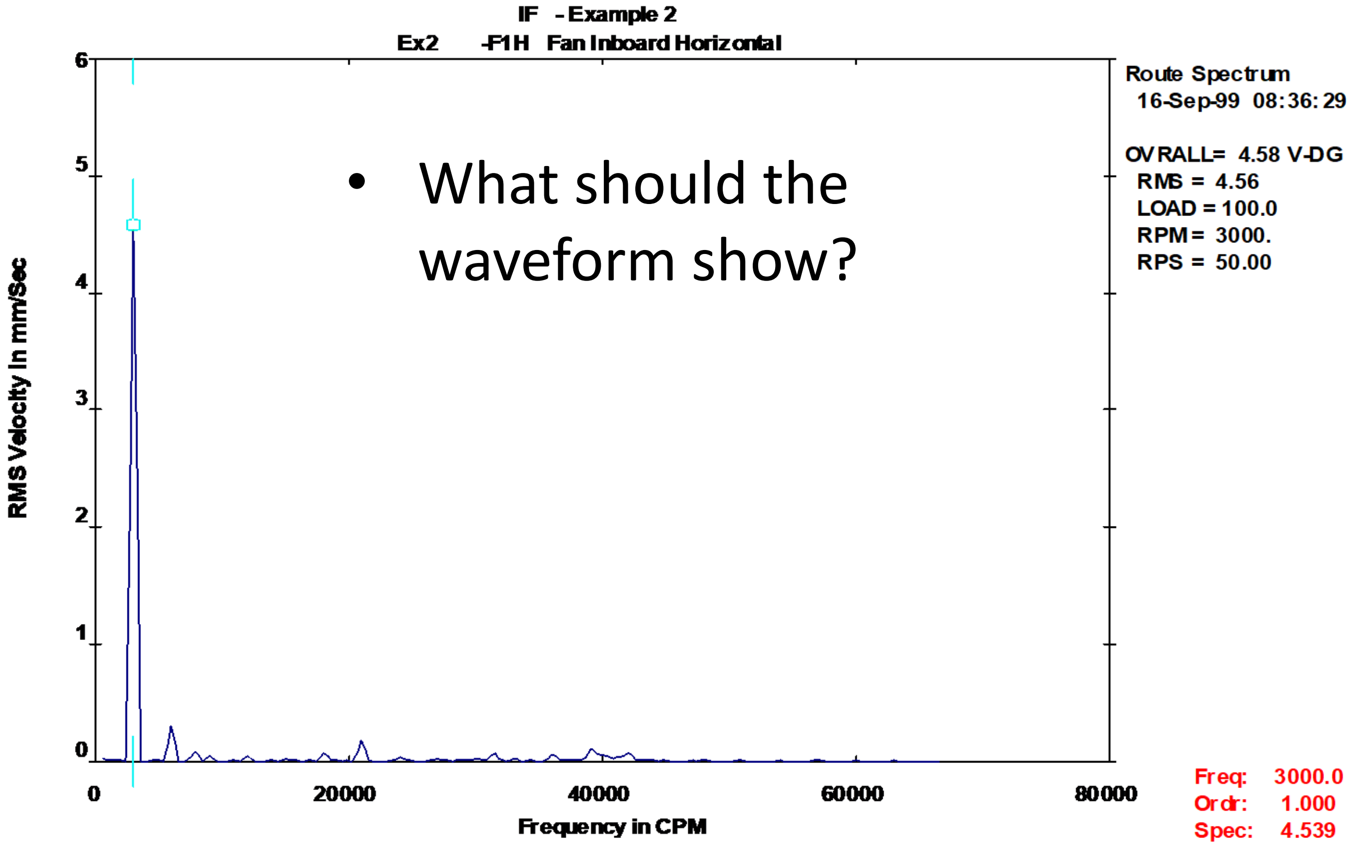
- **Causes of Imbalance**
  - Improper Assembly
  - Material build up / dirt
  - Wear to components
  - Broken or missing parts

All of the above conditions will result in an unbalanced state

- **Diagnostic Rules for Imbalance**
  - Periodic non-impacting sinusoidal waveform
  - Spectral peak at 1xTs (1 Order)
  - Very little axial vibration
  - Similar amplitudes between horizontal and vertical plains
  - Synchronous fault type
  - Amplitudes will increase with speed
  - Very low harmonics of 1xTs

Imbalance Spectral Data

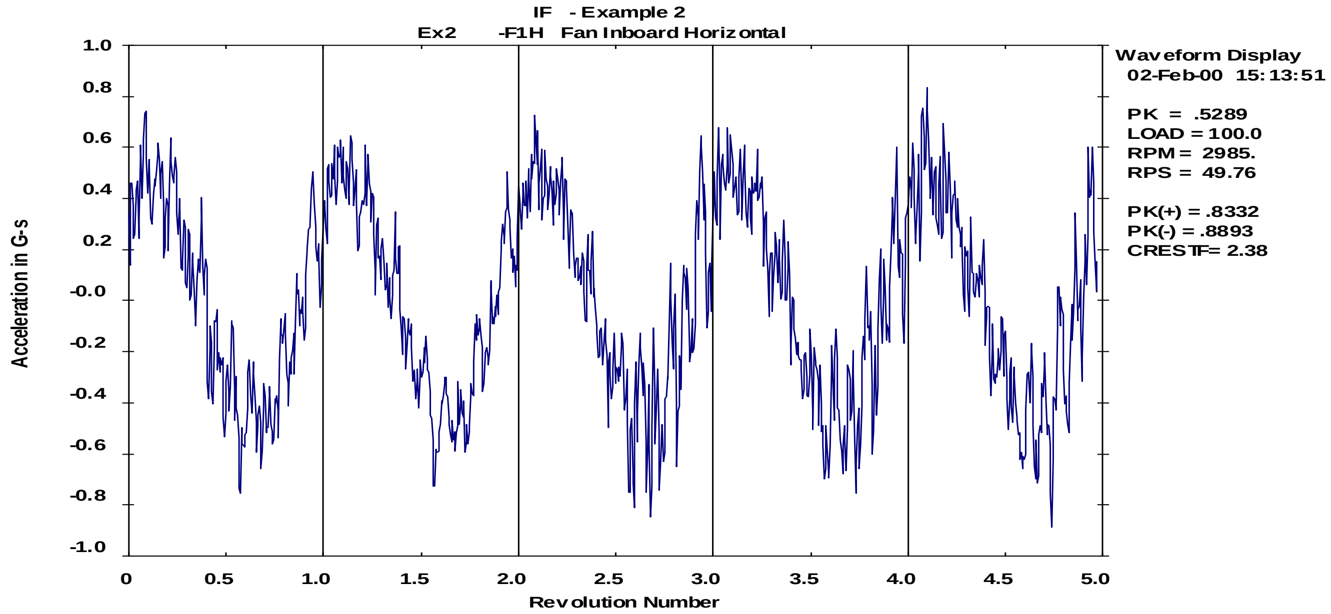
- The spectrum shown represents a simple unbalance state
  - Single peak at 1xTs (1 Order)
  - Little indication of harmonics



- What should the waveform show?

Imbalance Waveform Data

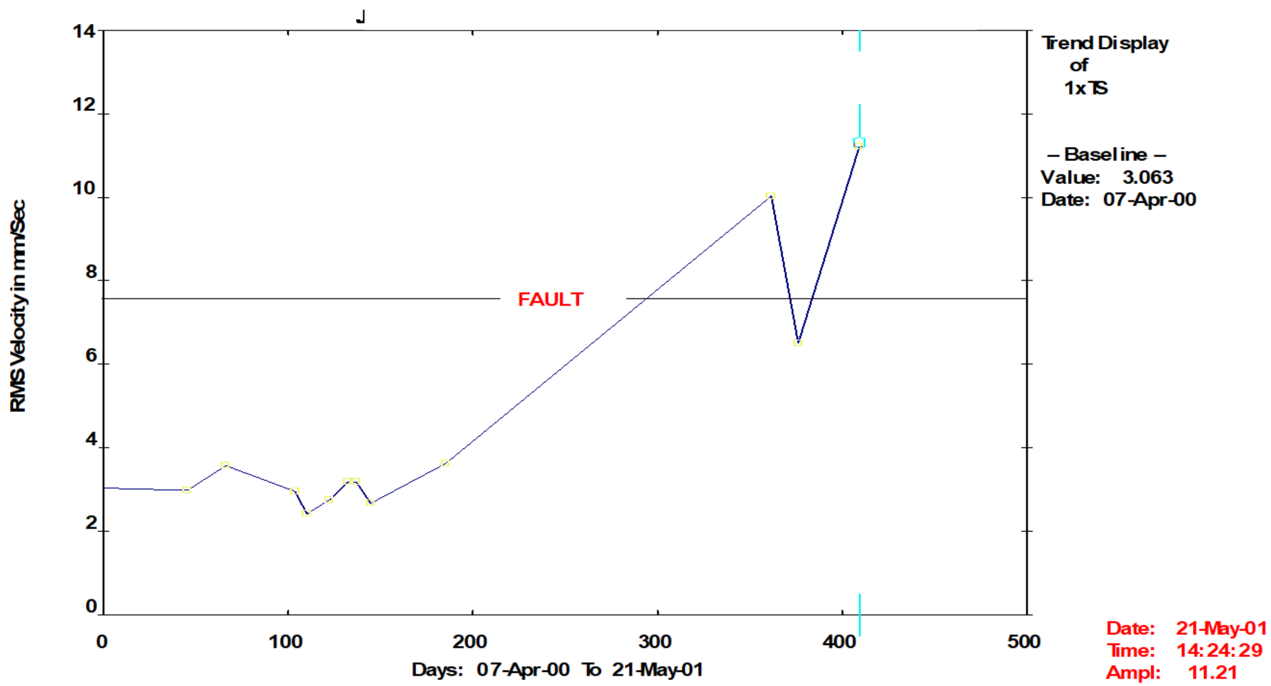
- Despite the waveform being displayed in Acceleration
  - Default unit for route based waveform data
- There is still a predominant sinusoidal waveform pattern
  - 1 x Revolution sine wave



- Changing the units to velocity would reduce the amount of high frequency noise residing on the waveform

Imbalance Trend Data

- The trend data is a good way of determining if there has been a change in condition, as this plots amplitude against time (where time is in days)
- Here the 1xTs parameter is being trended
  - Vibration has been steady at 3mm/sec for a period of time
  - A sudden change instate should alert the analyst to a fault developing

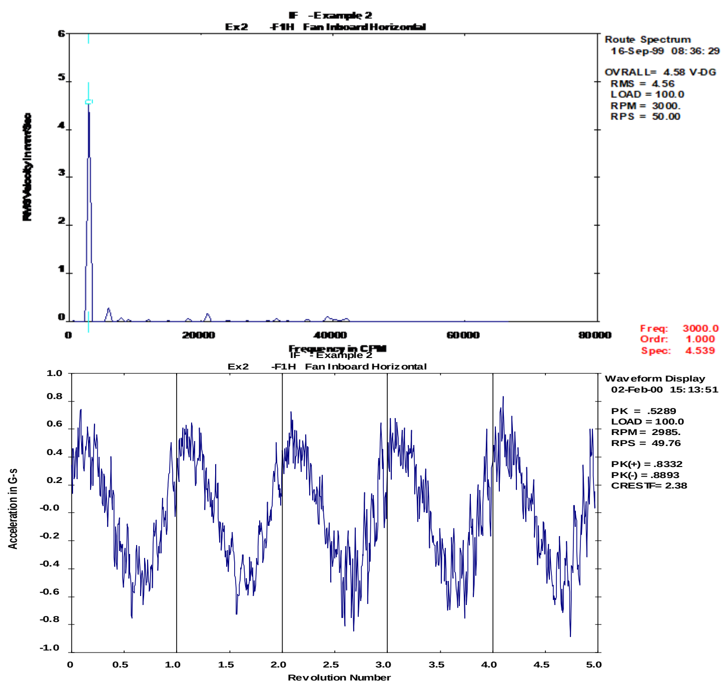


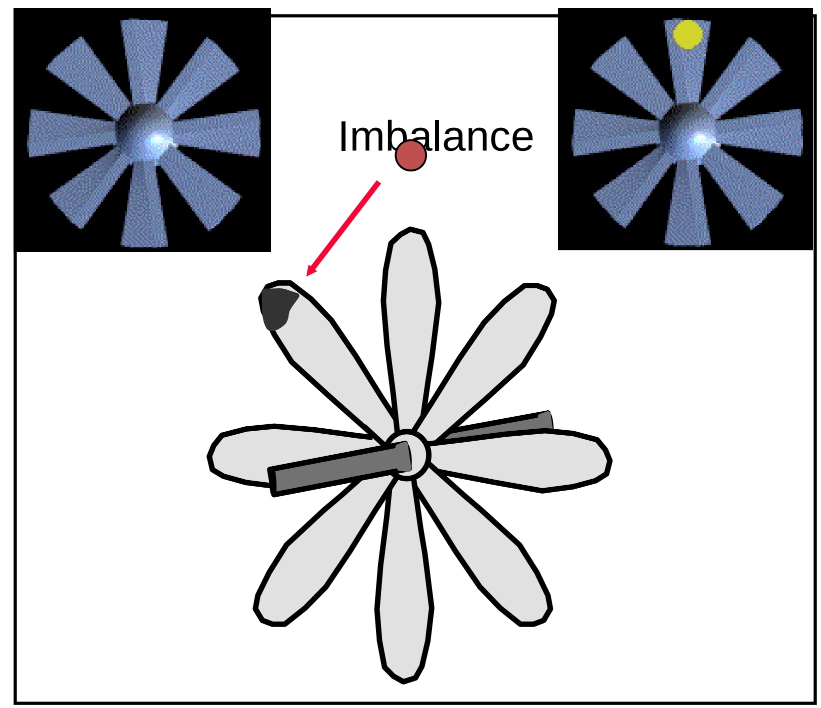
Fault Diagnostics

- Each type of machine *fault* or *defect* reveals a specific vibration *characteristic* in the spectrum and time waveform domain that distinguish that fault from another.
- Simply by gaining a basic knowledge of these patterns and applying a few *rules of thumb* we can start to analyse machine vibration and prevent machine failure.
- This section concentrates the characteristics / patterns and rules that apply to diagnose machine faults such as:
  - Imbalance Misalignment Looseness Gears
  - Bearings *(Peakvue)* Belts Electrical
  - Resonance

Imbalance Problem - Practical

- The following fan unit has an imbalance present on the rotor.
  - 1xTs Peak in the Spectrum
  - 1xTs Peak in the Waveform





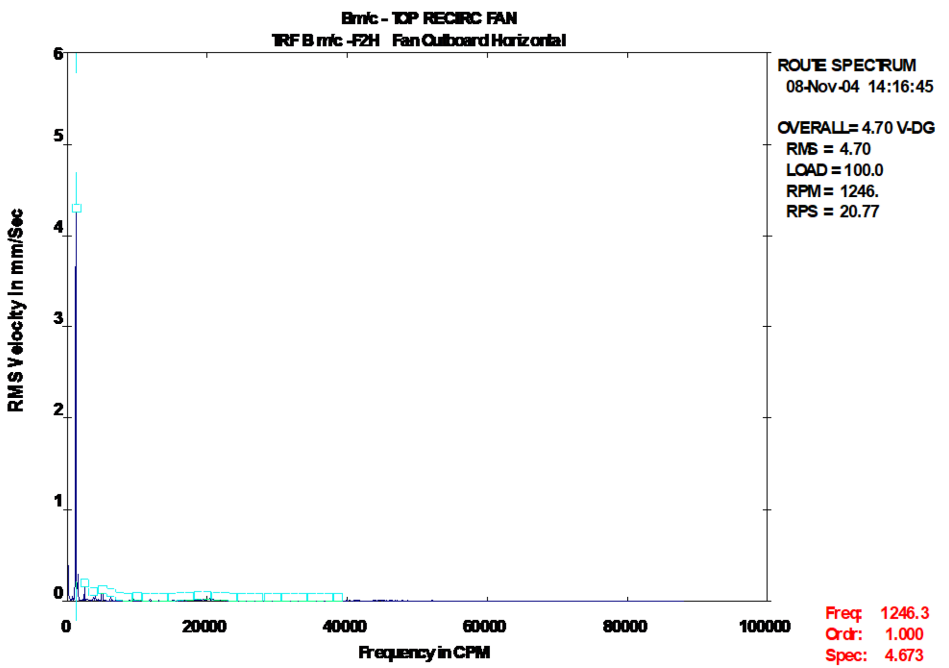
- What would happen to the data if the following occurred to the fan?

Imbalance Case Study 1

Background|:

- The following data is taken from a Recirculation Fan designed to circulate the hot air through an Oven to aid with drying the process. The oven is vertically mounted and the product comes into the oven from the top and exits at the bottom. There is one Recirculation Fan and one Extract Fan. Loss of function from either fan results in the oven being taken offline.

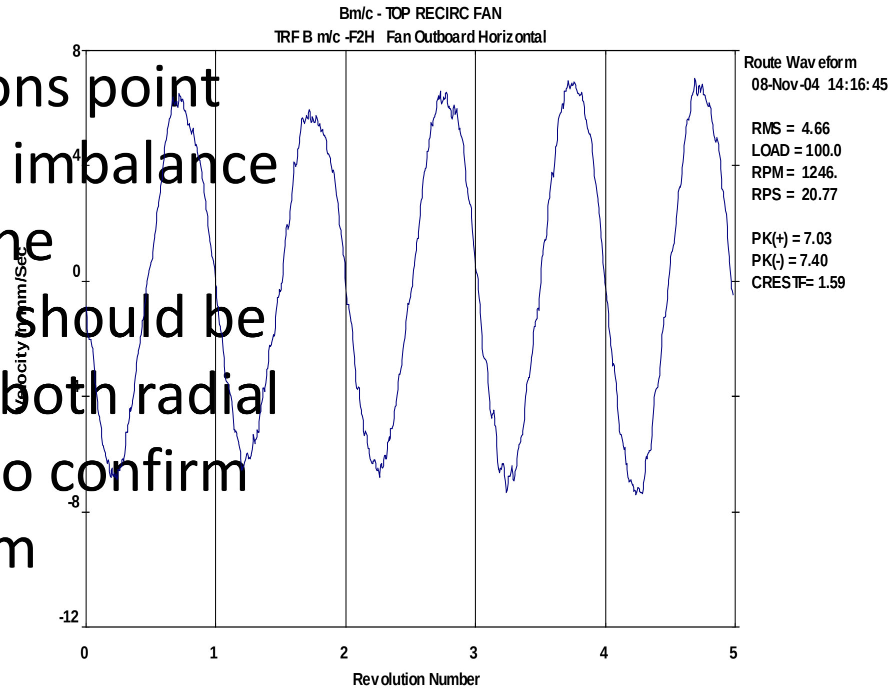
- The spectral plots shows a dominant 1xTs peak (1 Order) with very little other vibration present



Imbalance Case Study 1

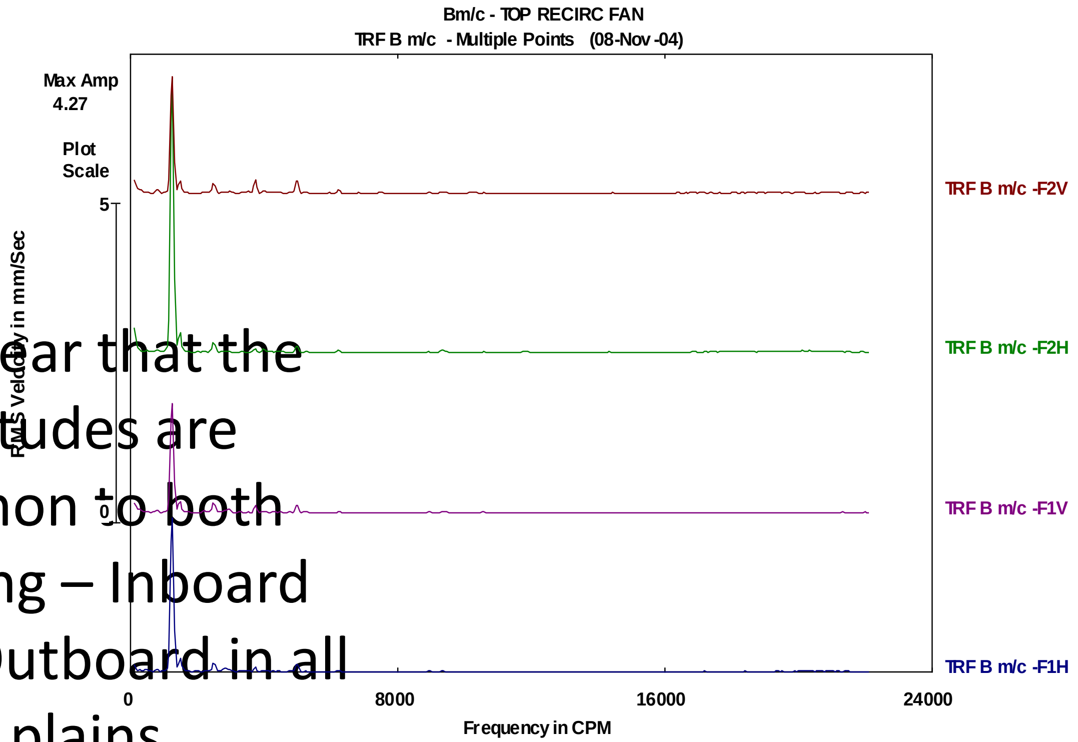
- The waveform from this data shown on the following page represents a sinusoidal waveform clearly shown once per revolution of the shaft – here the waveform is displayed in velocity.

- All indications point towards an imbalance problem. The amplitudes should be checked in both radial directions to confirm this problem



Imbalance Case Study 1

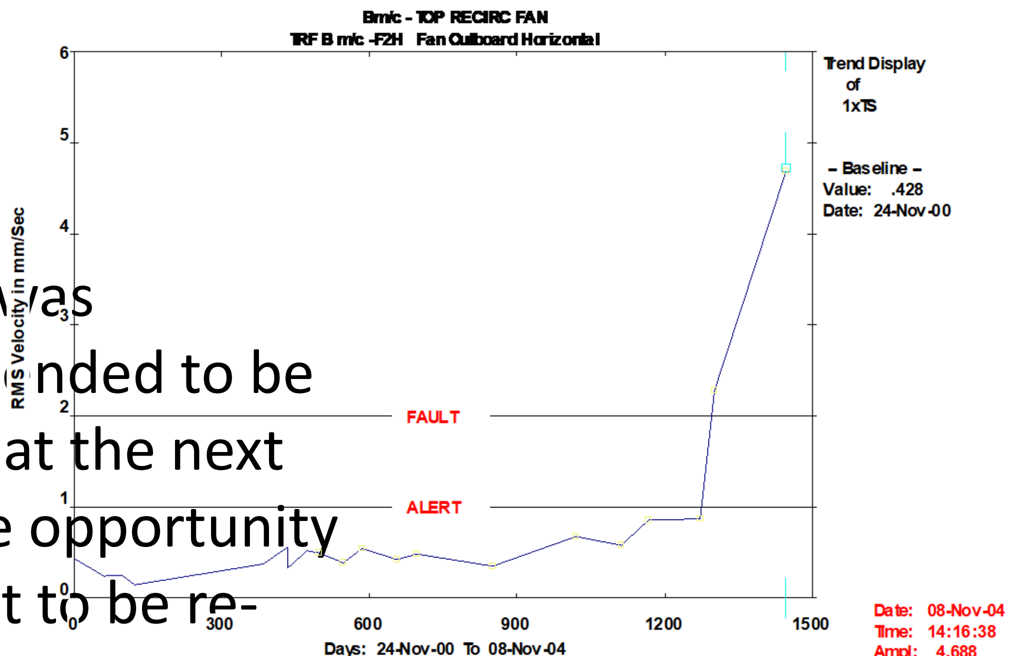
- The plot shown indicates a multi spectral plot showing all the radial directions.



- It is clear that the amplitudes are common to both bearing – Inboard and Outboard in all radial plains

Imbalance Case Study 1

- The trend data for the 1xTs parameter has been steady for a considerable amount of time. The last two readings has shown a significant increase in amplitude



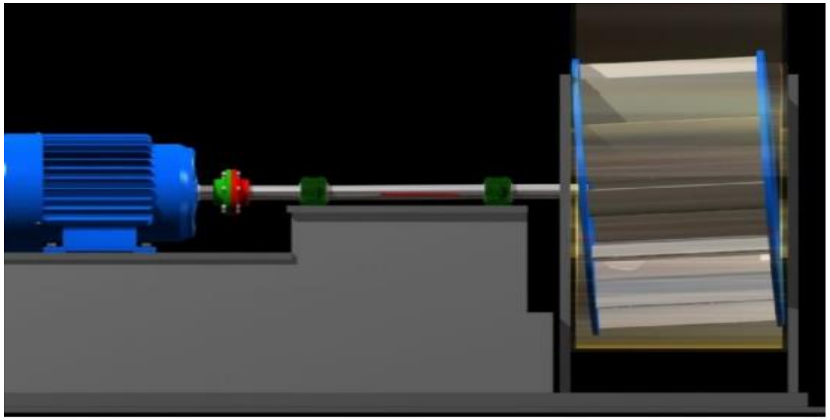
- The fan was recommended to be cleaned at the next available opportunity and for it to be re-tested afterwards

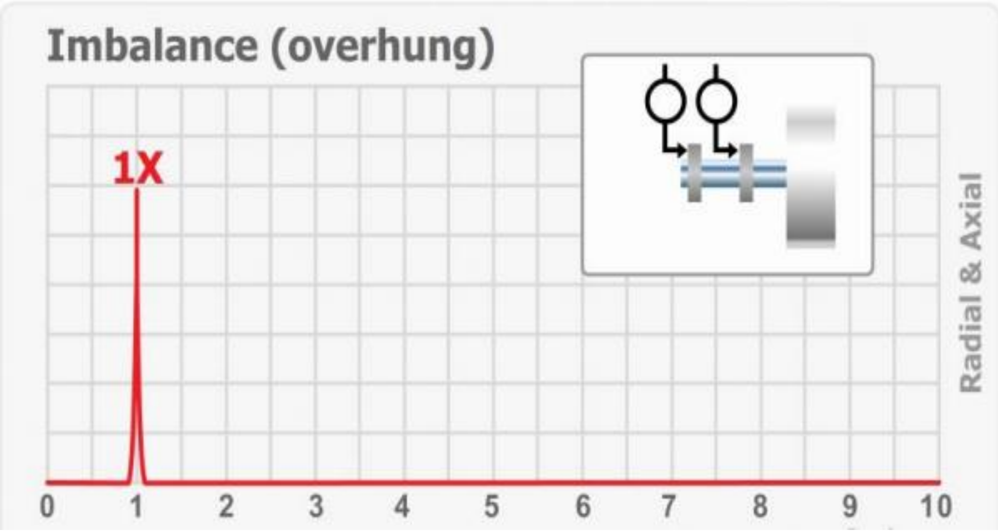
Imbalance Summary

- **Diagnostic Rules for Imbalance**
  - Periodic non-impacting sinusoidal waveform
  - Spectral peak at 1xTs (1 Order)
  - Very little axial vibration
  - Similar amplitudes between horizontal and vertical plains
  - Synchronous fault type
  - Amplitudes will increase with speed
  - Very low harmonics of 1xTs

Overhung Rotor unbalance

- **Diagnostic Rules**
  - High vibration at 1xTs (1 Order)
  - High in radial and axial direction
  - Measurement should be taken from the bearing closest to the overhung impeller
  - Phase reading will be ”0” degree in axial direction

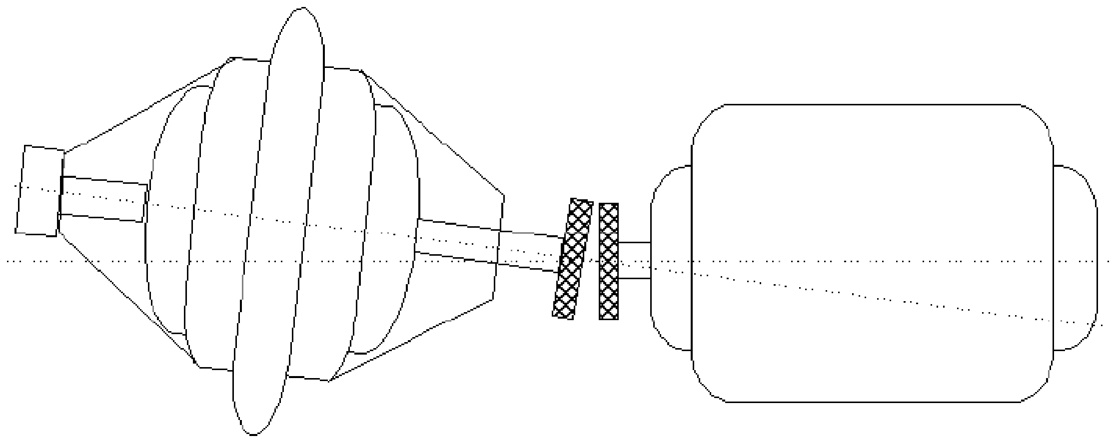




Misalignment

Misalignment

- When two mating shafts do not share the same collinear axis then misalignment is induced.



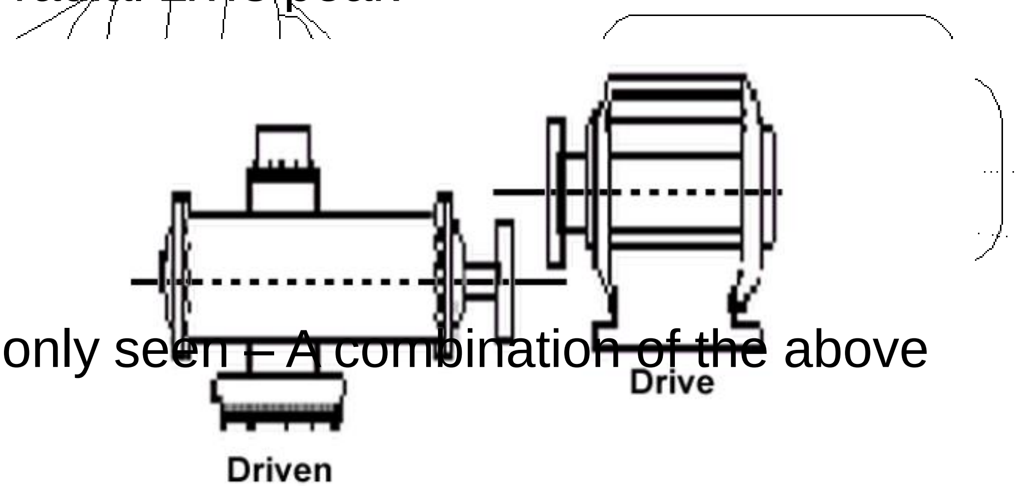
- Misalignment is one of the primary reasons for premature machine failure. The forces that are exerted on the machine and its components when in a misaligned state are greatly increased from normal operating conditions

Misalignment

- Misalignment can be broken into three basic categories, these are:

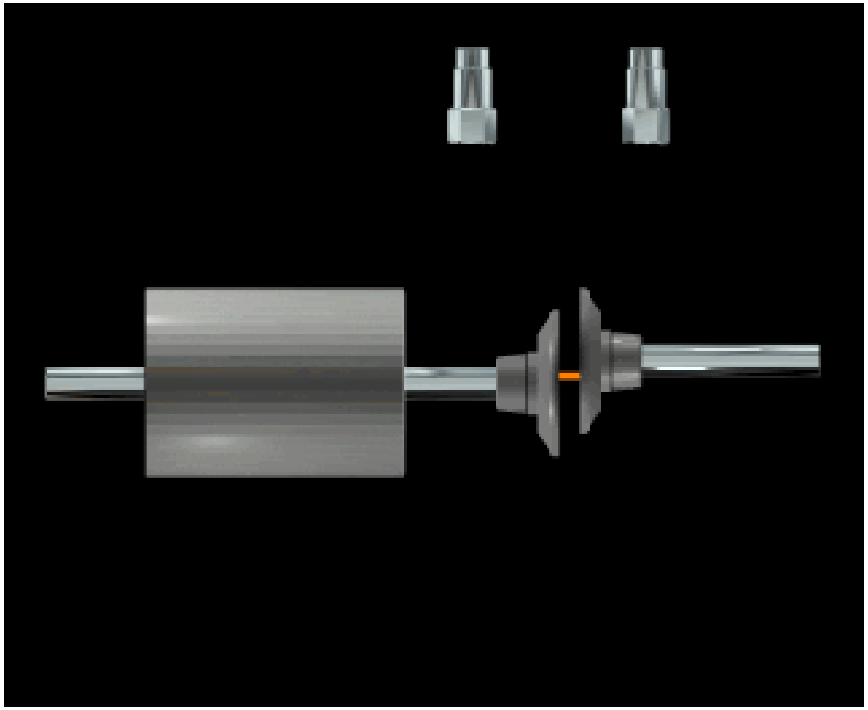
- Angular – Where the shaft centrelines cross producing a 1xTs peak axially

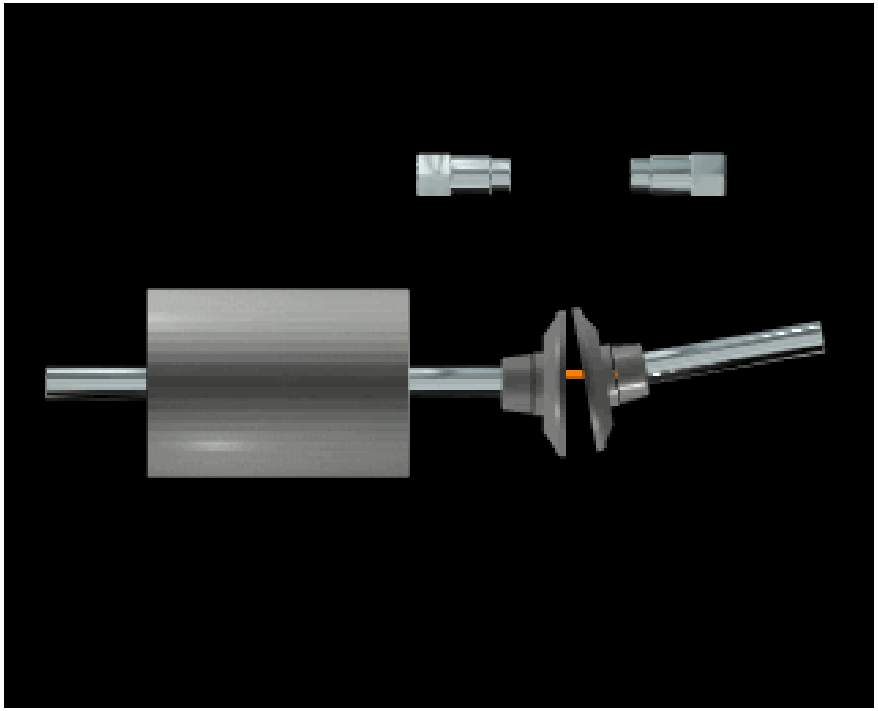
- Offset – Where the shaft centrelines are parallel but they do not meet producing a radial 2xTs peak



- More commonly seen – A combination of the above

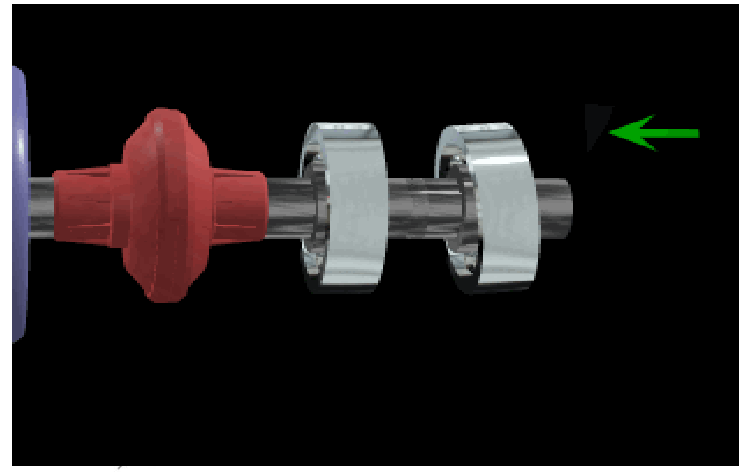
Misalignment

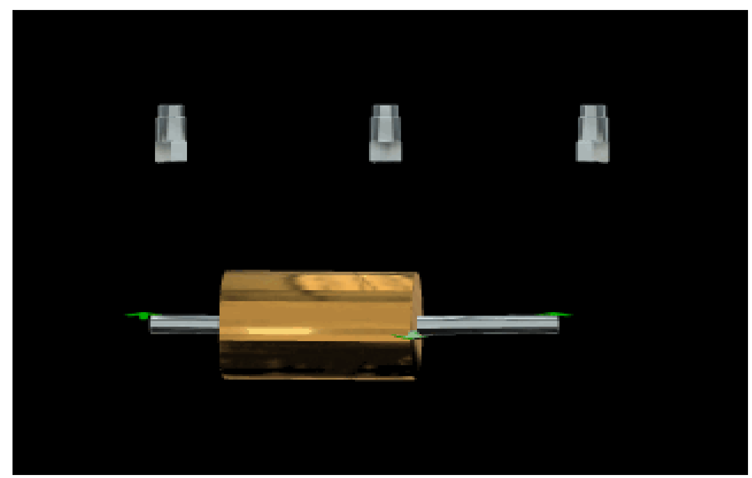




Misalignment

- Another common problem associated with alignment is ‘bearing misalignment’.
- Bearing misalignment occurs when the bearings are not mounted in the same plain possibly due to:
  - one or more of the bearings being cocked in the housing
  - The machine itself distorts due to thermal growth or soft foot conditions
  - Misalignment at the drive causes shaft bending.





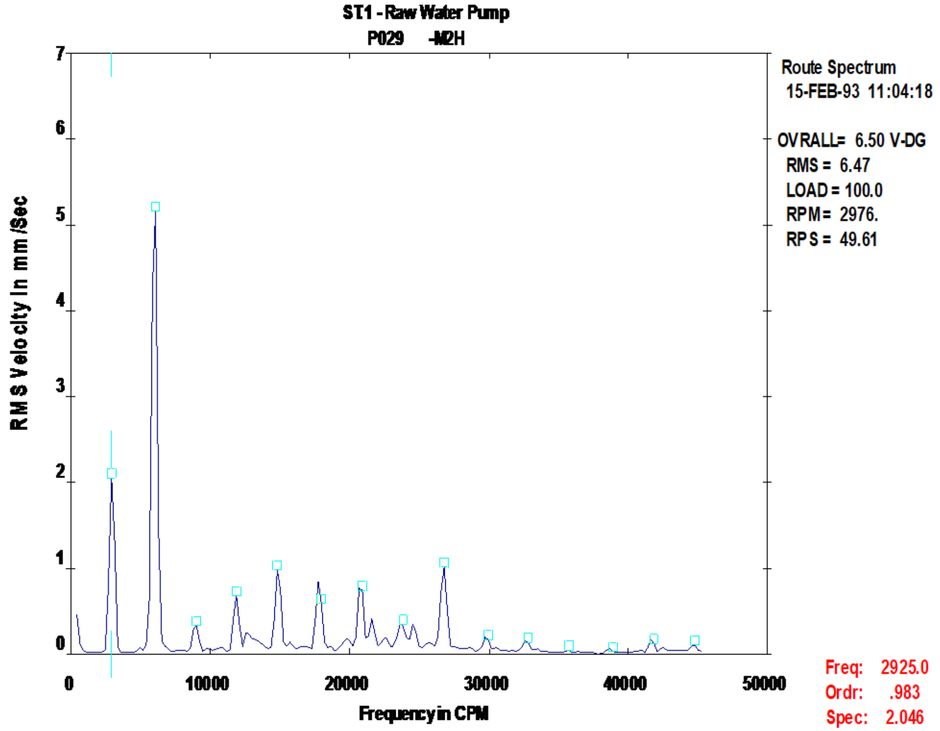
Misalignment

- **Diagnostic Rules for Misalignment**
  - High axial levels of vibration at 1xTs
  - High radial levels of vibration at 2xTs
  - Repeatable period sine waveform showing 1 or 2 clear peaks per revolution (Most likely “M” or “W” shape)
  - Data can usually be seen across the coupling

- Diagnostic Rules for Bearing Misalignment
  - High levels of vibration at 1xTs and 2xTs
  - Repeatable periodic sine waveform showing 1 or 2 clear peaks per revolution
  - Data usually shown either the driver or driven component

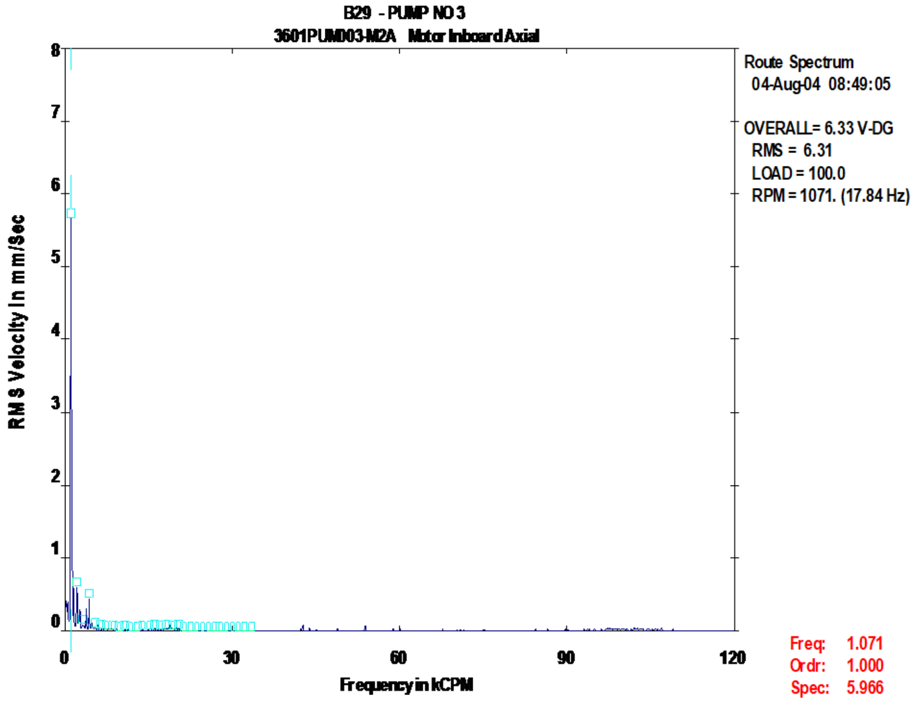
Offset Misalignment Spectral Data

- The spectral data shown represents a simple misalignment plot.
  - The primary cursor denotes the 1xTs peak while the harmonic cursors indicate a larger 2xTs peak. This type of data is common to that of Offset Misalignment



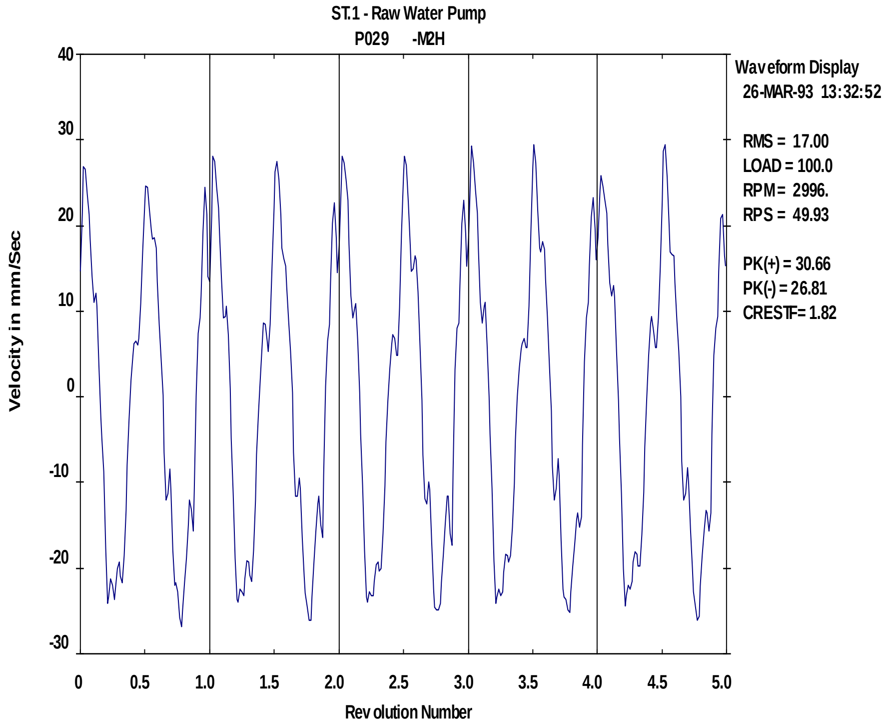
Angular Misalignment Spectral Data

- The spectral data below represents a simple misalignment plot.
  - The primary cursor denotes the 1xTs peak while the data was taken in the axial direction. This type of data is common to that of Angular Misalignment



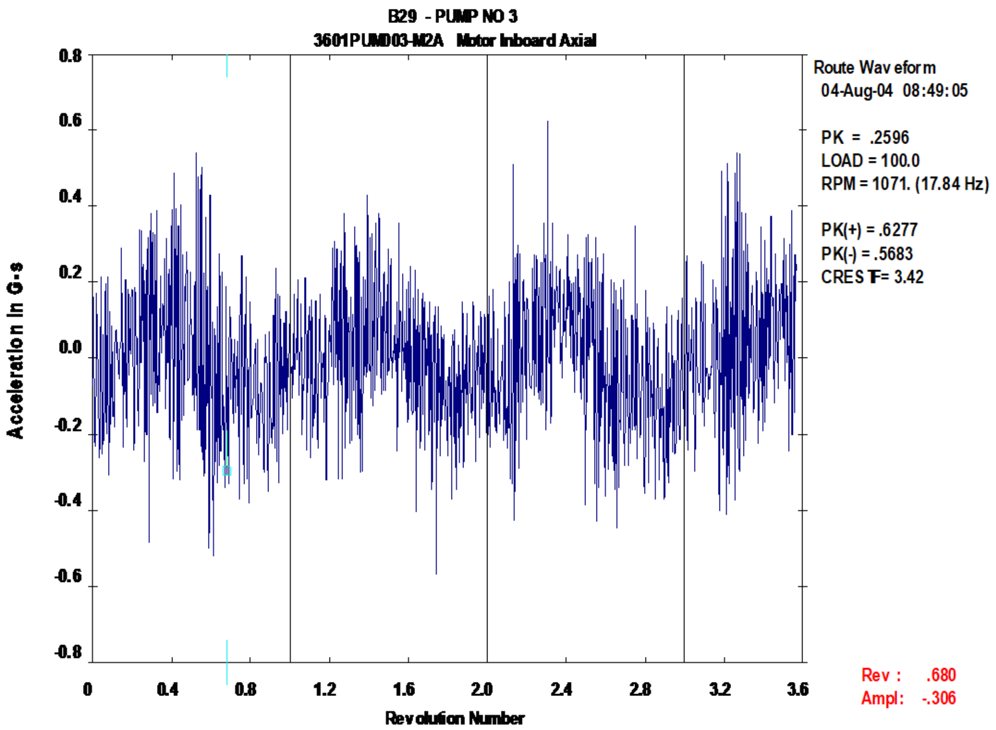
Offset Misalignment Waveform Data

- The waveform above is showing two clear peaks per revolution of the shaft. This type of waveform resembling an ‘M’ or ‘W’ shape is common to offset misalignment.
  - Data shown in velocity



Misalignment Waveform

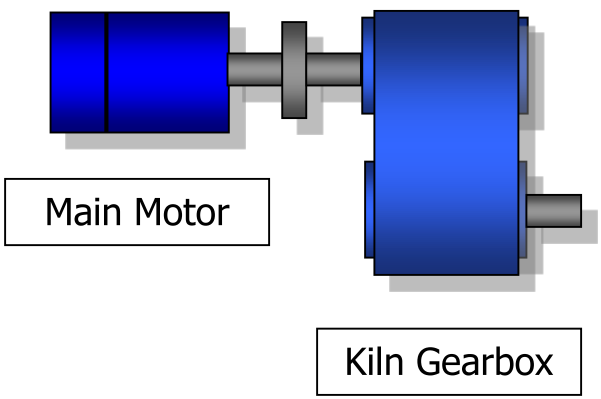
- The waveform data shown above is predominantly showing one sinusoidal waveform per revolution of the shaft.
  - Here the data is shown Acceleration



Case Study 2 – Kiln Main Motor Gearbox

Introduction:

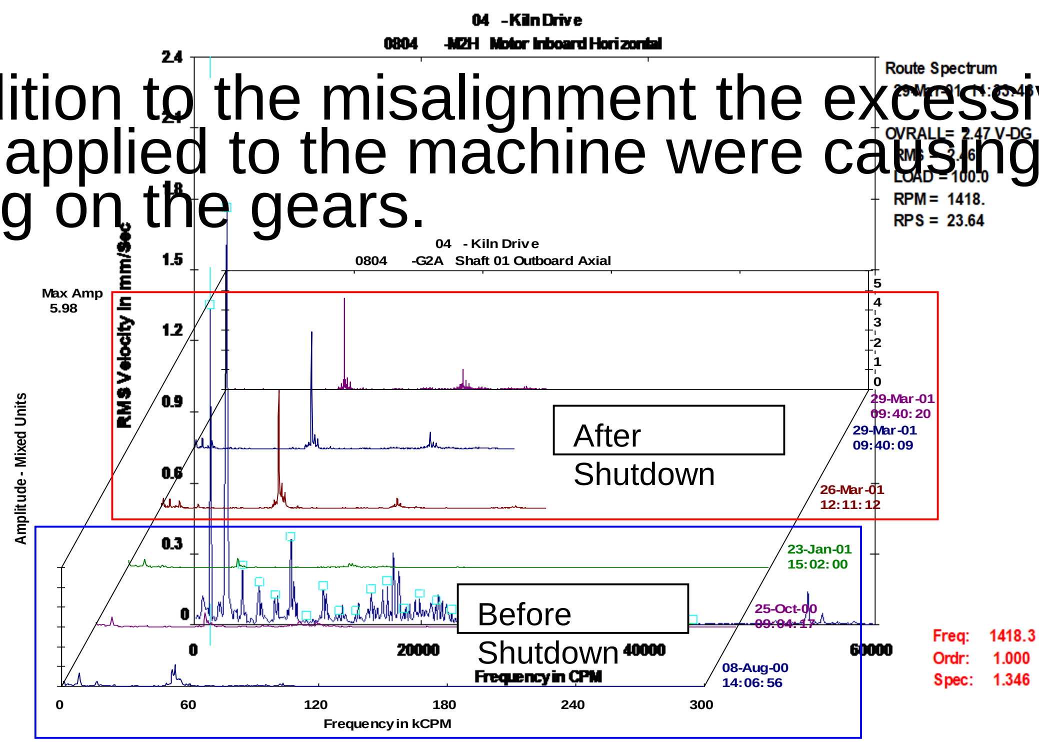
- The Kiln drive gearbox motor had been replaced during a planned plant shutdown.
- During the start up of the plant after the shutdown it was noted that the motor and gearbox were excessively noisy. Vibration data was taken during the run up of the plant to determine the cause of the problem.



Case Study 2 – Kiln Main Motor Gearbox

- The spectral plot shown above is the data taken from the drive end of the motor. Here there is a dominant 2xTs peak.

- In addition to the misalignment the excessive forces being applied to the machine were causing excessive loading on the gears.



Case Study 2 – Kiln Main Motor Gearbox

- During data collection it was also observed that the grouting around the front feet of the motor had begun to crack as a result of the excessive force being applied to the motor base and feet due to the misalignment.

Conclusion:

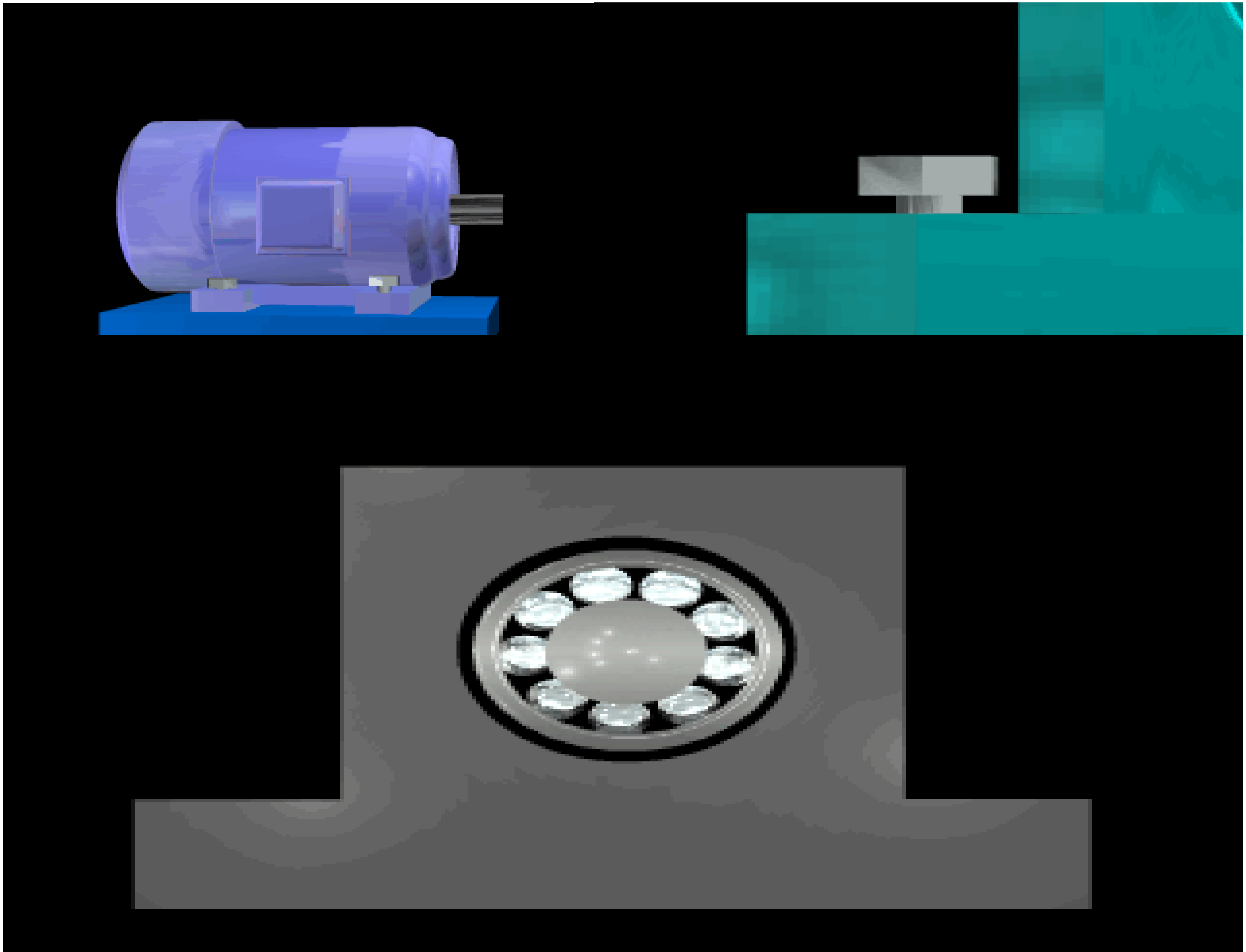
- It was confirmed the engineers that replaced the motor during the shutdown and assumed as long as they kept the shims in the correct place then alignment was not necessary.
- Corrective action was required and production was stopped so the motor could be re-aligned and the mountings re-secured.

Misalignment Summary

- **Diagnostic Rules for Misalignment**
  - Periodic non-impacting sinusoidal waveform with 1 or 2 clear peaks per revolution (Most Likely “M” or “W” shape)
  - Spectral peak at 1xTs and 2xTs
  - Axial vibration at 1xTs
  - Synchronous fault type
  - Data can be seen across the coupling or across the component itself

Looseness

How would looseness ?



Looseness

- Looseness can be broken down into two main categories, ***Structural*** and ***Component***
- **Structural** looseness occurs when there is free movement within the machines support structure causing excessive vibration. This can be a result of:
  - Loose support bolts to the components feet and supports
  - Cracked welds
  - Deterioration of the base itself.
- **Component** looseness generally occurs when there is excessive clearance to the components within the machine, such as:
  - Excessive clearance between the shaft and bearings
  - Excessive clearance between the shaft and an impeller etc.

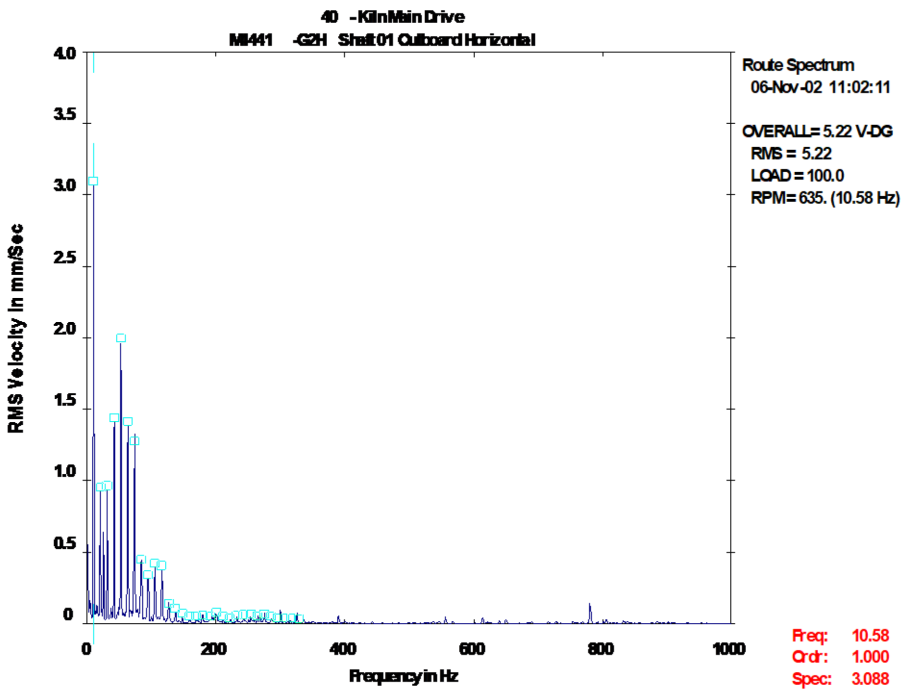
Looseness

Diagnostic Rules for Looseness:

- Multiple harmonics of the 1xTs peak - Structural
- Multiple Harmonics of the component that is loose - Component
- Number of harmonics will increase as the looseness progresses
- Random, non-periodic waveform - Structural
- Waveform shows predominant impacts - Component
- Raised noise level around the 1xTs + harmonics
- Half harmonics may also be present
- Can be present in all Directions

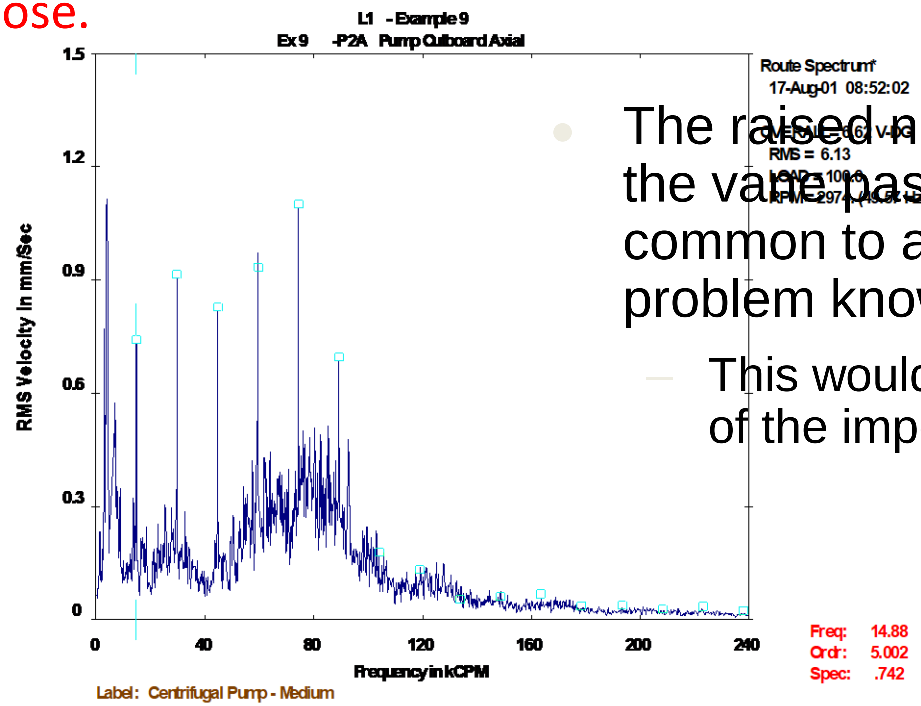
Looseness Spectral Data (Structural)

- The spectral plot shown is demonstrating Looseness.
  - The 1xTs peak has been highlighted by the primary cursor and the relevant harmonics have been displayed.
  - Multiple harmonics of 1xTs are shown up to around 10 orders of 1xTs.



Looseness Spectral Data (Component)

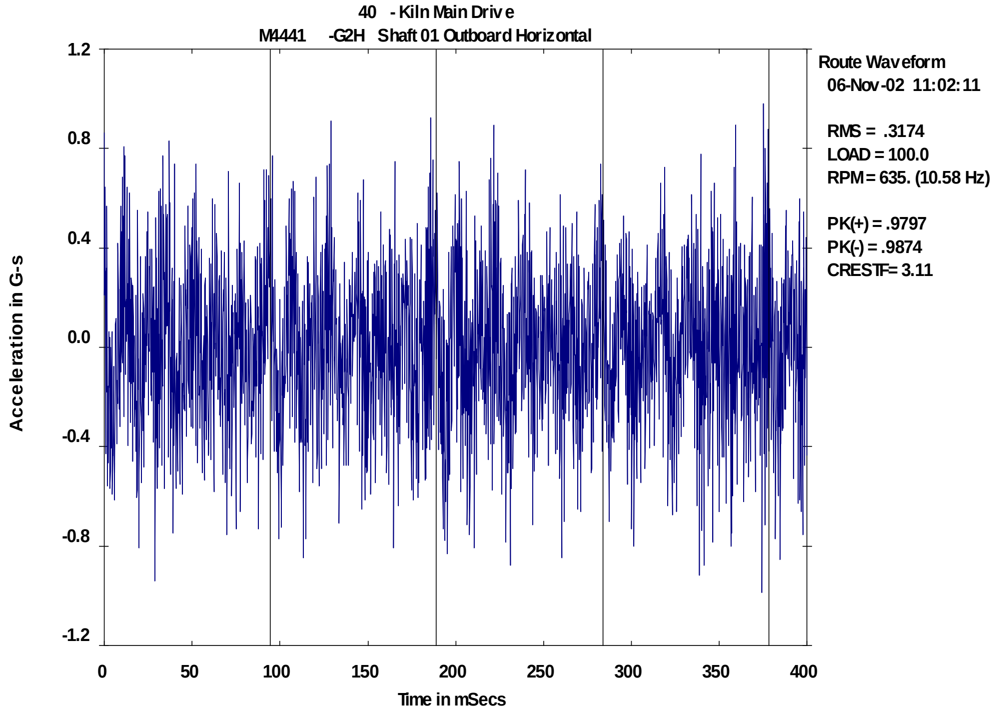
- The spectral plot shown is demonstrating rotational Looseness.
  - The primary cursor is on 5xTs peak
    - The 5 Order peak is vane pass frequency (5 vanes on the impeller)
  - Multiple harmonics of 5xTs are shown indicating the impeller has come loose.



- The raised noise level around the vane pass frequency is common to a pumping problem known as Cavitation
  - This would be the likely cause of the impeller problem

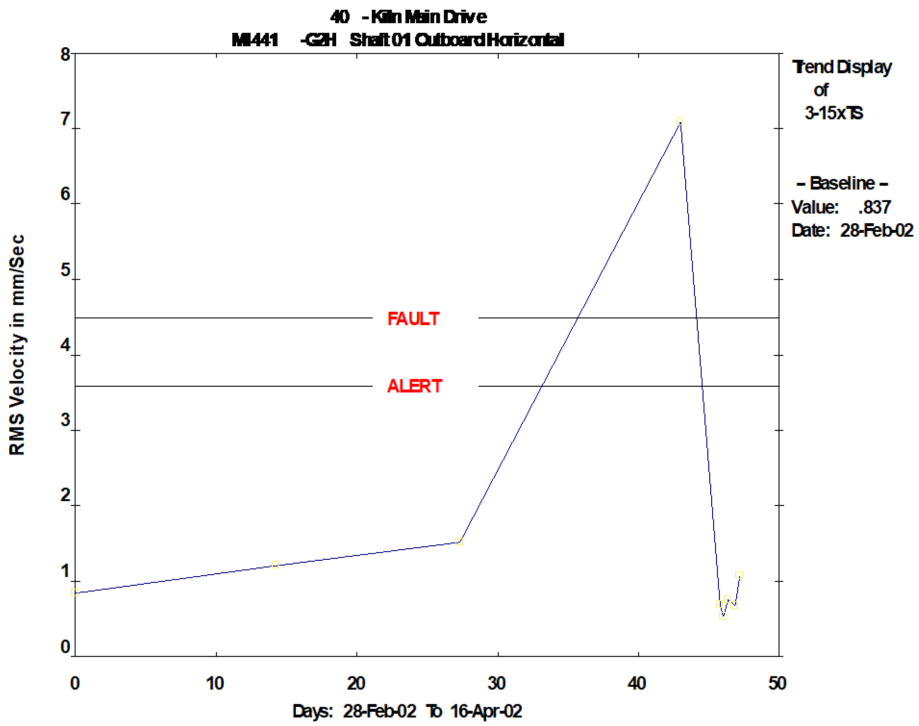
Looseness Waveform Data

- Here the waveform is demonstrating a lot of energy and appears to be more random and non-periodic.
  - Displaying the waveform in velocity may help to show the random non-periodic pattern.



Looseness Trend Data

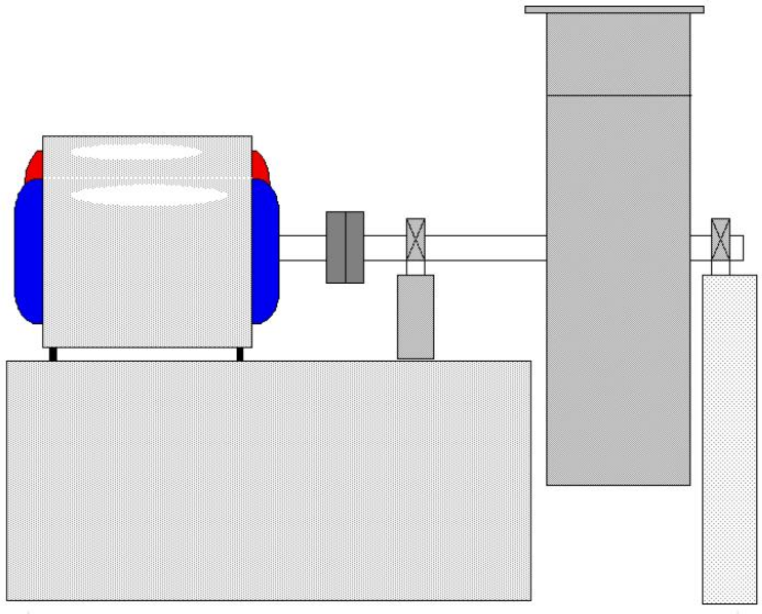
Here the trend plot is showing the parameter labelled as the 3-15xTs. This is measuring the amount of energy from 3 orders to 15 orders, which is where the harmonics of looseness will appear.



Case Study 3 – Reciprocator Fan

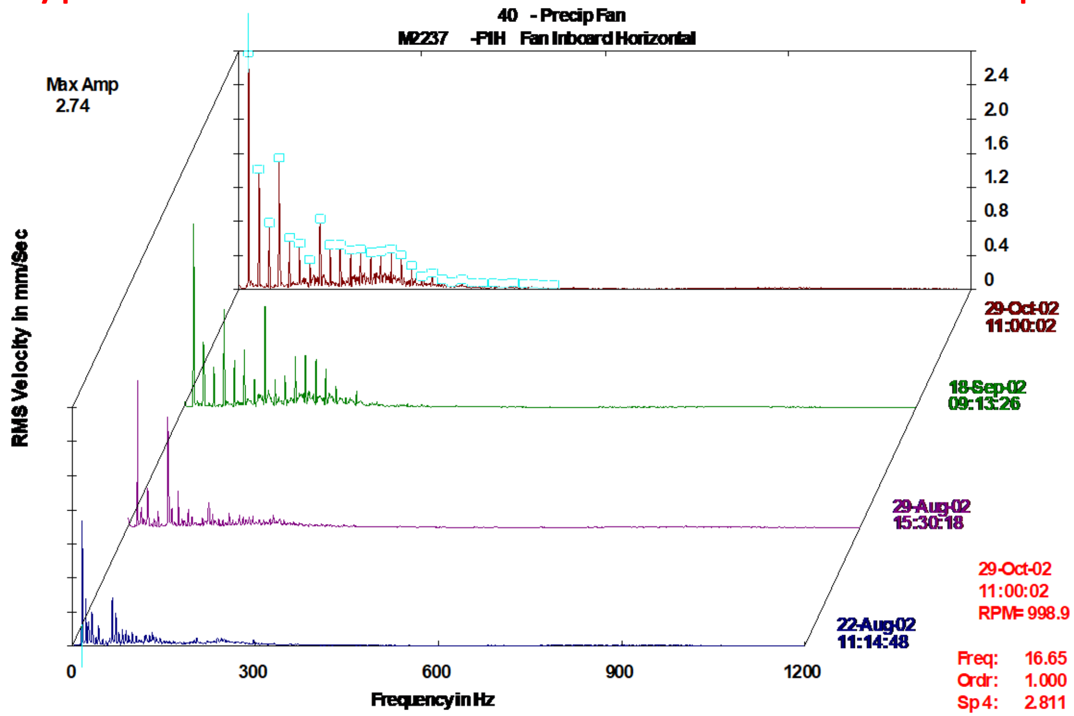
Introduction:

- Data had been collected on the following fan for several months as part of a routine periodic vibration data collection. During a routine visit to the machine it was observed that there was a lot of low frequency activity showing around the bearing on the inboard of the fan (F1H)



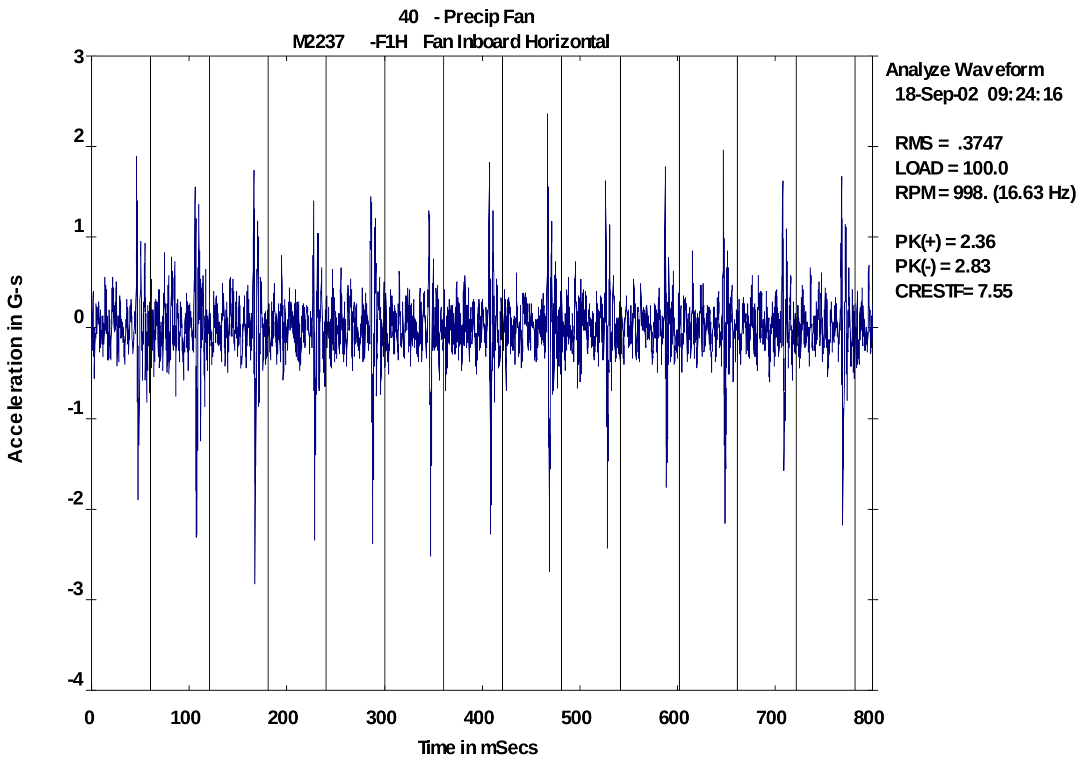
Case Study 3 – Reciprocator Fan

- The multiple plots shown above indicate the change over time from the data taken on F1H.
  - It is quite apparent that the data shown here is indicating multiple harmonics of the 1xTs frequency (the rise energy as you move further away from the 1xTs).
  - This type of data is common to that of a looseness problem.



Case Study 3 – Reciprocator Fan

- The waveform data taken for this particular point is not showing a random type of waveform pattern which you would expect from **Structural** looseness, but there is a more a repeatable (timed interval) pattern.



Case Study 3 – Reciprocator Fan

- This type of waveform would more be indicating **Component** looseness and may indicate a problem with a loose bearing.

Conclusion:

- It was recommended that the bearing should be inspected at the next available opportunity.
  - Upon inspection it was found that the bearing was a ‘Taper-Lock’ bearing and the taper lock was loose, thus resulting in excessive clearance between the bearing and the rotor.

Looseness Summary

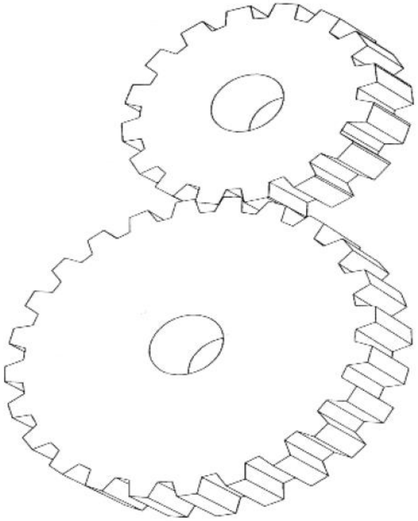
Diagnostic Rules for Looseness:

- Multiple harmonics of the 1xTs peak
- Number of harmonics will increase as the looseness progresses
- Random, non-periodic waveform – Structural
- Waveform shows predominant impacts - Component
- Raised noise level around the 1xTs + harmonics
- Half harmonics may also be present
- Can be present in all Directions

Gear Box Faults

Gear Defects

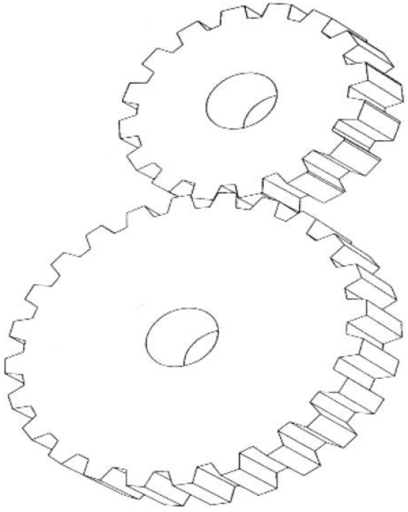
- There are many different types of gears and gear combinations available for various speed and power requirements.
- Regardless of gear type they all produce the same basic vibration patterns and characteristics when a defect is present



- The following topic will discuss the basic characteristics for the following types of gears:
  - Spur Gears
  - Helical Gears
  - Bevel Gears

Spur Gears

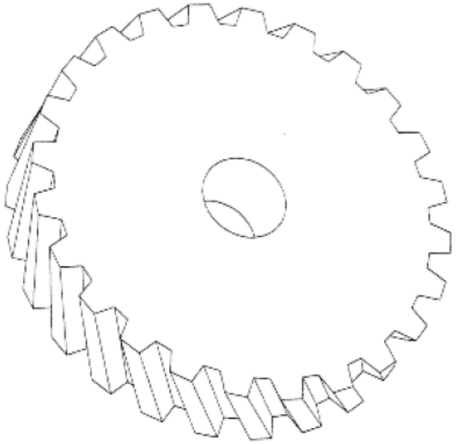
- ***Spur Gears*** are most commonly thought of when diagnosing gears. The teeth are cut parallel to the shaft. These gears are good at power transmission and speed changes but are noisier than other gear types.



- ***Spur Gear Advantages***
  - High efficiency
  - Low heat generation
- ***Spur Gear Disadvantages***
  - Can be very noisy

Helical Gears

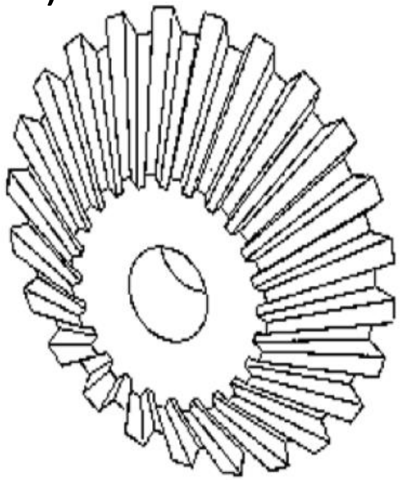
- ***Helical Gears*** have teeth cut at an angle to the shaft. These gears are much quieter than spur gears but due to the angular nature of the gear meshing, axial thrust and therefore axial vibration is higher than those of spur gears
  - Sometimes to counter act the axial thrust these gears can be double up and are known as ‘Double Helical’ or ‘Wishbone Gears’



- ***Helical Gear Advantages***
  - Quiet Operation
- ***Helical Gear Disadvantages***
  - Less power transmission efficiency and greater heat generation than spur gears
  - Axial loading on bearings

Bevel Gears

- ***Bevel Gears*** are used to transmit power and speed to an output shaft perpendicular to the drive shaft. These gears use a bevel design to transmit the power better.
  - These gears are most commonly seen on right angle gearboxes (where the input shaft is at 90 degrees to the output shaft)



- ***Bevel Gear Advantages***
  - Converts the direction of power transmission
- ***Bevel Gear Disadvantages***
  - Less efficient
  - Higher heat generation

Gear Analysis

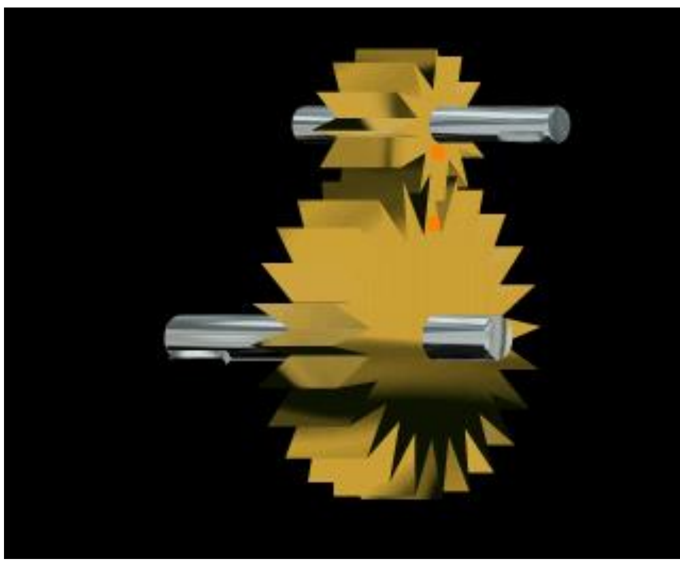
- Vibration analysis of gears can provide a wealth of information about the mechanical health of the gears. This section discusses the basic frequencies that may be present within a gearbox.

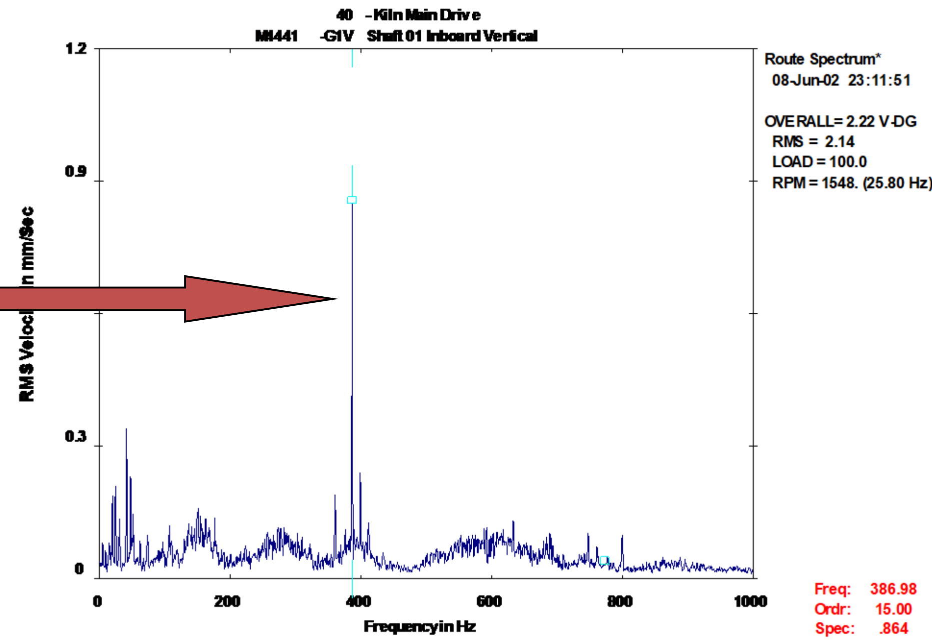
Gear Mesh Frequency Spectral Data:

- The gear mesh frequency (GMF) refers to the frequency at which to mating gears interact with each other and is the most commonly discussed gear frequency.
- However, GMF by itself is not a defect frequency. The GMF should always be present in the spectral data regardless of gear condition. What is important is the amplitude as this may vary depending upon gear condition or loading of the gear.

Gears

Two mating gears will generate a frequency known as the GMF and will show in the spectral data regardless of gear condition.



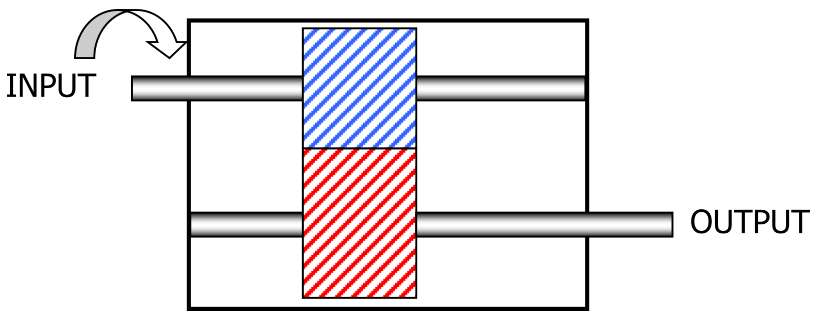


Calculating GMF – Single Reduction

- **Single Reduction Gear Train**
  - The GMF is simply defined as the number of teeth on a gear multiplied by its turning speed

GMF = (#teeth) x (Turning speed)

- **Example:**
  - Consider the following gear train,



Input = 1490RPM

Gear 1 = 44 Teeth

Gear 2 = 71 Teeth

GMF = #teeth x turning speed

GMF = 44teeth x 1490 RPM

GMF = 65560 CPM **or** 65560/60 **= 1092.6 Hz**

Calculating GMF – Multi Reduction

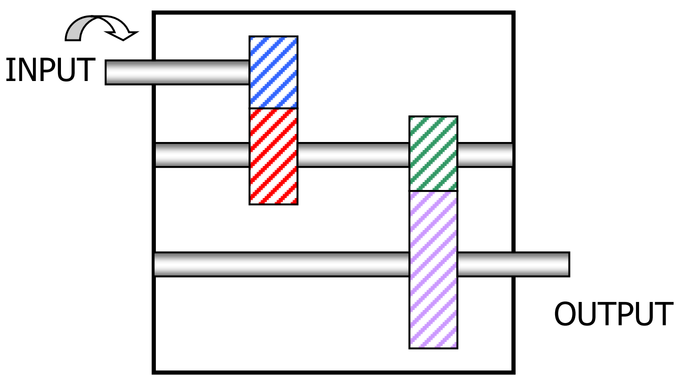
- Calculating the GMF for gearboxes that have multiple trains use the following.

GMF = (#teeth) x (Turning speed)

Gear Ratio = (#teeth in) / (#teeth out)

Speed out = (Speed in) x (Gear Ratio)

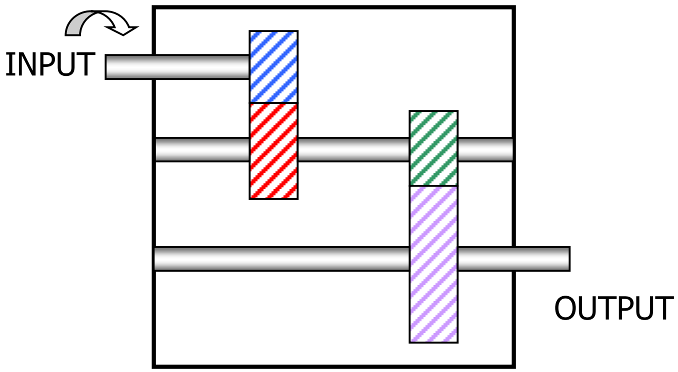
- **Example:**
  - Consider the following gear train:



Input	= 1490RPM
Gear 1	= 15 teeth
Gear 2	= 21 teeth
Gear 3	= 19 teeth
Gear 4	= 54 teeth

[redacted]

Calculating GMF – Multi Reduction



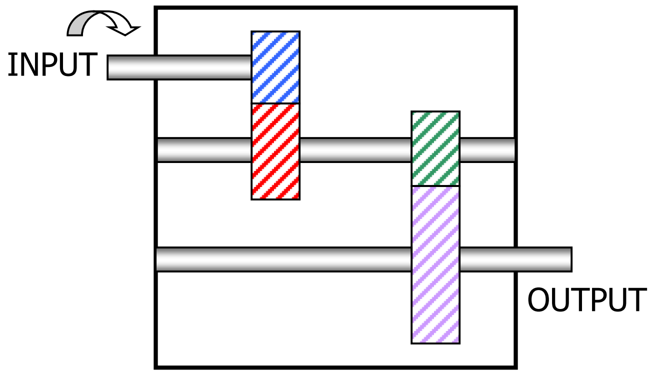
Input	= 1490RPM
Gear 1	= 15 teeth
Gear 2	= 21 teeth
Gear 3	= 19 teeth
Gear 4	= 54 teeth

Gear Ratio 1	= 15 teeth / 21 teeth	= **0.714**
Speed Out	= 1490 RPM x 0.714	= **1064.28 RPM**
Gear Ratio 2	= 19 teeth / 54 teeth	= **0.351**
Speed Out	= 1064.28 RPM x 0.351	= **374.47 RPM**

GMF 1 = 1490 RPM x 15 teeth = **<u>22350 CPM</u>**
GMF 2 = 1064.28 RPM x 19 teeth = **<u>20221.32 CPM</u>**

GMF Calculation Exercise

- Using the formulas on P153 from the manual calculate:
  - Speeds of all shafts
  - All GMF from the following gearbox arrangement

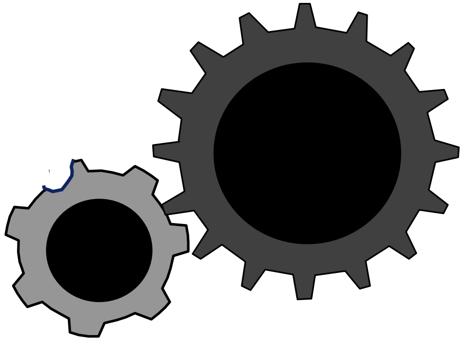


Input	= 1000 RPM
Gear 1	= 10 teeth
Gear 2	= 40 teeth
Gear 3	= 10 teeth
Gear 4	= 20 teeth

- Gear Ratio 1 = 10/40 = 0.25
- Shaft 2 speed = 1000 x 0.25 = **250 RPM**
- Gear Ratio 2 = 10/20 = 0.5
- Shaft 3 Speed = 250 x 0.5 = **125 RPM**
- GMF 1 = 1000 x 10 = **10000 CPM**
- GMF 2 = 250 x 10 = **2500 CPM**

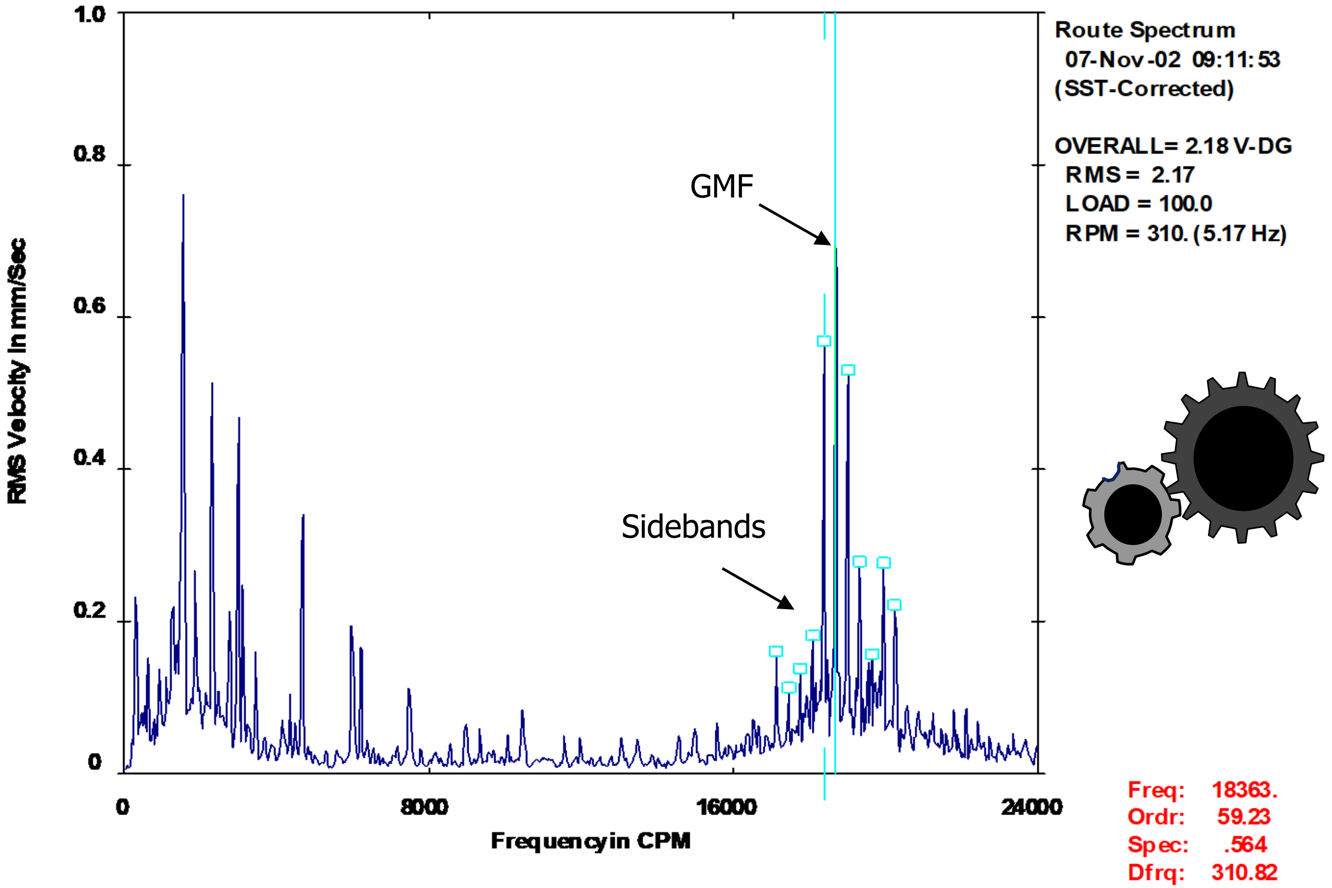
Gears – Sideband Frequencies

- Sidebands are the most common indication that a gear is defected.
  - Sidebands are equally spaced frequencies in the spectral data that materialise either side of the main GMF peak.
  - The sideband frequency spacing is equal to either the turning speed of the input gear or the turning speed of the output gear.
- Sidebands show in the data when either the gear is worn, loose or eccentric.
  - The speed of the shaft with the bad gear on it will produce the most dominant sidebands in the spectral data.



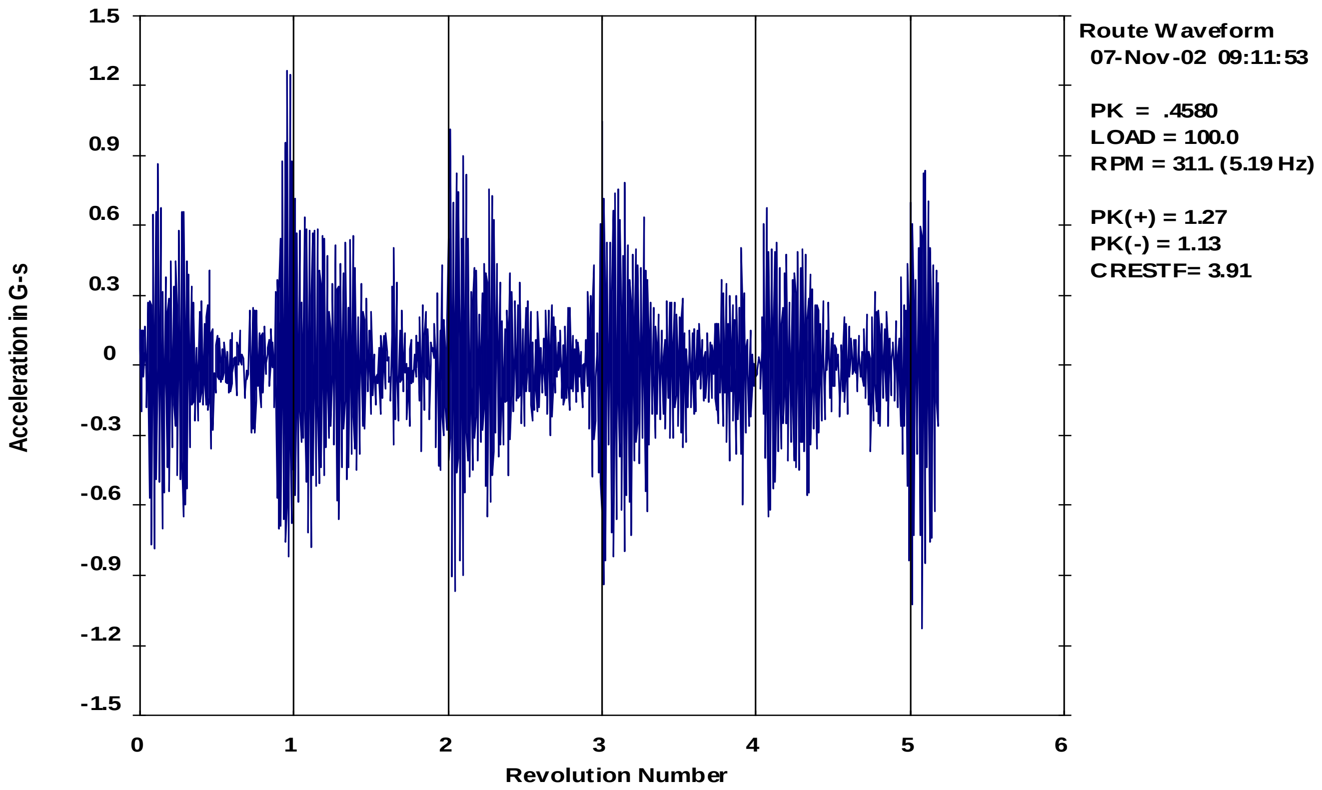
Gears

- The spectral data shows GMF with sideband data.
  - The sidebands are equally spaced at intervals of 310 CPM. This is indicating the gear that rotates at 310 RPM is the one that is worn or damaged.



Gears – Waveform Data

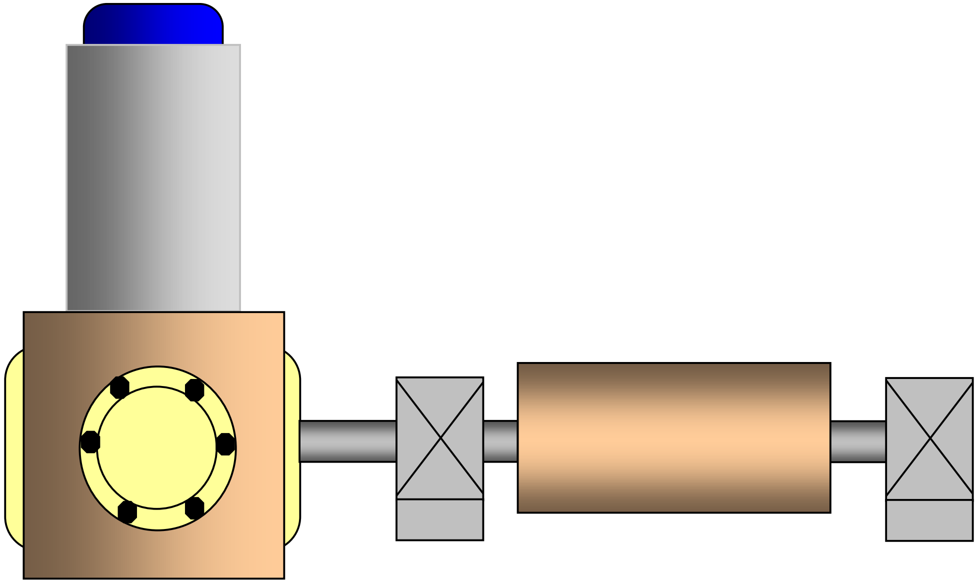
- Gears can produce different types of waveforms, the one shown below is indicating gear wear.
  - As the defective teeth come into mesh the noise generated increases showing an increase in amplitude in the vibration data



Case Study 4 –Gearbox

- The following case study is from a motor gearbox unit that drives a roller.
  - Product (Fibre) is fed along the top of the roll while being washed through a series of baths.
  - There are several of these Wash Nip Rollers in a continuous stream, failure of any one of them results in lost production

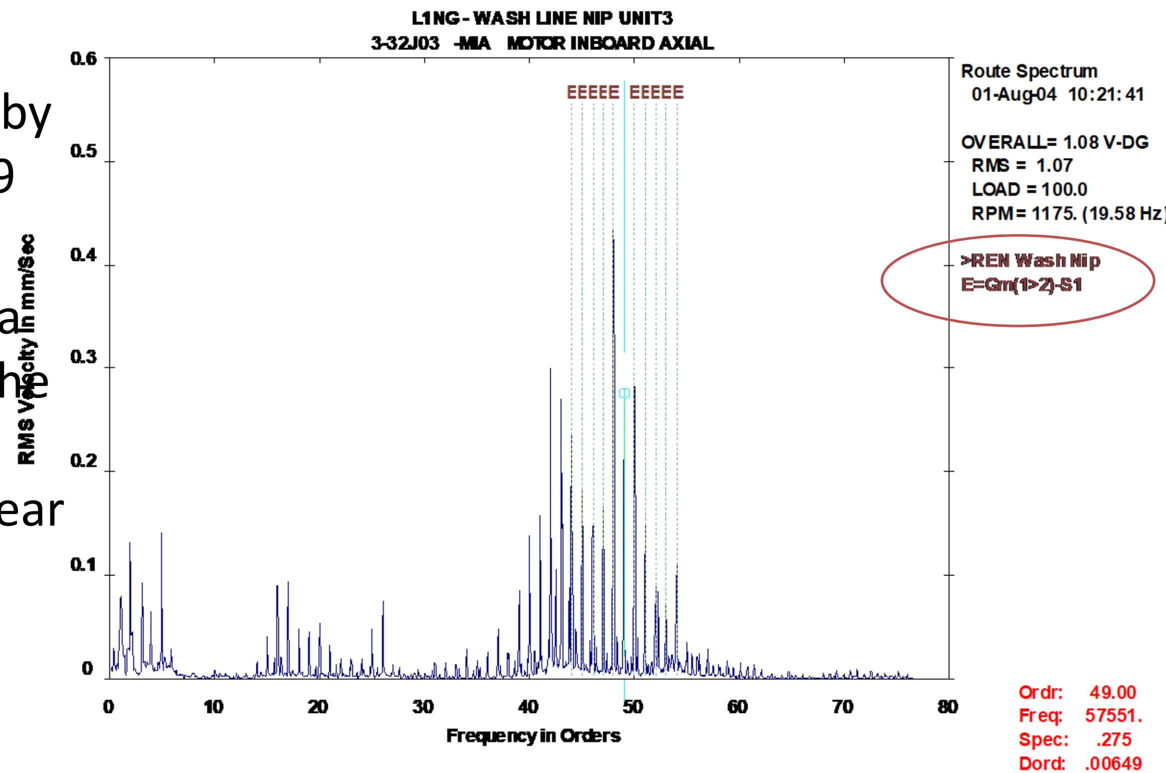
- Data is collected on a fortnightly basis as part of a routine data collection route



Case Study 4 –Gearbox

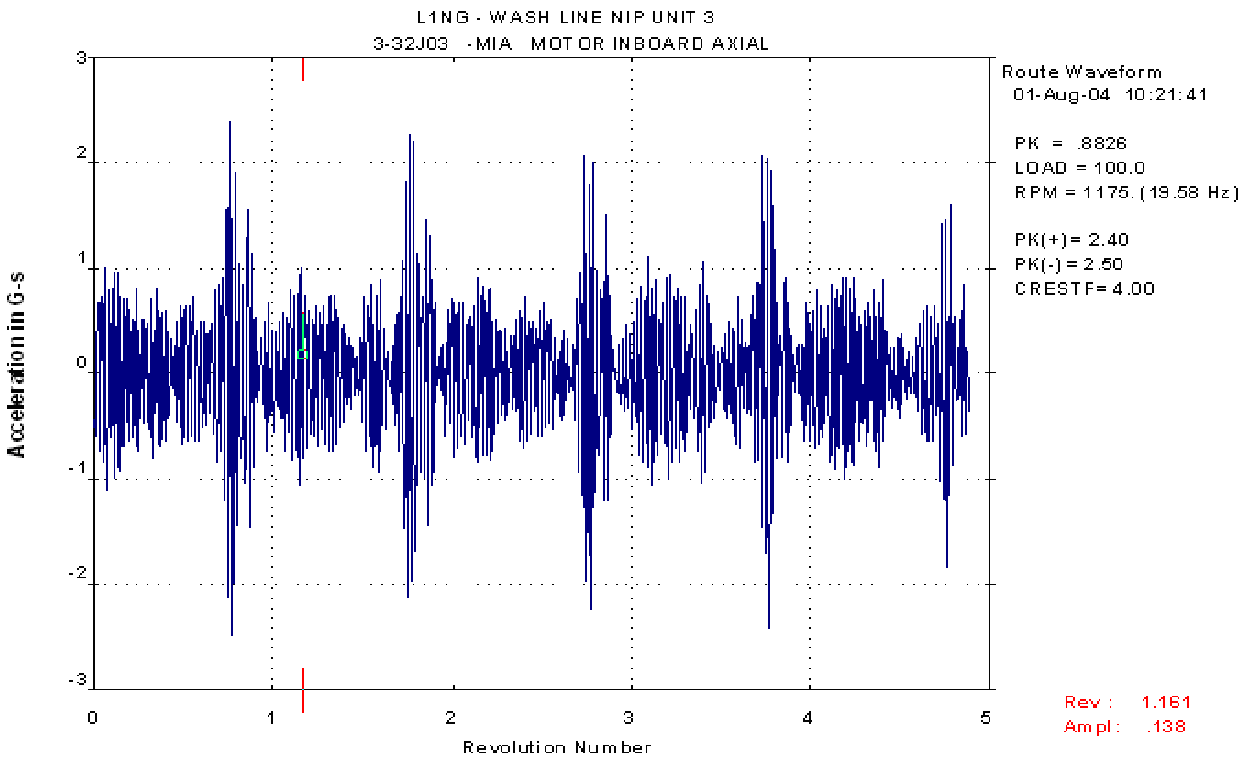
- The spectral data shown below is taken from the motor in the axial direction
  - (As the motor is mounted directly into the gearbox the first helical gear is mounted on the end of the motor shaft).

- The GMF is highlighted by the primary cursor at 49 Orders
- The fault frequency data (dotted lines) indicate the sideband data showing gear wear on the first gear in the gear train



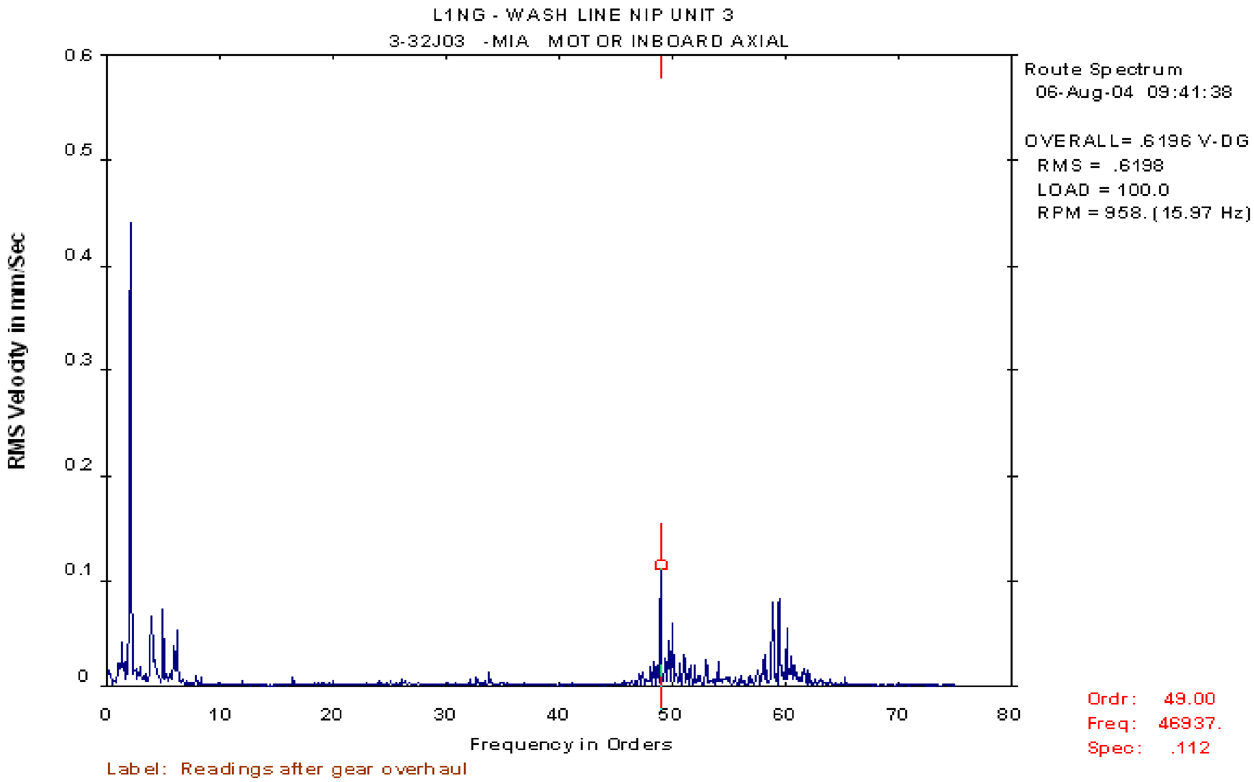
Case Study 4 –Gearbox

- The waveform data is showing a distinct pattern commonly associated with gears.
- The amplitude increases In noise as the damaged teeth come into mesh
  - Producing over 2G-s of force in both the positive and negative direction



Case Study 4 –Gearbox

- The gears were inspected due to the critical nature of the asset. It was found the gear to be severely damaged.
- A new gearbox was fitted and new data was taken showing the difference between the good and bad gear



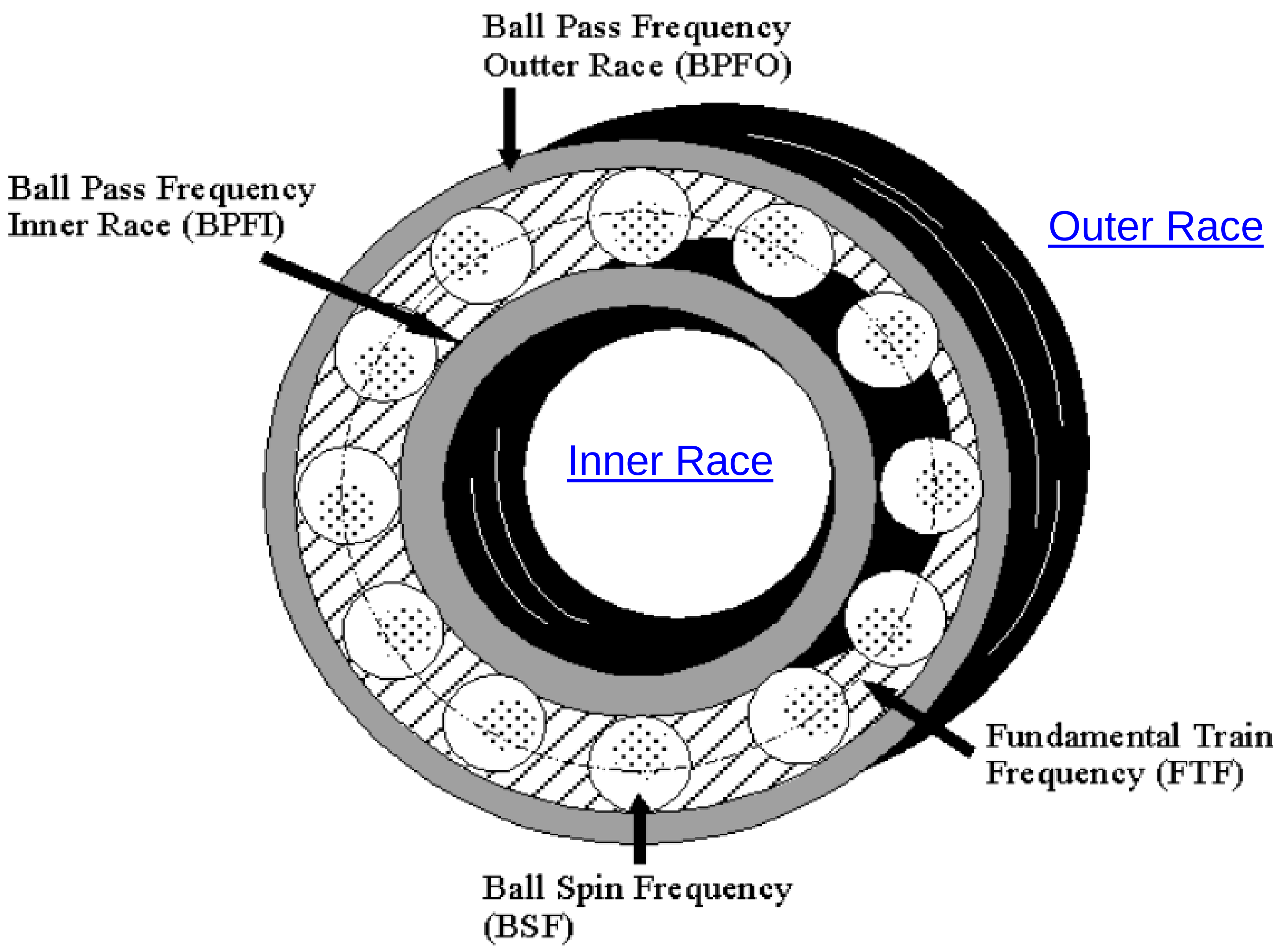
Rolling Element Bearing Faults

Rolling Element Bearings

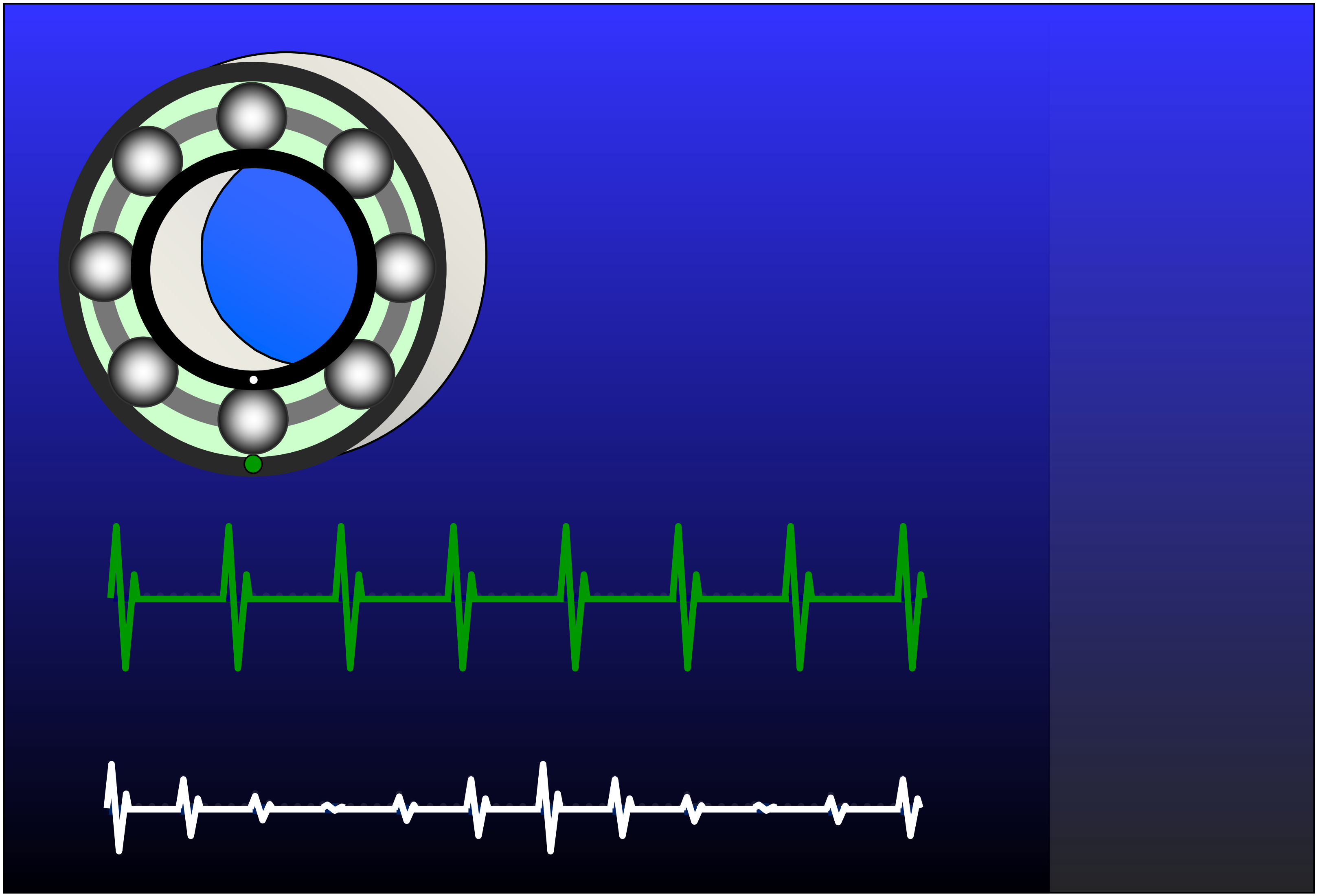
- Rolling element bearings have specific bearing failure modes that can be observed in the spectral and waveform data.

- Bearing frequencies differ from most other frequencies present within the spectral data because unless the bearing has a defect there will be no frequency peaks in the data relating to the bearing. *Only if the bearing has a defect will frequencies show in the spectral data.*
- *There are **four** main fundamental bearing defect frequencies these are:*

Rolling Element Bearings



How Bearing Faults Generate Vibration



Rolling Element Bearings

- Bearing defect frequencies are calculated based upon the geometry of the bearing these calculations may include:
  - Number of rolling elements
  - Pitch Circle Diameter
  - Rolling element diameter
  - Contact angle
    - Defined within Machinery Health Manager there are over 100000 predefined bearing stored in the CSI bearing warehouse

BEARINGS in CSI Warehouse:

c:\RBMsuite\SysData\CSI_CMP.WH

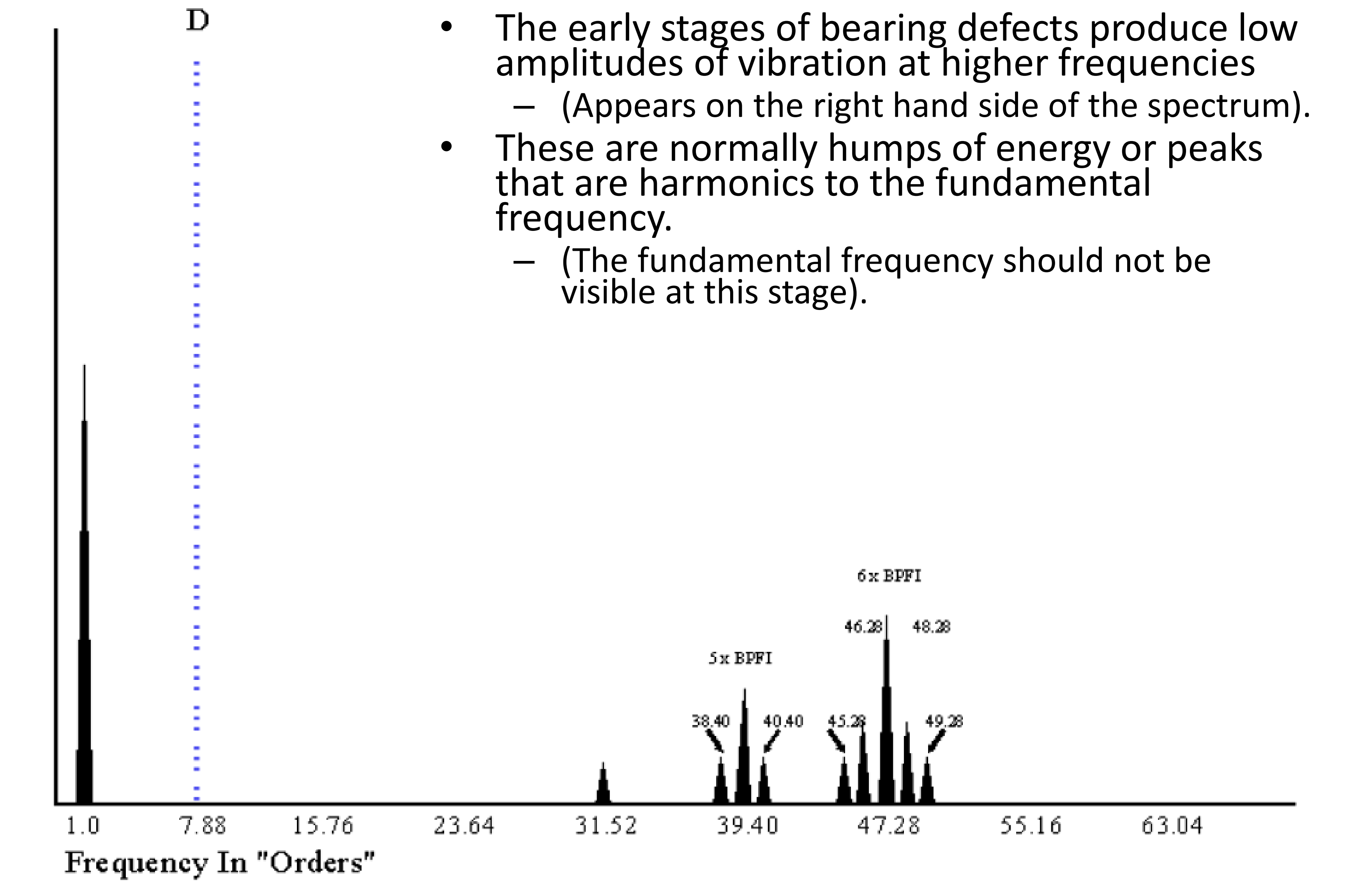
****

BRG ID	Bearing Type	#B/R	FTF	BSF	BPFO	BPFI
12143	RHP 6218	11	0.418	2.967	4.598	6.402
24421	SKF 6313E	8	0.376	1.894	3.009	4.991
25372	SKF I-26313	19	0.433	3.568	8.219	10.781

Rolling Element Bearings

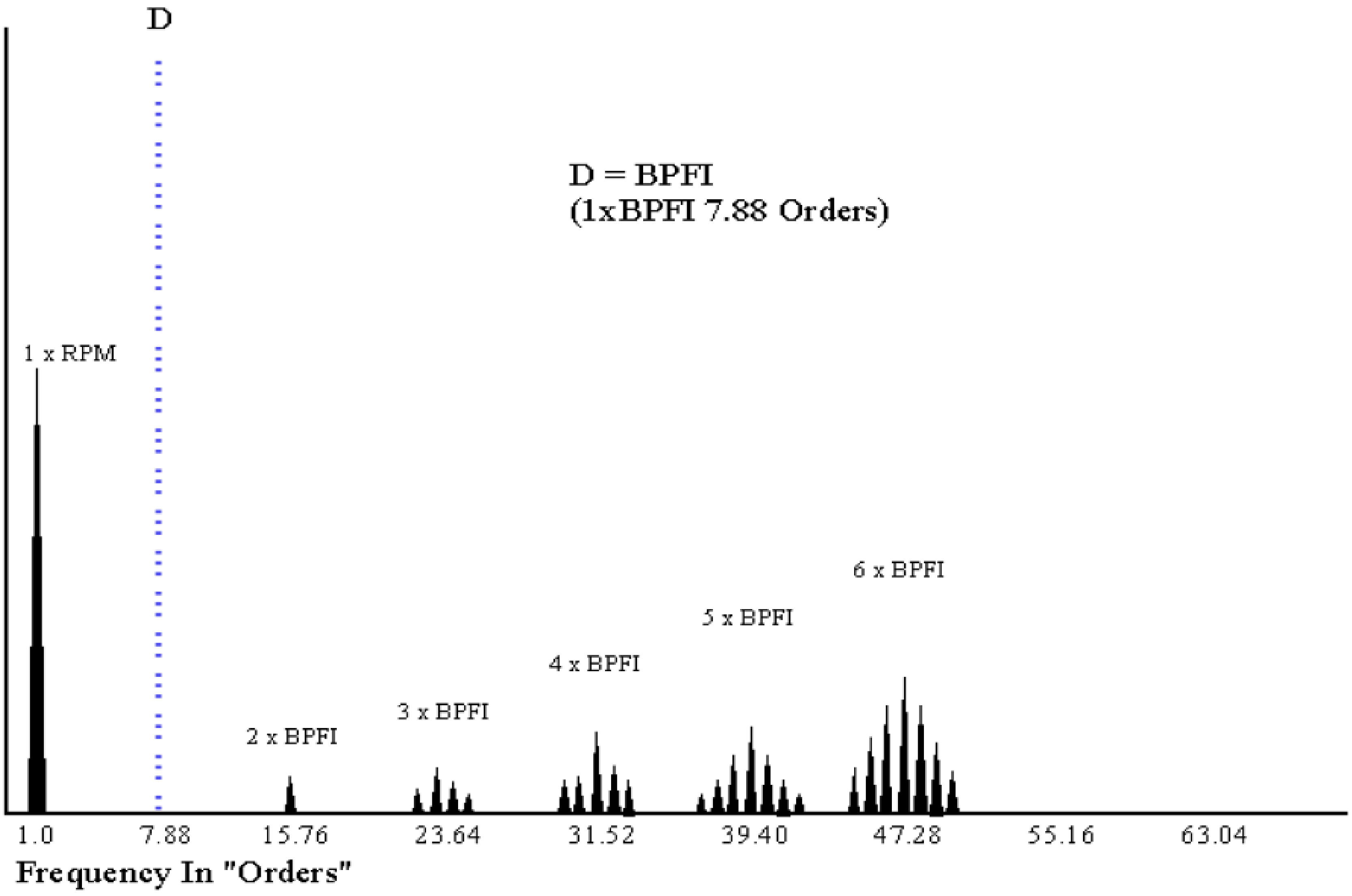
- **Characteristics of Bearing Defects**
  - High frequency raised noise level (Hump of energy)
  - Non-Synchronous harmonic peaks (Both low and high frequency)
  - Time waveform will show a lot of noise/impacting
  - Early stages of bearing wear may show better if viewed in acceleration in the frequency domain
  - Fundamental bearing defect frequency (First calculable frequency) may not be present in the spectral data

Failure Mode 1

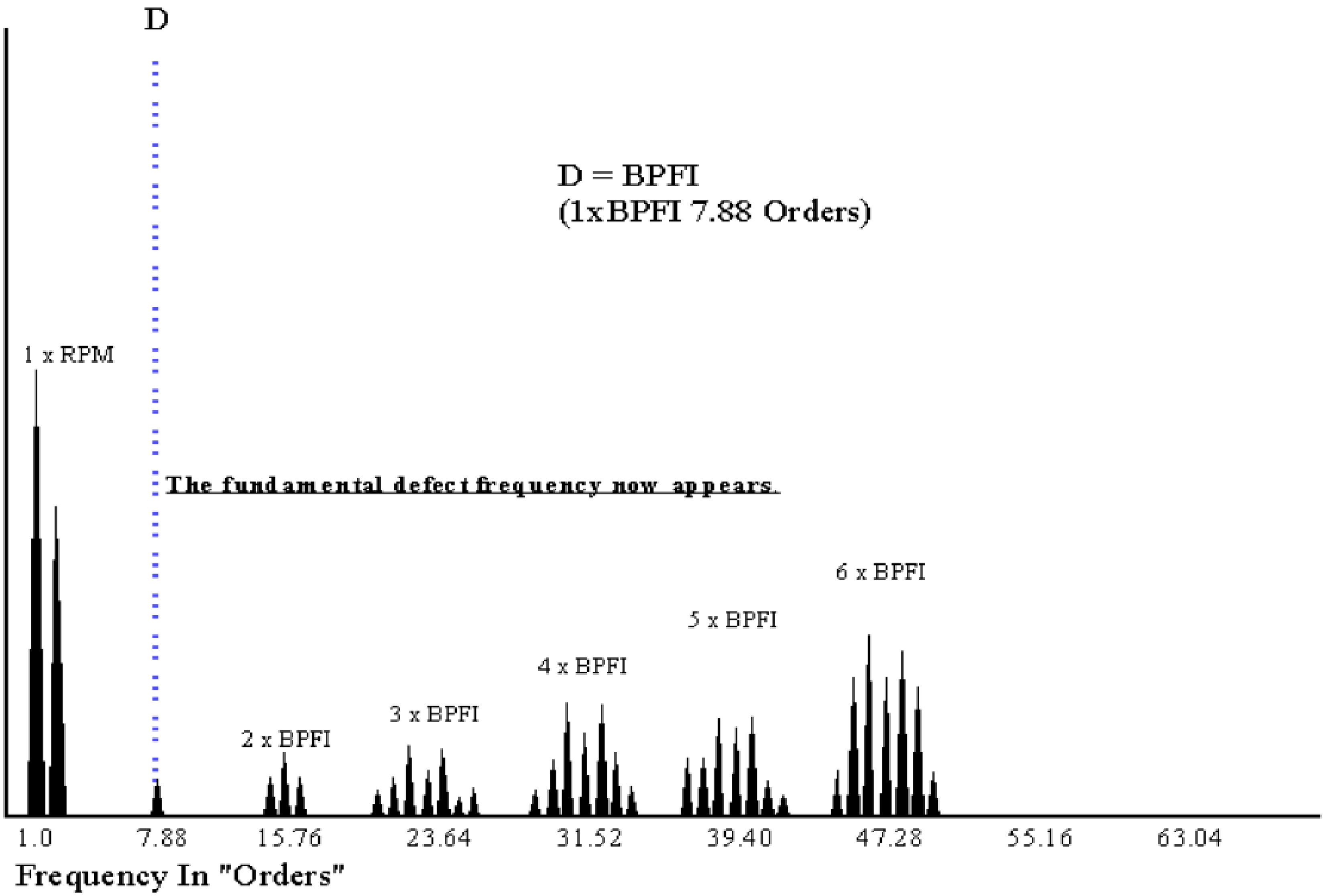


- The early stages of bearing defects produce low amplitudes of vibration at higher frequencies
  - (Appears on the right hand side of the spectrum).
- These are normally humps of energy or peaks that are harmonics to the fundamental frequency.
  - (The fundamental frequency should not be visible at this stage).

Failure Mode 2

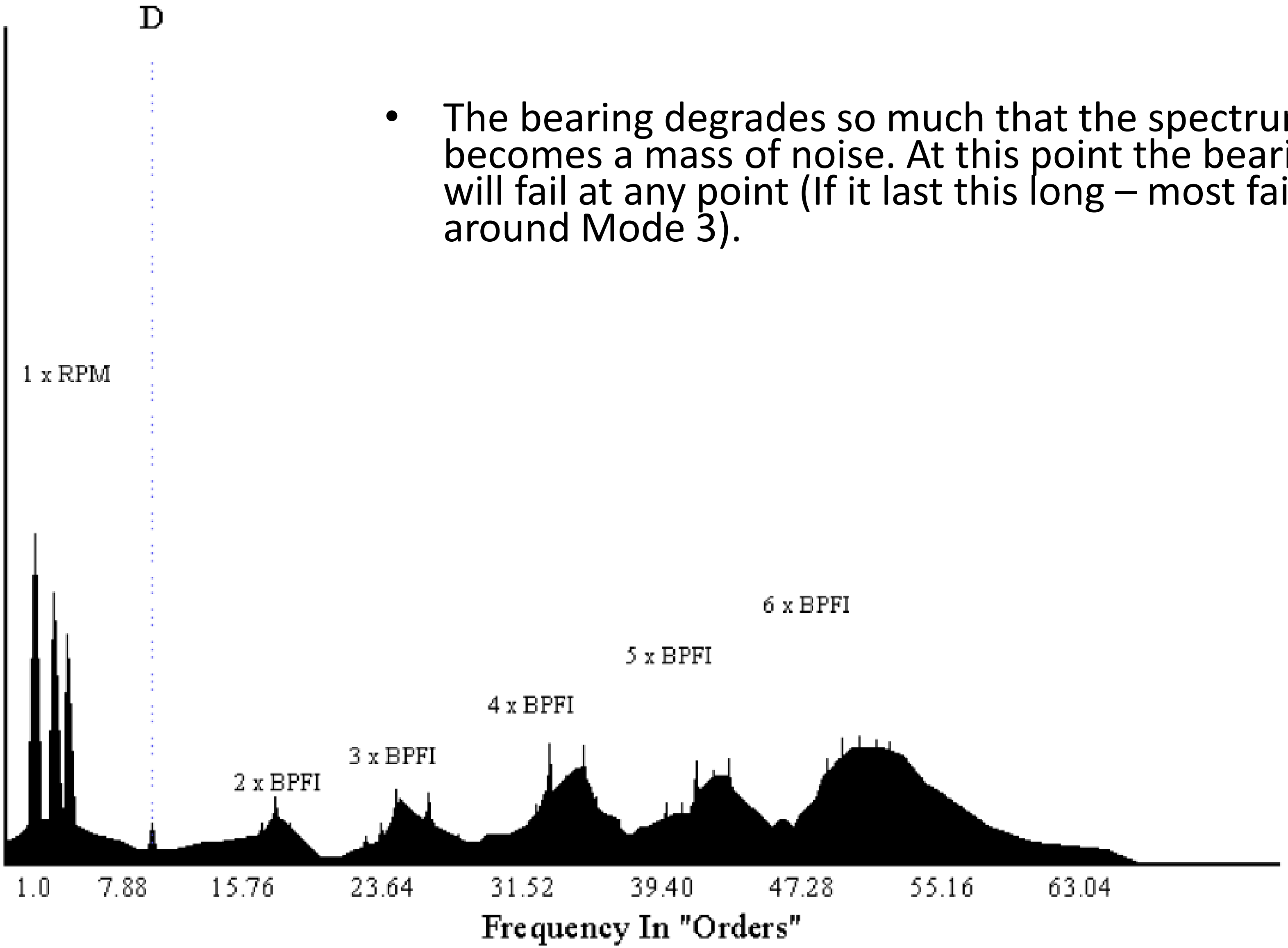


Failure Mode 3



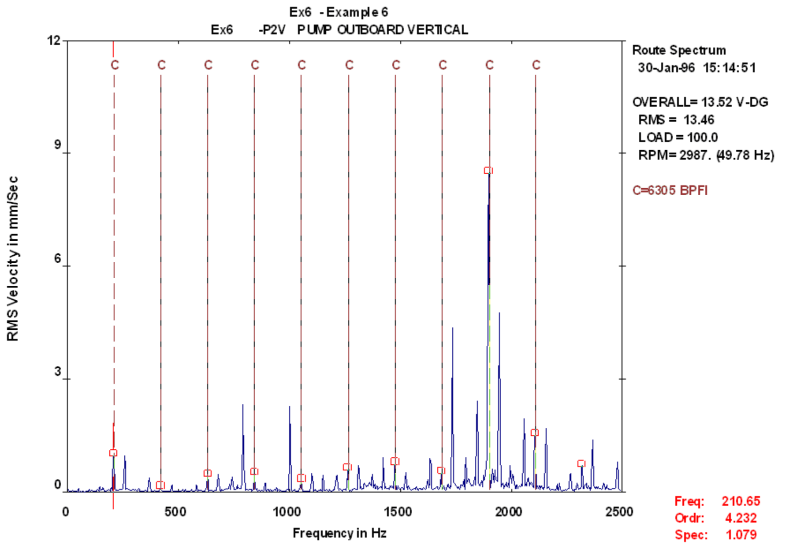
Failure Mode 4

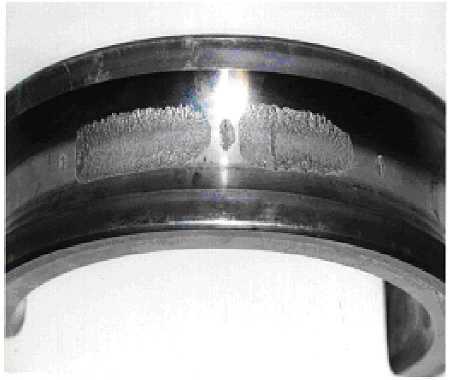
- The bearing degrades so much that the spectrum becomes a mass of noise. At this point the bearing will fail at any point (If it last this long – most fail around Mode 3).

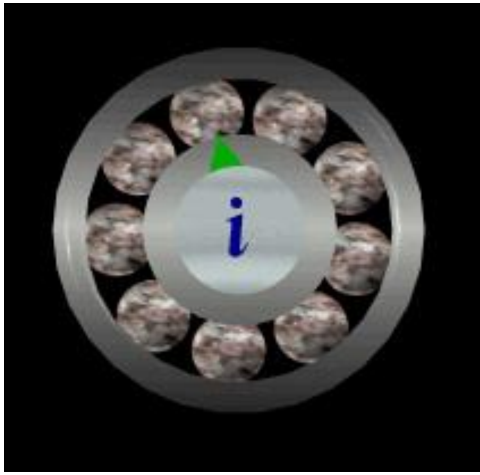


Rolling Element Bearings - BPFI

- Typical data showing a defected inner race
  - *Fundamental frequency showing*
  - *Harmonics low and high frequency + sidebands*

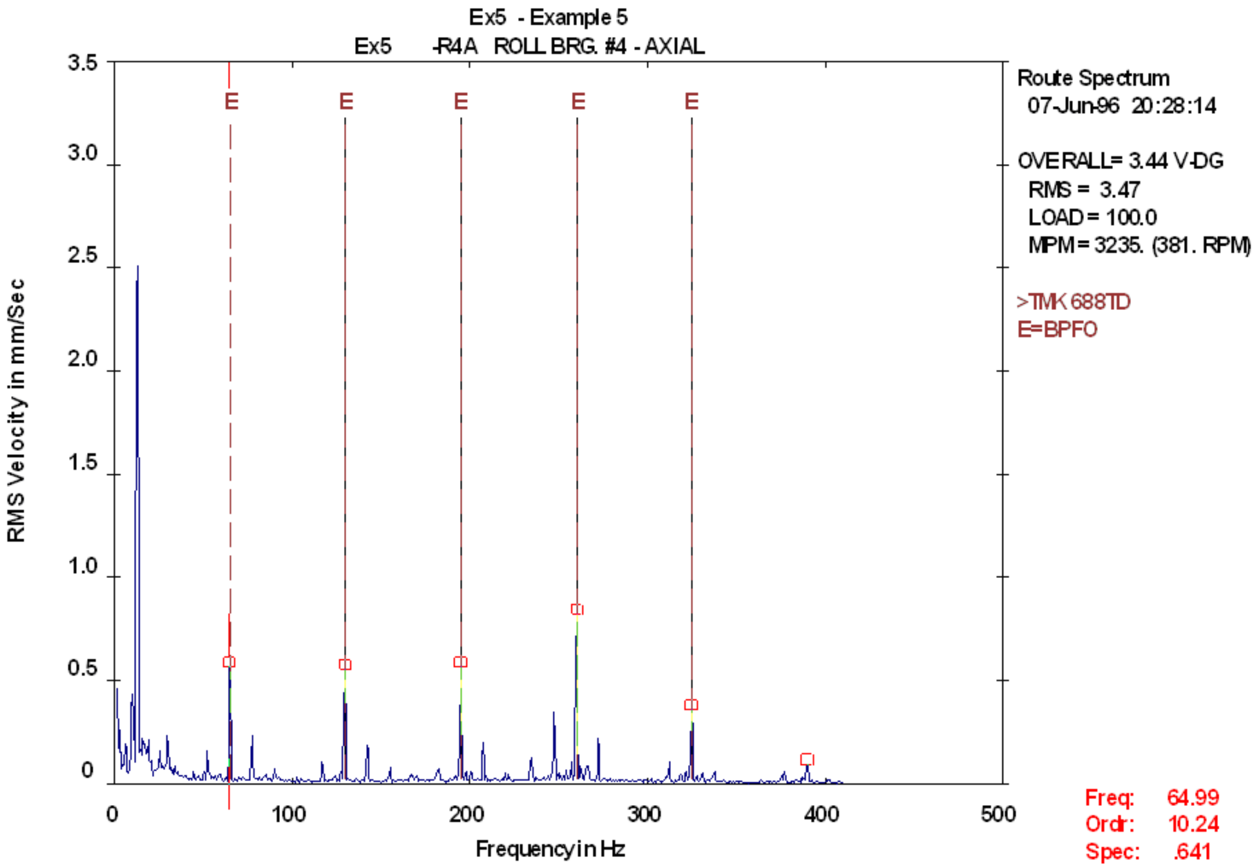


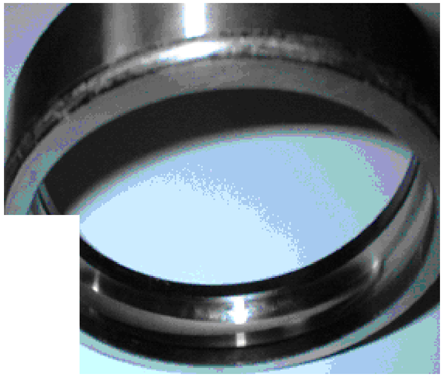


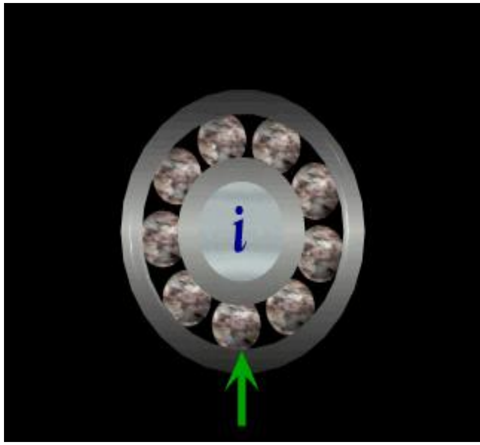


Rolling Element Bearings - BPFO

- Data showing a defect related to the BPFO
  - *The fundamental frequency is showing*
  - *Harmonics from low to high frequency*

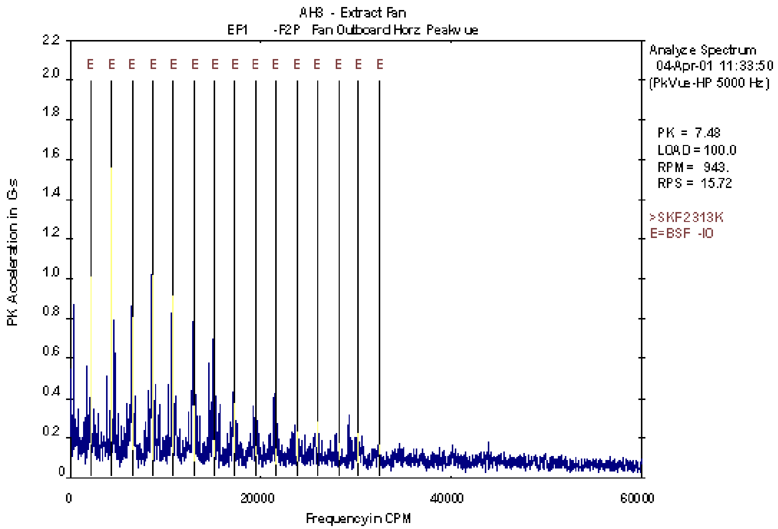


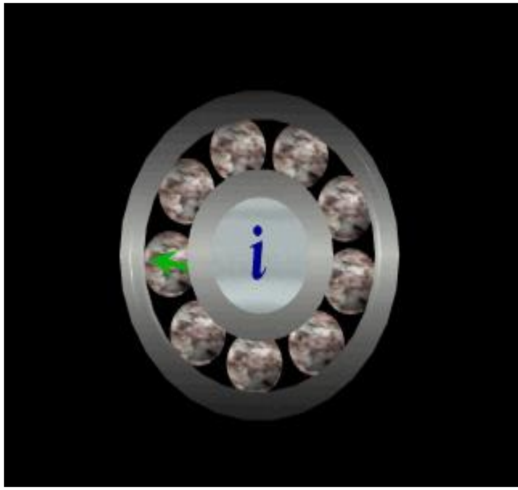




Rolling Element Bearings - BSF

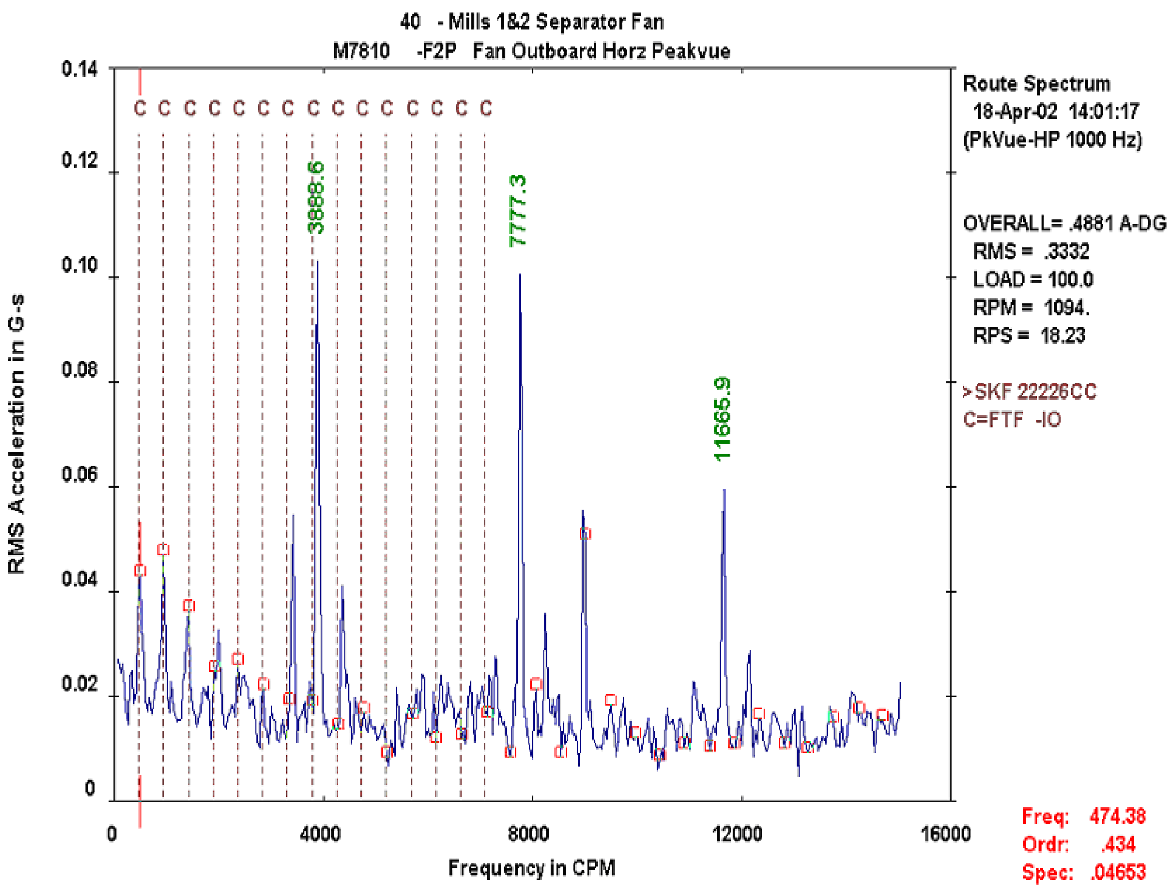
- Bearing defect showing the BSF – Rolling elements
  - *Sidebands around the BSF = FTF*

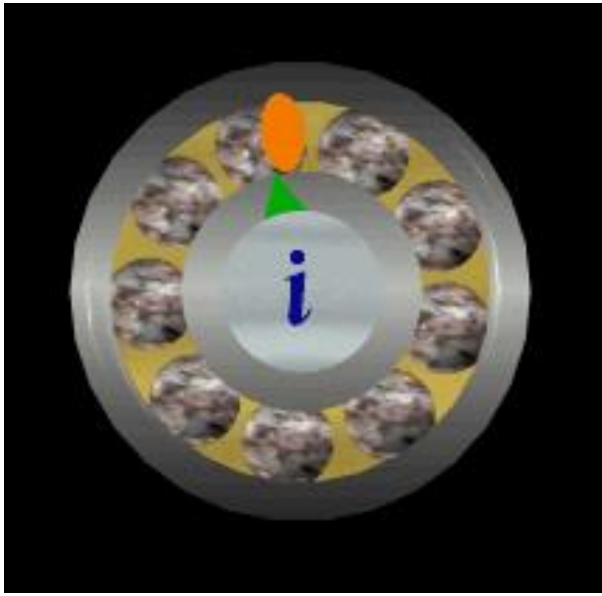




Rolling Element Bearings - FTF

- The FTF is the only bearing frequency that is sub-synchronous
  - May not detect then with conventional vibration data
  - FTF defect at 0.4 orders shown in Peakvue



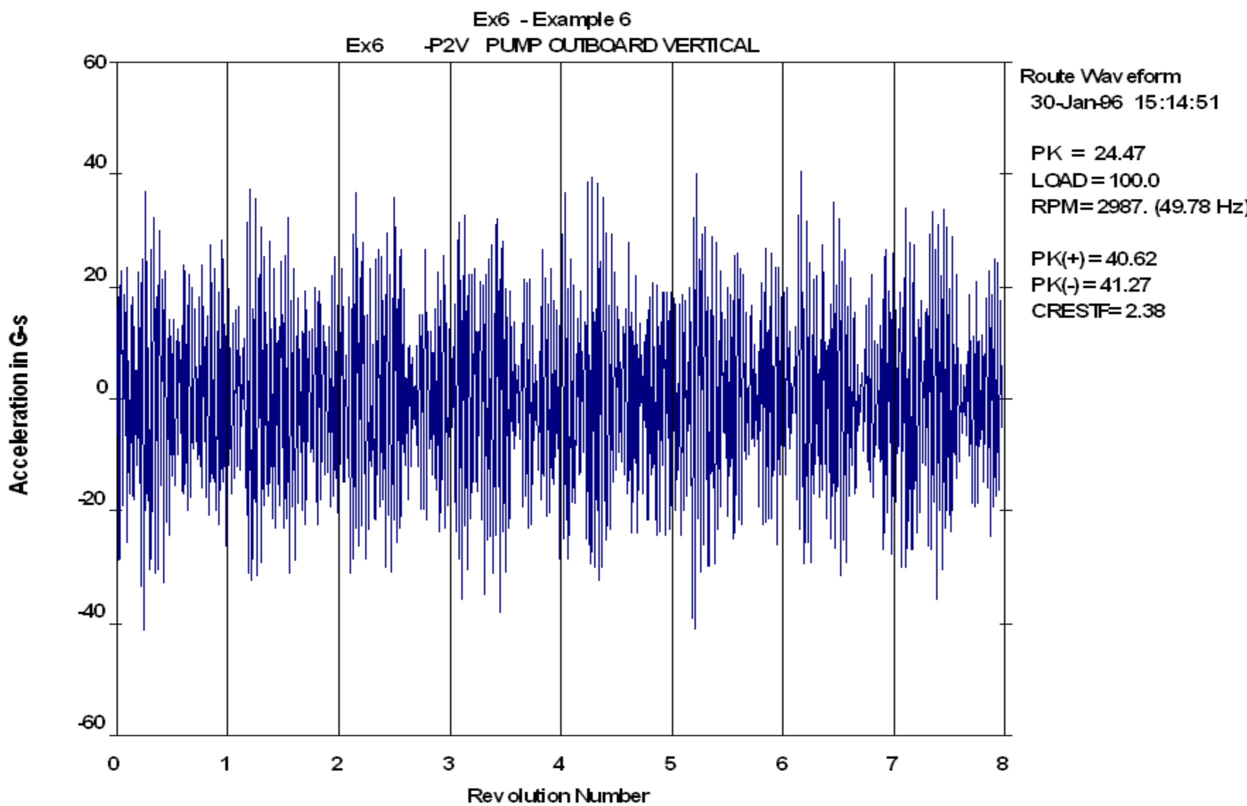


FTF & BSF

BPFI & BPFO

Rolling Element Bearings - Waveform

- As a bearing becomes defected then the amount of noise/force generated as the rolling elements impact the defective area increases.
  - This can show significant G-levels in the time waveform. This value is trended in the software as the Peak-Peak value

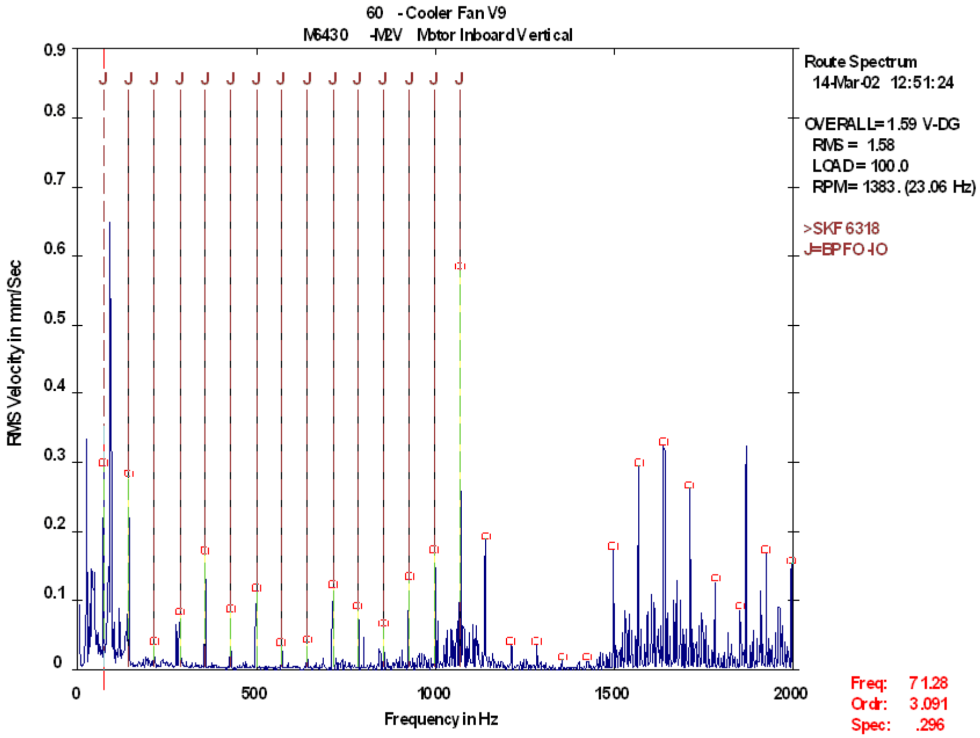


; taken from a
a damaged

ce levels are
g 40G-s

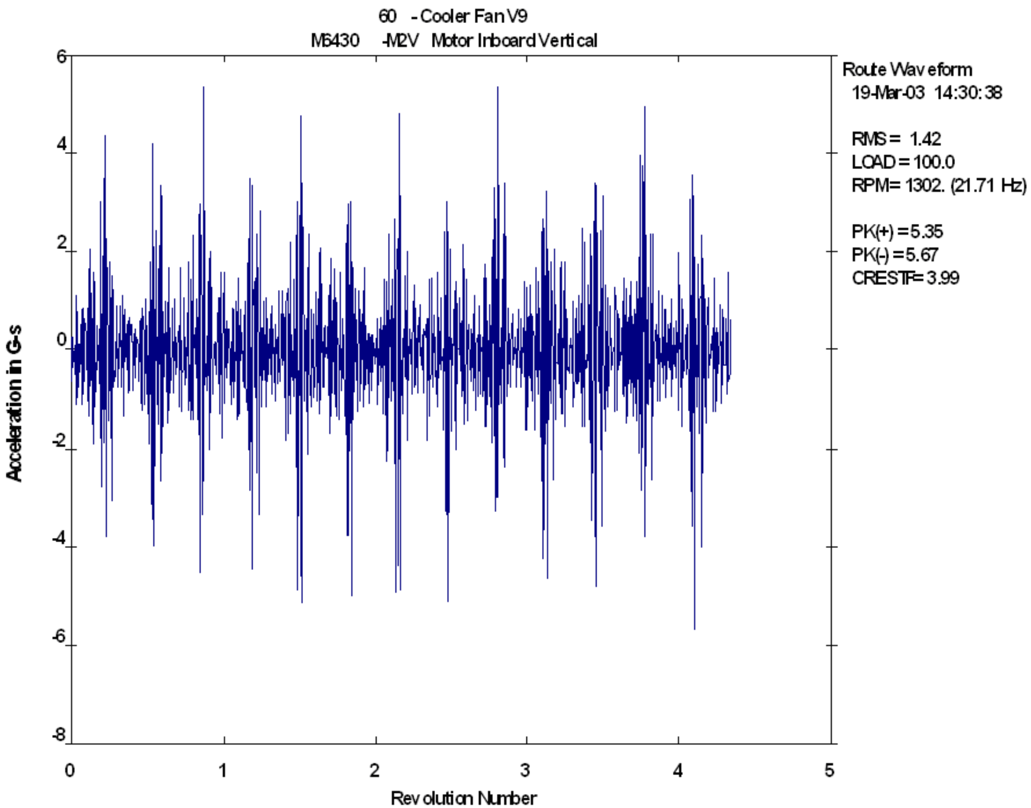
Case Study 5 – Bearing Defect

- The spectral plot below is showing the data from the inboard vertical direction of the motor.
  - The primary cursor is indicating the fundamental defect BPFO frequency + harmonics.
  - The frequency range of the harmonics covers both low and high frequency ranges suggesting the bearing is more advanced stages of failure.



Case Study 5 – Bearing Defect

- The time waveform is showing significant impacting levels reaching in excess of +/- 8G-s of force.
  - This level of impacting is higher than would be suspected for a motor of this type.

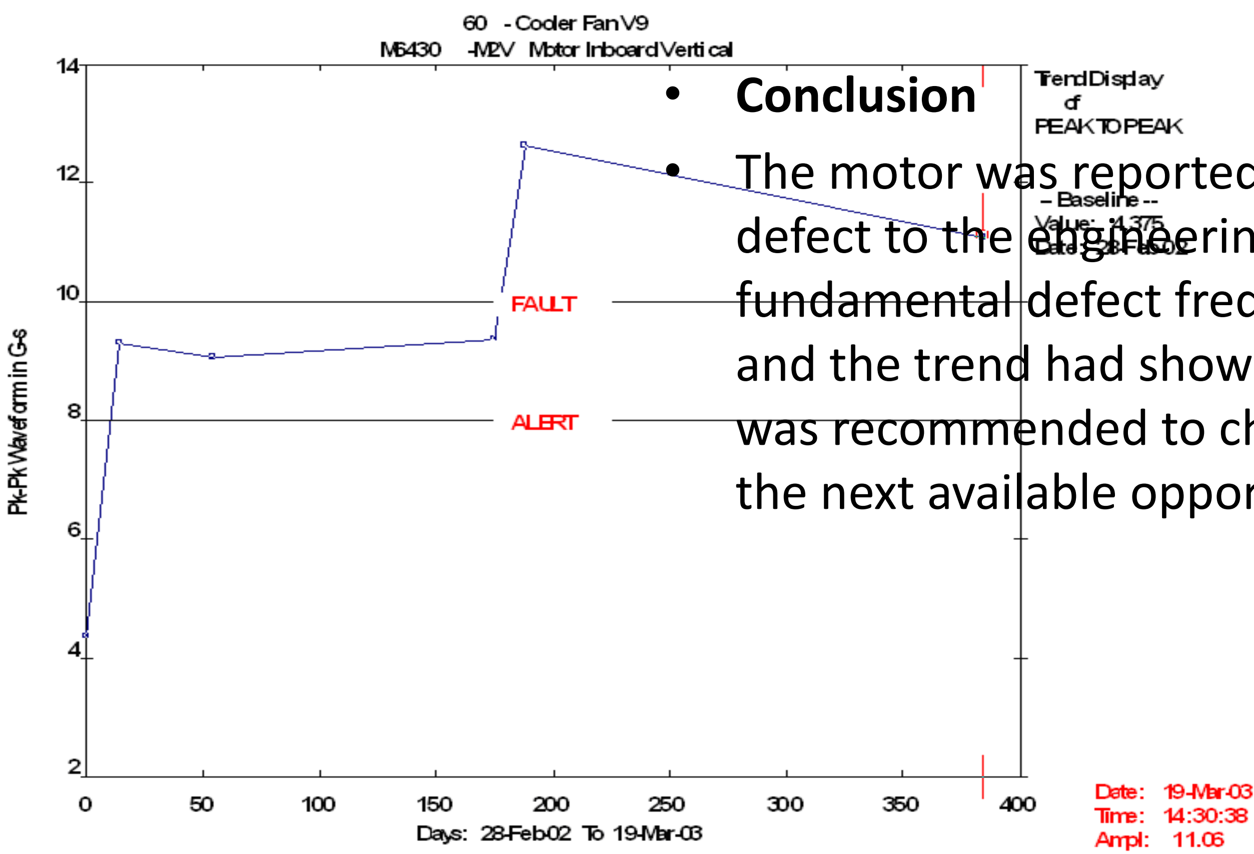


The repetitive impacting pattern shown above is common to antifriction bearing defects.

- In this instance the impacting is representing the rolling elements striking a defect on the race.

Case Study 6 – Bearing Defect

- The trend plot above is showing the increase in amplitude of the Peak-Peak parameter.
  - The peak-peak parameter is measuring the amount of energy in the time waveform from the Peak+ to the Peak-



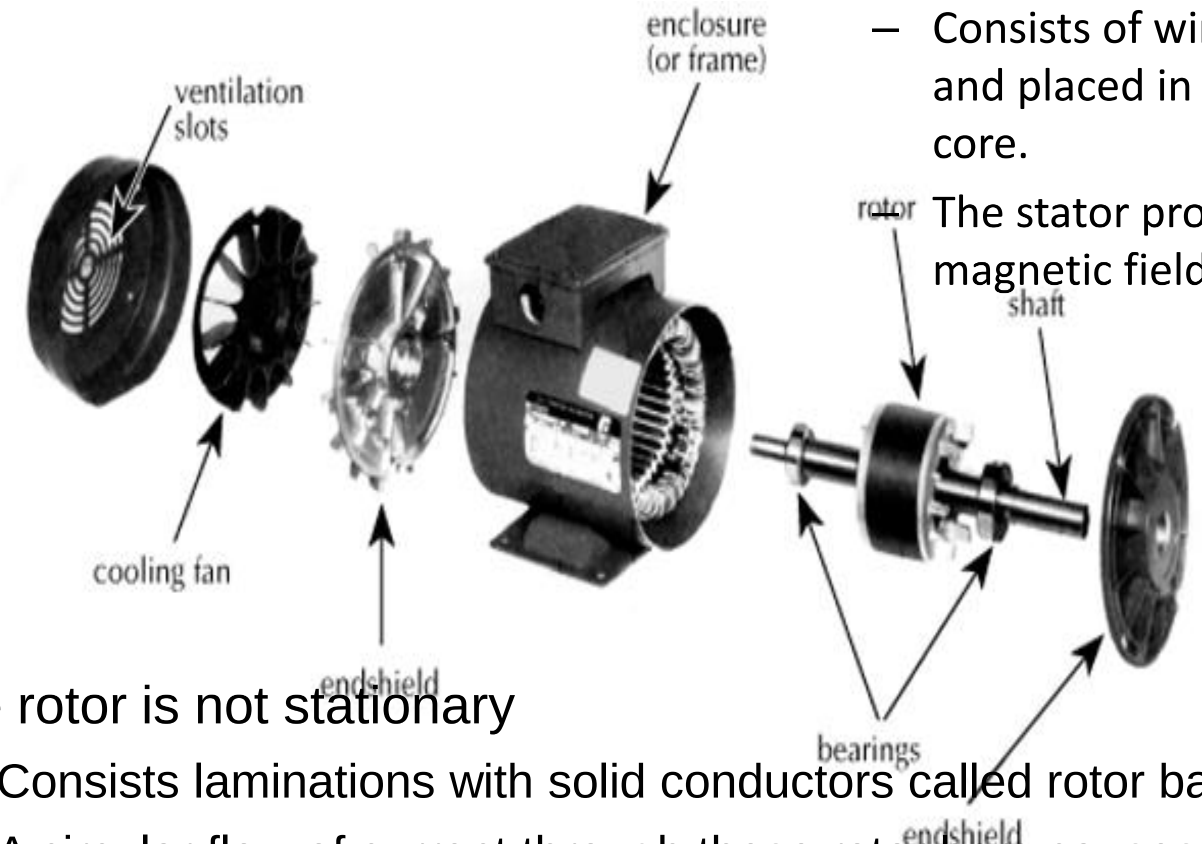
- **Conclusion**
- The motor was reported as having a bearing defect to the engineering group. As the fundamental defect frequency was present and the trend had shown sudden increases it was recommended to change the bearing at the next available opportunity.

Electric Motor Faults

Electrical Defects

- A motor can be simply broken down into two key components
  - Rotor
  - Stator

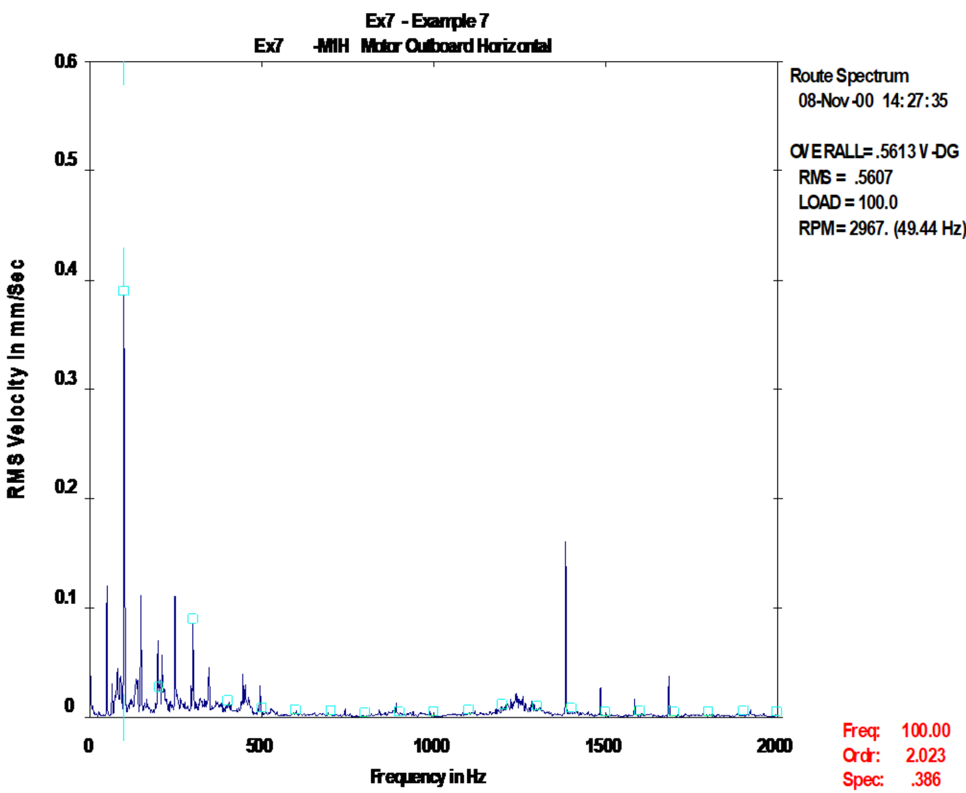
- The stator is stationary
  - Consists of wire wound in coils and placed in slots of an iron core.
  - The stator produces a rotating magnetic field.



- The rotor is not stationary
  - Consists laminations with solid conductors called rotor bars
  - A circular flow of current through these rotor bars causes the rotor to become an electromagnet which will rotate in a magnetic filed.

Electrical Defects – Spectral Data

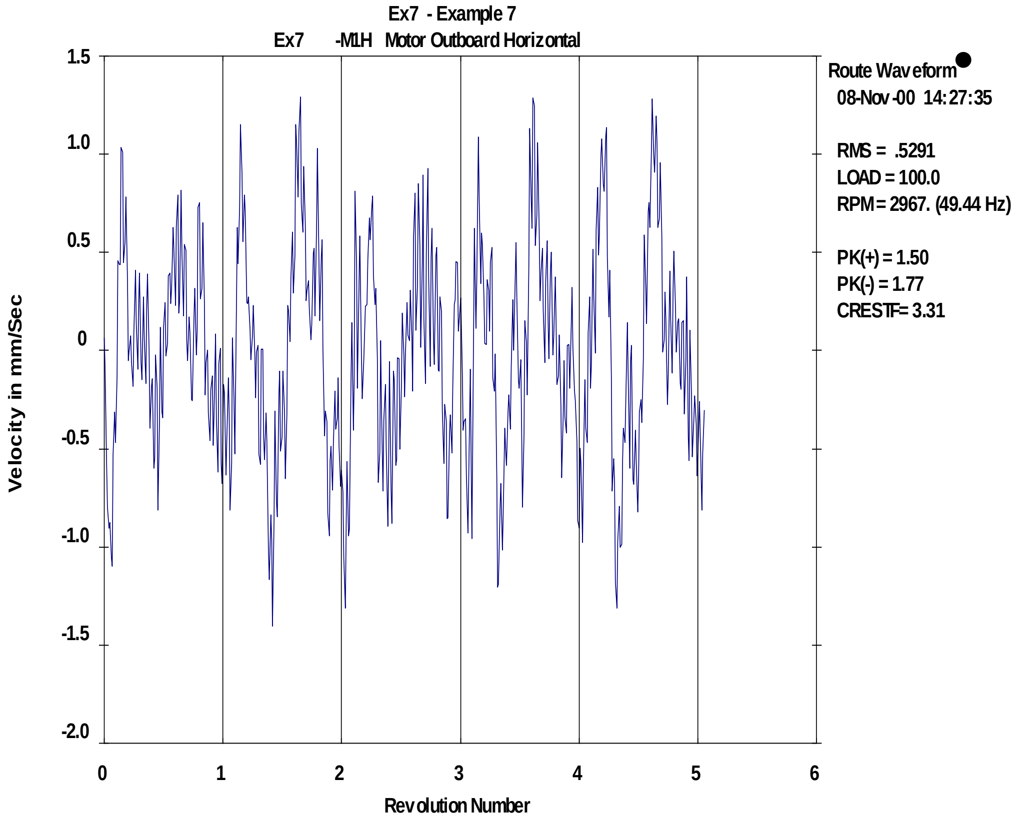
- The most common electrical frequency that materialises in the spectral data is the 2 x Line Frequency.
  - For most industrial applications the line frequency used to supply motors is 50Hz (Europe).
  - Therefore the frequency of concern for most electrical faults would be 100Hz (2xLf [Lf=line frequency])



- The spectral plot is showing a peak at 100Hz (6000cpm)
  - 2xLf
  - This can be mistaken for misalignment

Electrical Defects – Waveform Data

- The waveform data from a 100Hz peak will show a sinusoidal pattern like the waveform shown below



- Again this type of pattern can be associated with misalignment.
  - Usually misalignment would produce higher force (Higher waveform levels) than those from electrical defects due to the stress being applied to the machine

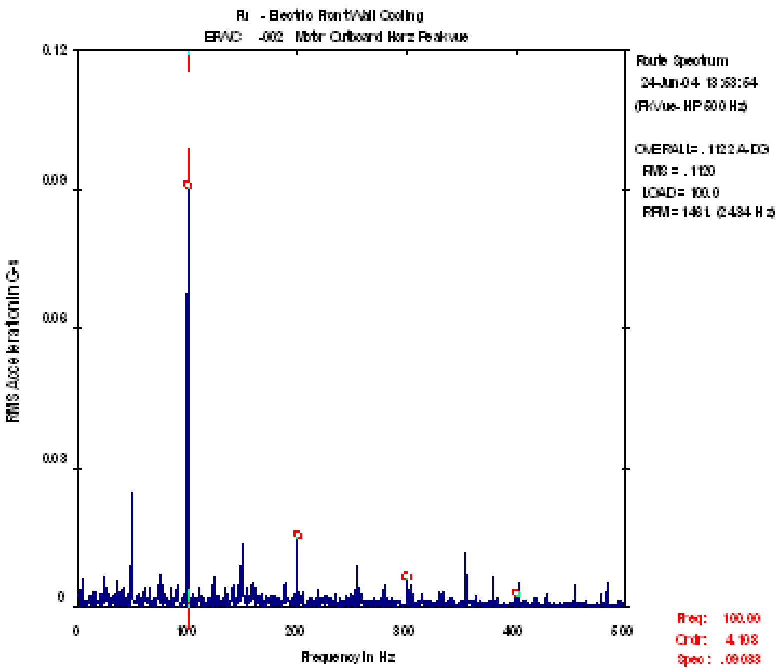
Electrical Defects - Causes

Common fault types that can produce the 2xLf peak are as follows:

- Dynamic Eccentricity – Usually Rotor Related
- Static Eccentricity – Usually Stator Related
- Loose Iron or Slot Defect – Rotor or Stator
- Open or Shorted Windings
- Insulation Breakdown or Imbalanced Phase
- Loose Connectors

Case Study 7 – Electrical Defect

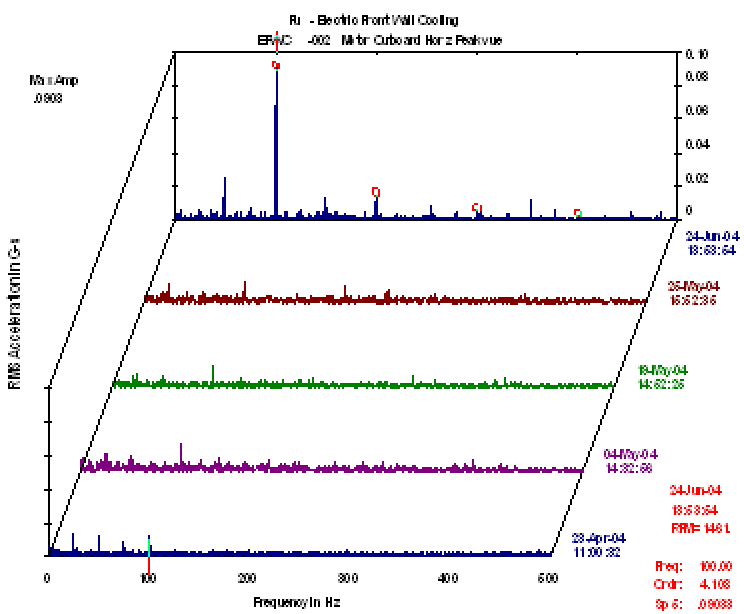
- The following case study was taken from a glass manufacturer. The data was from the 'Electric Front Wall Cooling Fan'.
  - This fan unit is a critical fan to the process and has no standby unit.
  - In this particular instance the motor failed shortly after the data was collected.



- The Peakvue data taken on the motor non-drive end is showing a dominant 100Hz peak.
  - This frequency is at 2xLf and is associated with electrical problems

Case Study 7 – Electrical Defect

- The multi-plot above shows the same measurement point going back over the last 5 route readings.
  - This particular plot is useful for determining rate of change.
  - It is quite clear how this particular frequency suddenly appeared



- **Conclusion**
  - As the motor failed shortly after data collection no action was taken to prevent failure.
  - The investigation in the motor showed one of the connectors had come loose causing the motor to burn out.

Common Belt Drive Faults

Belt Defects

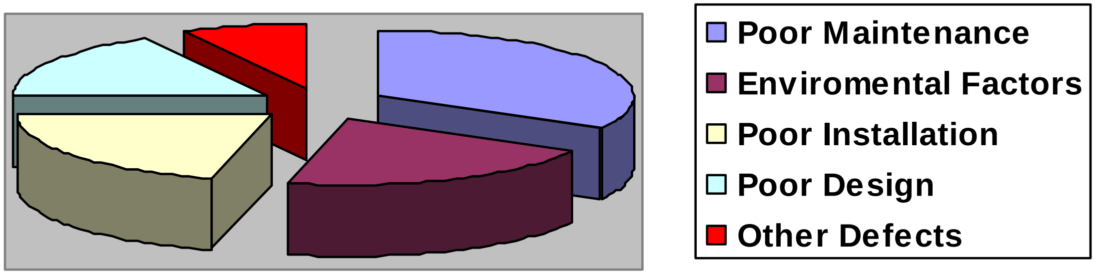
- Belts are the most common low cost way to transmit power from one shaft to another.
  - Belt drives rely on friction between the belt and pulley to transmit power between drive and driven shafts
- The ability of belt to transmit power depends upon
  1. Belt Tension (tension on the belt holds it tightly against the sheave)
  2. Friction between the belt and sheave
  3. The arc of contact between the belt and sheave (**Wrap**)
  4. The speed of the belt

- However, belts can be easily damaged by heat, oil and grease and since belts slip with in the sheaves they can not be used where exact speed changes are required (except for timing belts)

Belt Defects

- Belt defects can be considered non-critical faults by many maintenance groups due to the relative ease of replacement requiring minimum downtime.
  - But belt defects are a major contributor to the overall vibration of the machine resulting in premature failure of other machine components.

Sources of belt drive defects

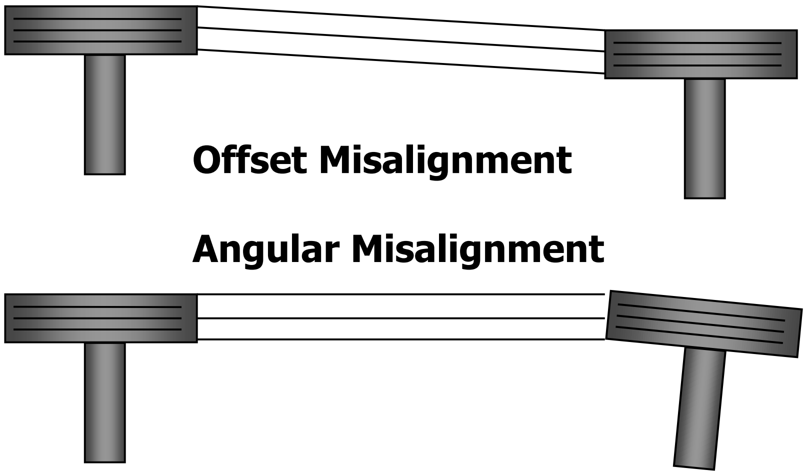


Belt Defects – Fault Characteristics

- Belt defects, such as cracks, broken or missing pieces, hard and soft spots can generate vibration at the turning speed of the belt (1xbelt) and harmonics
  - Due to the length of the belt in relation to the pulleys (sheaves) the 1xbelt frequency is **sub-synchronous** and very often the 2xbelt frequency may be sub-synchronous as well
- The predominant harmonic is typically the 2xBelt frequency and can be seen in the radial plain in-line with the belts.
  - **Severity is judged by the number and amplitude of the harmonics seen in the spectral data**

Belt Defects – Fault Characteristics

- Just like two mating shafts, belt drive systems can also be misaligned in both angular and offset directions.
  - When misalignment is induced into a belt drive system then the life of the belt is significantly reduced as well as the overall vibration of the system increases.



- Pulley misalignment results in high **axial vibration** at the **shaft turning speed**.
  - If the belt is also defected then 1xbelt frequency and harmonics may also show in the axial direction

Belt Defects – Calculations

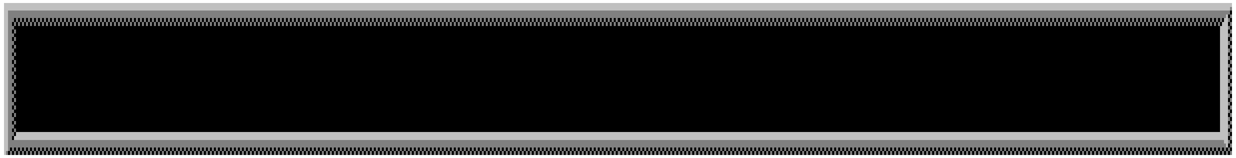
- The fundamental belt frequency can be calculated using the following equation:

$$\textbf{Belt Freq.} = \frac{(3.142 * \text{Pulley Ts} * \text{Pulley PCD})}{\text{Belt (Length)}}$$

  – Where:
    - Ts = Turning Speed
    - PCD = Pitch Circle Diameter
    - **Note:** The PCD and belt length must be in the same units

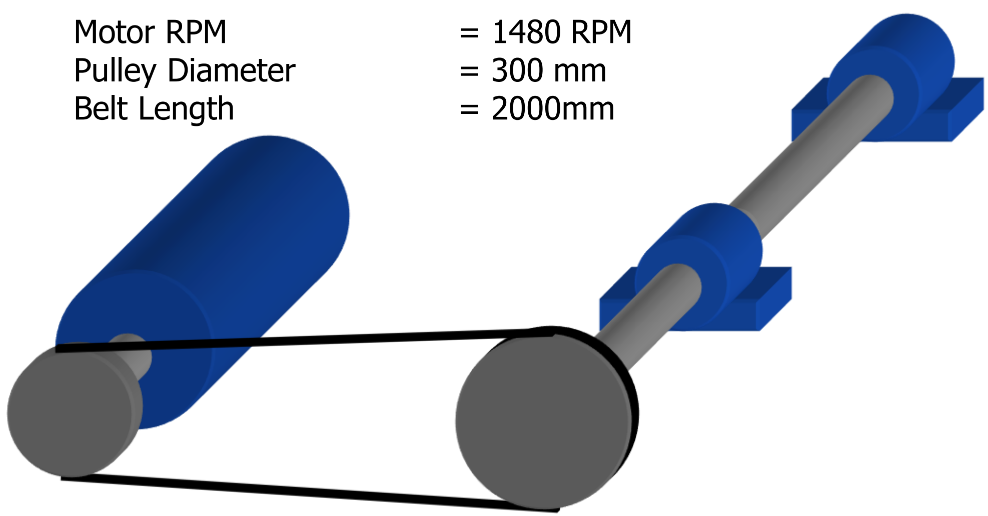
- A timing will belt will also have a specific frequency related to the number of teeth on the pulley

Timing Belt Freq. = (Pulley Ts) * (# Pulley Teeth)



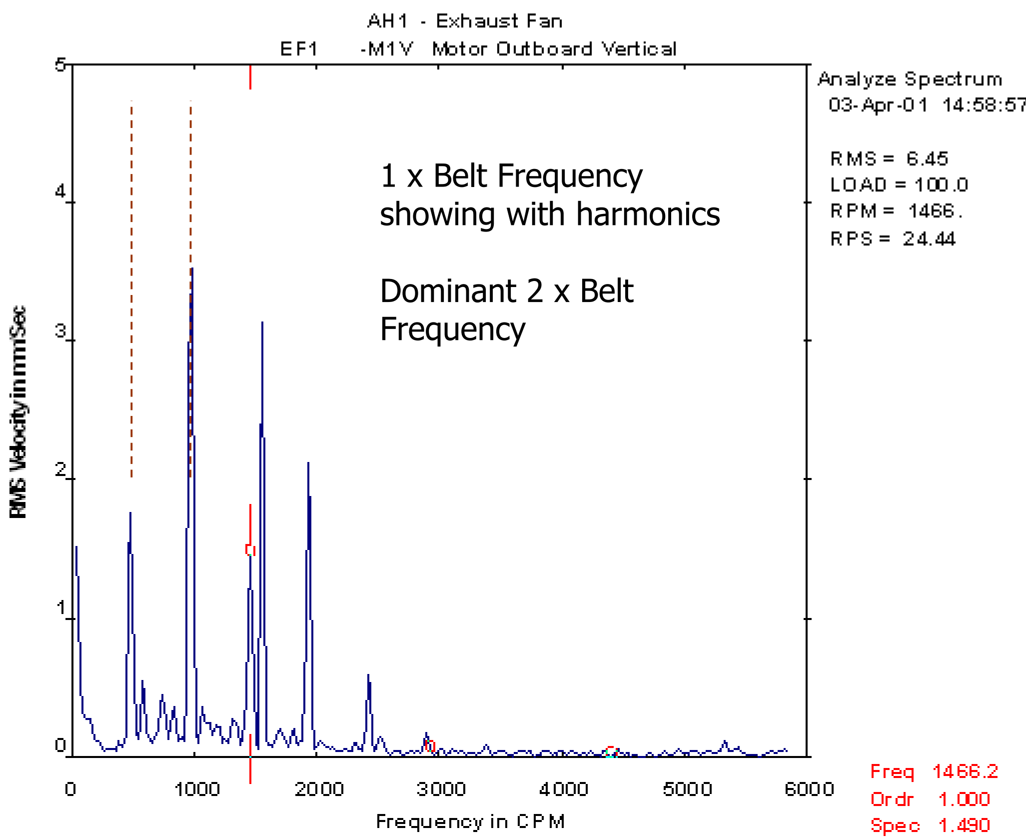
Belt Defects – Calculation Example

- Belt Frequency Calculation
- Belt Frequency = (3.142 * 1480 * 300) / (2000)
- Belt Frequency = (1395048) / (2000)
- Belt Frequency = **697.524 CPM**
  - **This is sub-synchronous to the 1xTs of the pulley**



Belt Defects – Spectral Data

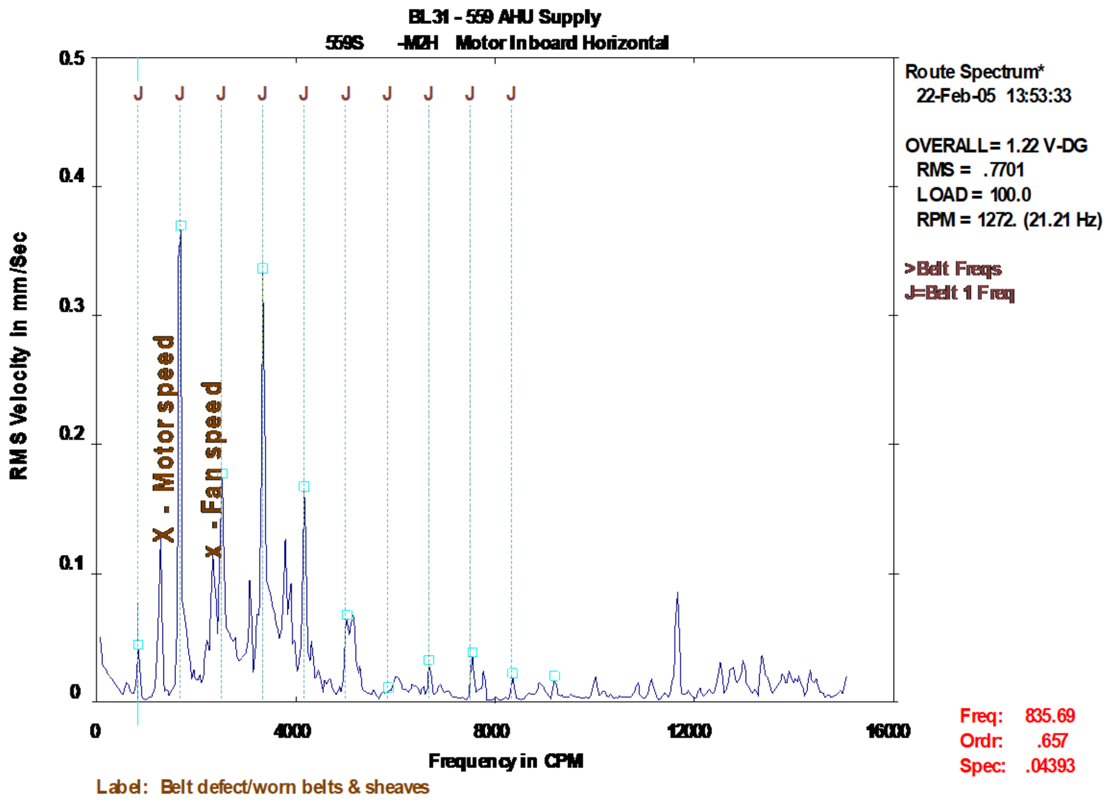
- The spectral data above is data taken of a motor from an Air Handling Unit.
  - The frequency highlighted by the primary cursor is showing the 1xTs of the motor (1 Order)



- There are a lot of sub-synchronous peaks showing in this data.
  - The first peak is the fundamental frequency of the belt rotation.
  - The second peak is the 2xbelt frequency suggesting there is damage to the belt
  - As the harmonics of the belt increase in number they surpass the 1xTs of the motor and in this case the third harmonic becomes non-synchronous data.

Case Study 8 – Belt Defect

- The following data was taken on an Air Handling Unit. The Air Handling Unit is a supply fan from shared services. This is a stand alone unit with no stand by capability



- The data shows the motor turning speed along with a sub-synchronous peak of the belt frequency.
- The primary cursor is highlighting the 1xbelt with several harmonics.
- The 2xbelt is very dominant suggesting there is damage to the belts.

Case Study 8 – Belt Defect

- As this is a critical machine it was recommended on the next available opportunity that the belts needed to be checked for damage and re-aligned.

- The machine was stopped and the belts were inspected based upon the recommendation.
- Significant damage was found to several of the belts during this inspection as well as worn pulleys. Both the belts and pulleys were replaced and correctly aligned before re-starting the machine.

Resonance

Resonance

- Resonance is defined as:

***An excitation of a natural frequency by a periodic forcing function*.**

- ***All*** assets contain natural frequencies that vary depending upon the stiffness and mass.
  - Resonance can be considered to be a vibration amplifier, that takes the force level of the periodic forcing function and amplifies it; which significantly increases the movement of the asset.

If Vibration is a Fire, The Resonance is a Fuel

Resonance

- There are two factors that determine the natural frequency of an asset these are;
  1. Mass – The heavier an object the lower the natural frequency
  2. Stiffness – The more rigid a structure the higher the natural frequency

- Resonance is becoming more of a problem in industry in recent years due to:
  - Older equipment having to run faster to meet current production demands (often above what it was designed for)
  - Equipment is being built cheaper and lighter
- This is resulting in amplification of the forcing function creating excessive machine movement resulting premature machine failure.

Characteristics of Resonance

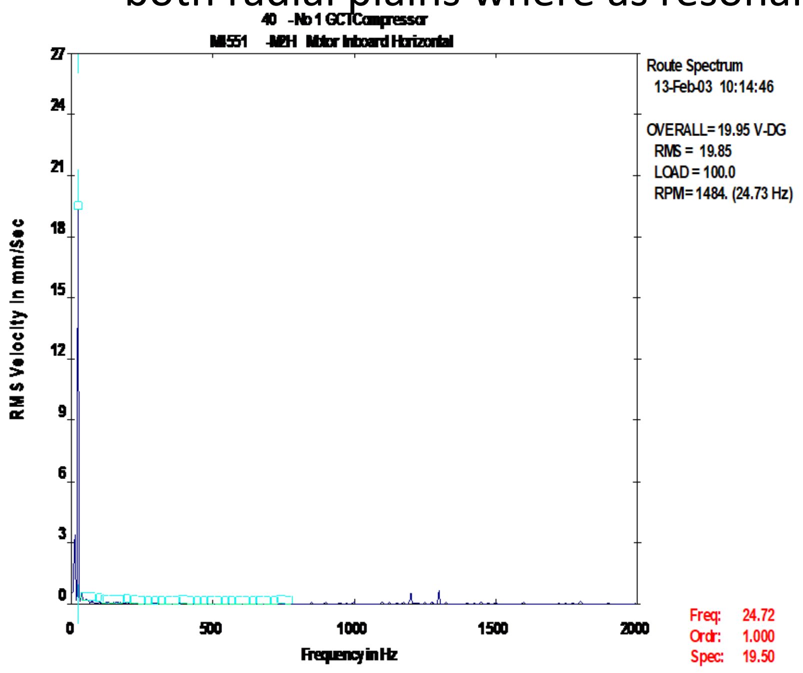
- **Characteristics of Resonance**
  - Resonance is very directional in nature (Movement may be greater in one plain than the other)
  - Vastly different amplitudes of the forcing function from one direction to the other (between Horizontal and Vertical – Rule of thumb ratio is 3:1 difference)
  - Resonance is very speed sensitive (small changes in speed can show large differences in amplitude of the forcing function)
  - Resonance can occur at any frequency but most commonly associated with the 1xTs

Resolving a Resonance

- There are a number of alterations to the system that can be made to resolve a resonance condition.
  - However if structural changes are to be made you need to be careful you don't excite another natural frequency once the change has been made?
- Once you are sure you have a resonant condition it can be corrected by one of the following methods:
  - Change the Mass
  - Change the Stiffness
  - Remove the forcing function
  - Dampen the structure
  - ❖ Dampening is a method used to convert mechanical energy into thermal energy. It does not remove the resonant condition only controls the amount of movement.

Resonance – Spectral Data

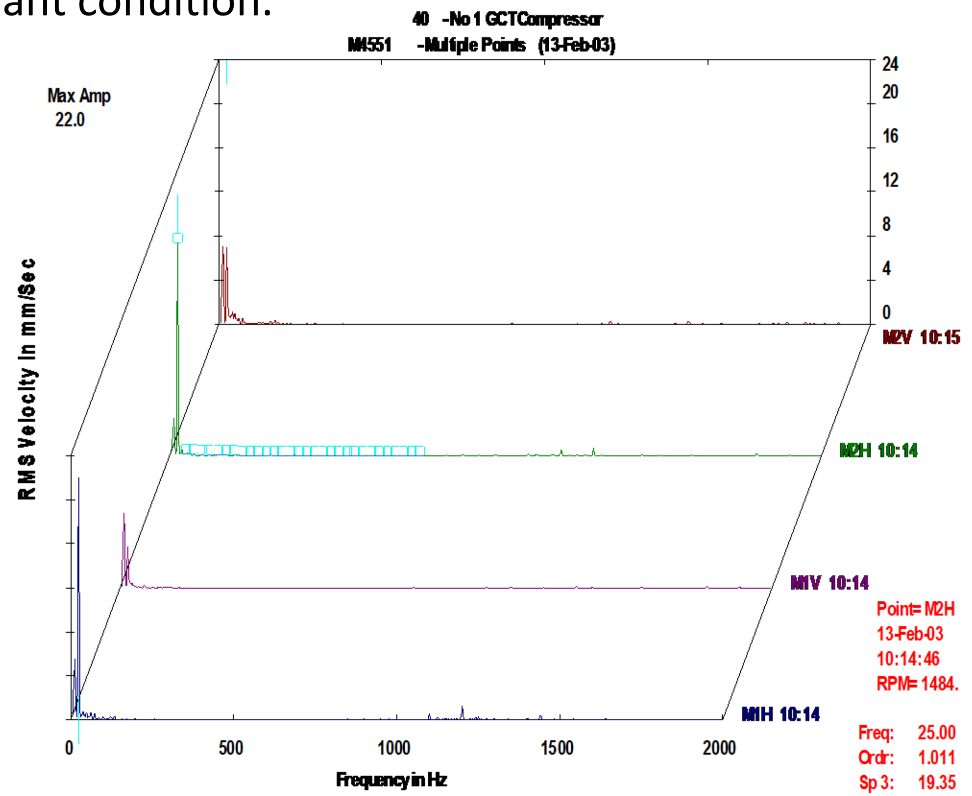
- The spectrum is showing the 1xTs peak of the motor with amplitudes reaching 19mm/sec.
  - This is high for the 1xTs.
- Very often this type of data can be mistaken for Imbalance as this defect can also produce a high 1xTs peak.
  - However Imbalance is a centrifugal force and should show similar amplitudes in both radial plains where as resonance is very directional.



- In order to help resolve this issue we need to check the amplitude of the 1xTs 90 degrees to this point (horizontal to vertical)
  - This can easily be done by using the *'multi point plot'* in the software

Resonance – Multi Plot

- The multi point plot allows the analyst to display several measurement points on the same plot. Here we are showing all the radial points from the motor.
  - It is very clear that the amplitudes of the 1xTs peak are excessive in the horizontal direction when compared to the vertical. This is a characteristic of a resonant condition.



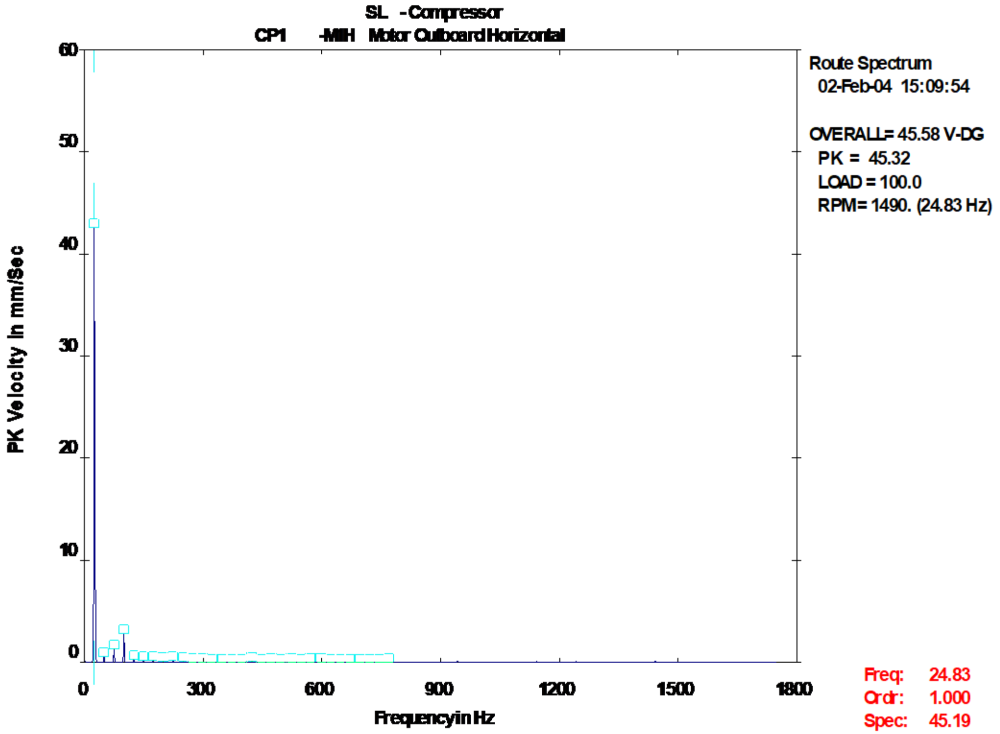
Case Study 9 – Resonance

- The following case study is taken from a motor and a reciprocating compressor. The unit is mounted on a steel frame which, in turn sits on spring mounts designed for dampening

- Recently the motor had been replaced due to bearing defect; however the new motor was smaller and lighter but delivered the same power as the previous motor.
- When the compressor was put back into service it was noted there was excessive vibration coming from the unit. The unit was left to run like this for several months until the vibration became to excessive.

Case Study 9 – Resonance

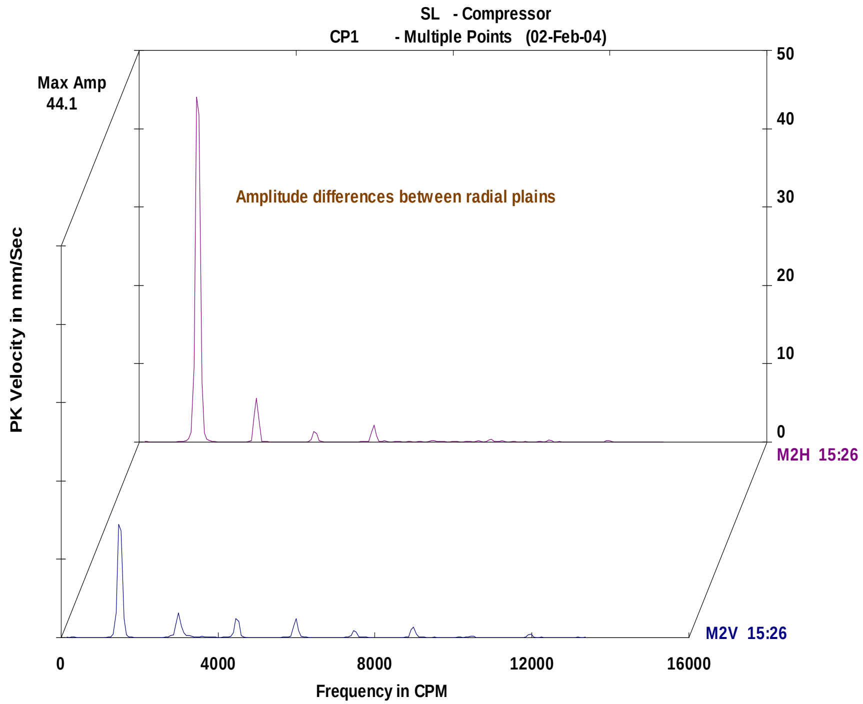
- Data was taken across the unit using route based data collection.



- The plot above is taken from the motor showing a 1xTs peak in excess of 40mm/sec.

Case Study 9 – Resonance

- This data is very high in amplitude.
- The data was then displayed in a multi plot format to show how the amplitude was across the radial plains.
- Due to the vastly different amplitudes at the 1xTs frequency the defect on this motor was Resonance.

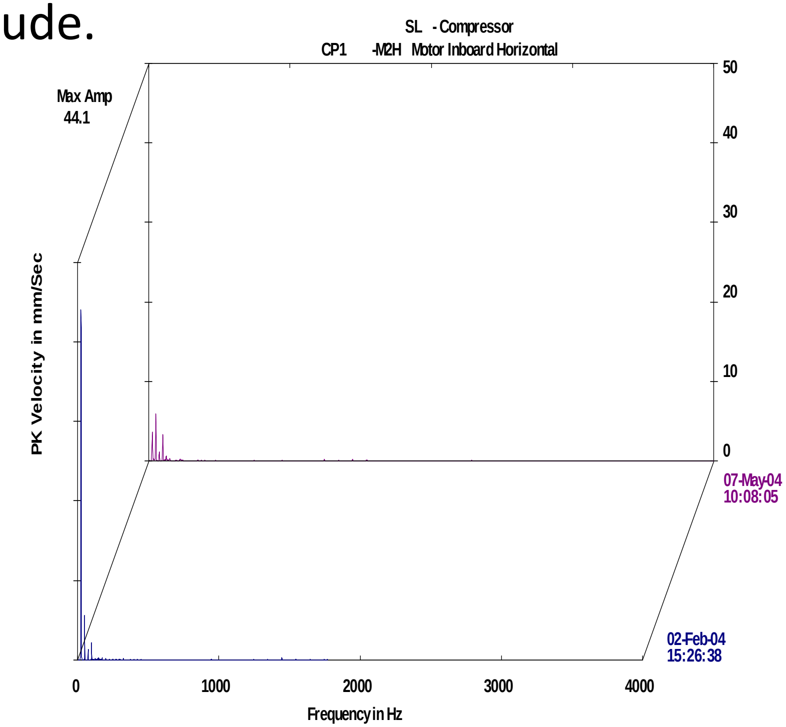


Case Study 9 – Resonance

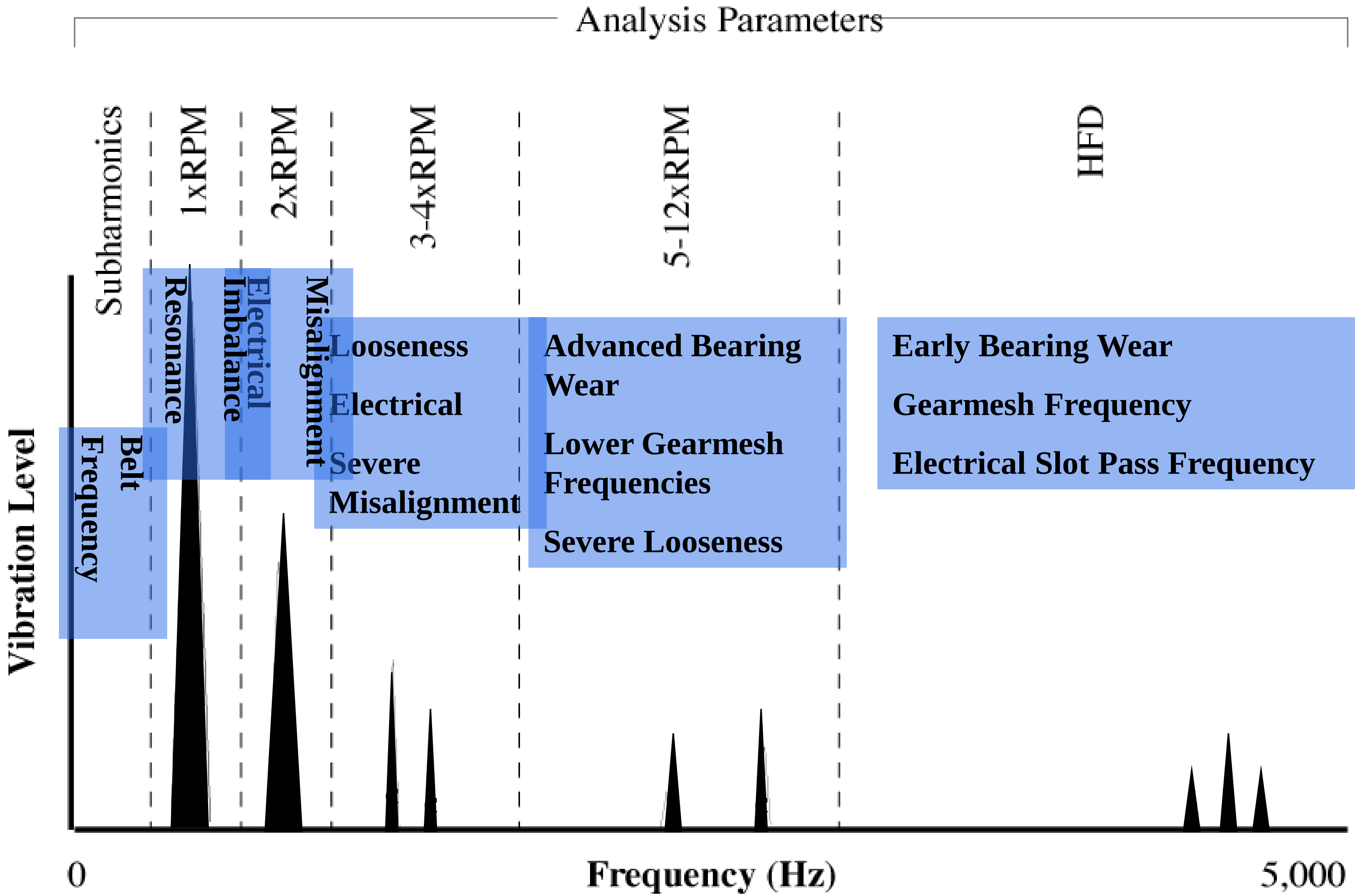
- **Recommendation**
- It was determined that the change in motor size may be the cause of the resonance as the mass had been altered. A visual inspection of the frame work also revealed that one of the support beams had cracked along the weld – this altering the stiffness of the structure. The support was welded and strengthened and more data was acquired to determine if any effect on the resonance had occurred.

Case Study 9 – Resonance

- The spectra, shows the 'Before' and 'After' plot of the motor inboard horizontal. It shows a significant drop in amplitude of the 1xTs peak.
  - By stiffening the structure the natural frequency had increased moving it away from the 1xTs peak thus resulting in a significant drop in amplitude.



Summary of Faults



Frequency In Terms Of RPM	Most Likely Causes	Other Possible Causes & Remarks
1 x RPM	Unbalance	1) Eccentric journals, gears or pulleys 2) Misalignment or bent shaft - If high axial vibration 3) Bad Belts - If RPM of belt 4) Resonance 5) Reciprocating forces 6) Electrical problems 7) Looseness 8) Distortion - soft feet or piping strain
2 x RPM	Mechanical Looseness	1) Misalignment - if high axial vibration 2) Reciprocating forces 3) Resonance 4) Bad belts - if 2 x RPM of belt
3 x RPM	Misalignment	Usually a combination of misalignment and excessive axial clearances (looseness).
Less than 1 x RPM	Oil Whirl (less than $^1/_2$ RPM	1) Bad drive belts 2) Background vibration 3) Sub-harmonic resonance 4) "Beat" Vibration
Synchronous (A.C. Line Frequency)	Electrical Problems	Common electrical problems include broken rotor bars, eccentric rotor unbalanced phases in poly-phase systems, unequal air gap.
2 x Synch. Frequency	Torque Pulses	Rare as a problem unless resonance is excited
Many Times RPM (Harmonically Related Freq.)	Bad Gears Aerodynamic Forces Hydraulic Forces Mechanical Looseness Reciprocating Forces	Gear teeth times RPM of bad gear Number of fan blades times RPM Number of impeller vanes times RPM May occur at 2, 3, 4 and sometimes higher harmonics if severe looseness
High Frequency (Not Harmonically Related)	Bad Anti-Friction Bearings	1) Bearing vibration may be unsteady - amplitude and frequency 2) Cavitation, recirculation and flow turbulence cause random, high frequency vibration 3) Improper lubrication of journal bearings (Friction excited vibration) 4) Rubbing

Thanks