A Guide to

Vibration Analysis and Associated Techniques In

Condition Monitoring

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Direction and Knowledge

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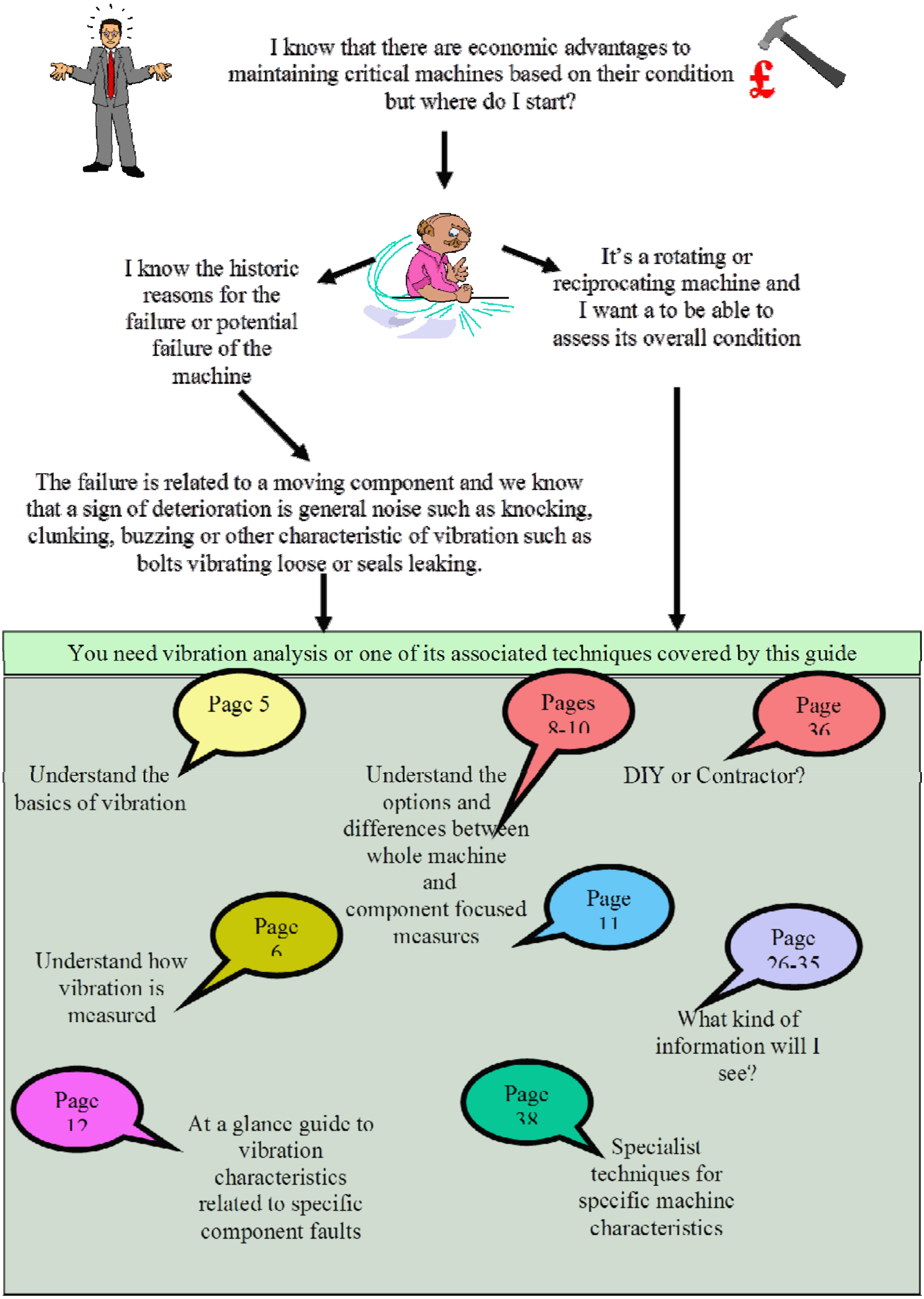
An Overview of Vibration Analysis associated techniques and this guide



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1. About this Guide

The introduction of technology that allows the condition or 'health' of machinery to be checked with the minimum of or no intrusion is one of the most cost-effective maintenance tools currently available. Official figures from the late 1980's indicated that companies with an effective Condition Monitoring (CM) programme were saving 25% on maintenance spend. With the advent of more compact and easy to use equipment the advantages of monitoring machines through their vibration characteristics can now be realised for outlays of well under £1k.

This Guide is aimed at practising maintenance personnel, maintenance managers, and plant engineers. It addresses the principle of CM, a range of the more common vibration and associated techniques available, the kind of condition information you can expect to see and through case studies, examples of how that information can be best used. It will equip you with enough background knowledge to be able to ask the right questions, understand the options and identify the basic technique commercially available packages promote.

The main principle of CM is that we determine 'normal' machine vibration levels (and accepting that deterioration in mountings, rotating and related components and imbalance will be reflected by a change in vibration characteristics); quantify the degree and severity of degradation and respond with the appropriate maintenance.

These 'appropriate responses' targets resources, improves plant reliability and availability and reduces overall maintenance intervention and hence spend. It also provides the flexibility to determine and plan repair needs in advance and carry out maintenance only when needed and preferably when production demand is low.

Nothing can identify defects before they happen but vibration analysis can identify the signs of machine deterioration, allowing opportune intervention and avoiding further damage and the consequences of catastrophic failure.

The two most important outputs from vibration analysis are diagnosis and prognosis. Diagnosis identifies what is wrong with the machinery, and prognosis estimates how bad the condition is or, ideally, answers the question, "How long will it last?"

2. VIBRATION

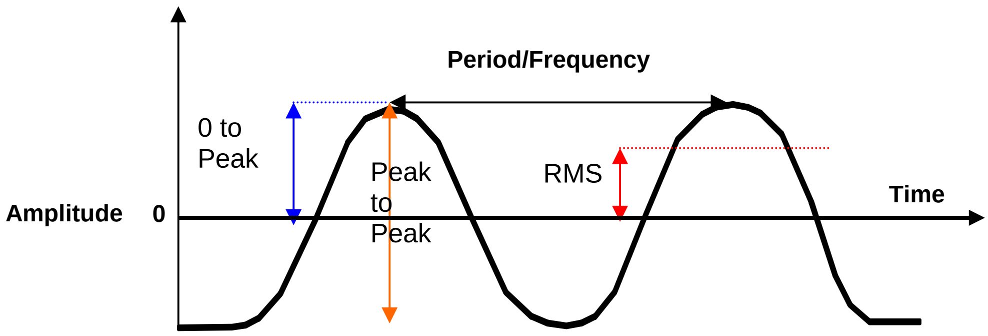
2.1 Understanding vibration

Our senses of touch and hearing are quite sensitive and often the experienced operator or technician can sense from experience when ‘the machine doesn’t feel (or sound) right’. Although this is not a quantifiable measure the experienced maintenance manager knows to ignore such warnings at their peril. Quantifying these feelings is another matter, but what if they could be quantified, comparisons made in a meaningful way and the sensitivity enhanced? Vibration analysis provides just such a capability, allowing us to detect subtle changes in a machine’s operation over time either by establishing normal variation - measuring and trending data to determine condition; or by comparing the vibration values obtained against established standards.

Simple vibration

All machines suffer from vibration, this is triggered either by an internal or external force (excitement), or due to the imbalances that are an inevitable feature of the mass of rotating components not acting through their centre of gravity (a feature of build tolerance). Vibration is the oscillating motion of a particle about a reference position, the motion repeating itself, exactly, over a defined period of time.

The simplest form of vibration is a single frequency system.



As can be seen the amplitude varies with time across each cycle and the motion is that of a simple harmonic or sine wave.

Amplitude is the magnitude of dynamic motion and indicates the severity of vibration, it can relate to displacement, velocity or acceleration and is commonly expressed as Peak to Peak value, 0 to peak value or Root Mean Square value (RMS).

2.2 Vibration as a measure of machine health

The basic method of measuring machine 'health' is by measure of dynamic motion commonly called the 'whole machine', 'overall', or absolute value. Recording and trending of results against the machine's normal value (obtained by establishing a trend history) is the most accurate method of condition assessment but "one-shot" or initial machine assessment is usually against ISO and other associated standards.

With advances in technology and the miniaturisation of analysis equipment a range of vibration measurement devices are now available. At the basic end of the market are whole machine devices which tend to operate in the 10Hz to 1kHz frequency range. This range is considered optimum for assessing rotational and structural defects such as:

- Imbalance
- Resonance
- Misalignment
- Looseness
- Mechanical stresses
- Mounting (foundation) softness
- Drive belt problems
- Eccentricity
- Rotor vane loss or damage and rotor bow

It is important to understand the relationship between frequency, displacement, velocity and amplitude, because it is this which governs which parameter is best monitored (and what intruments are used to measure) to suit monitoring needs. Basically if you monitor the wrong parameter you may miss the condition information you want.

- Frequency is measured in cycles per second (Hz)
- Machine rotational speeds in revolutions per minute (RPM)

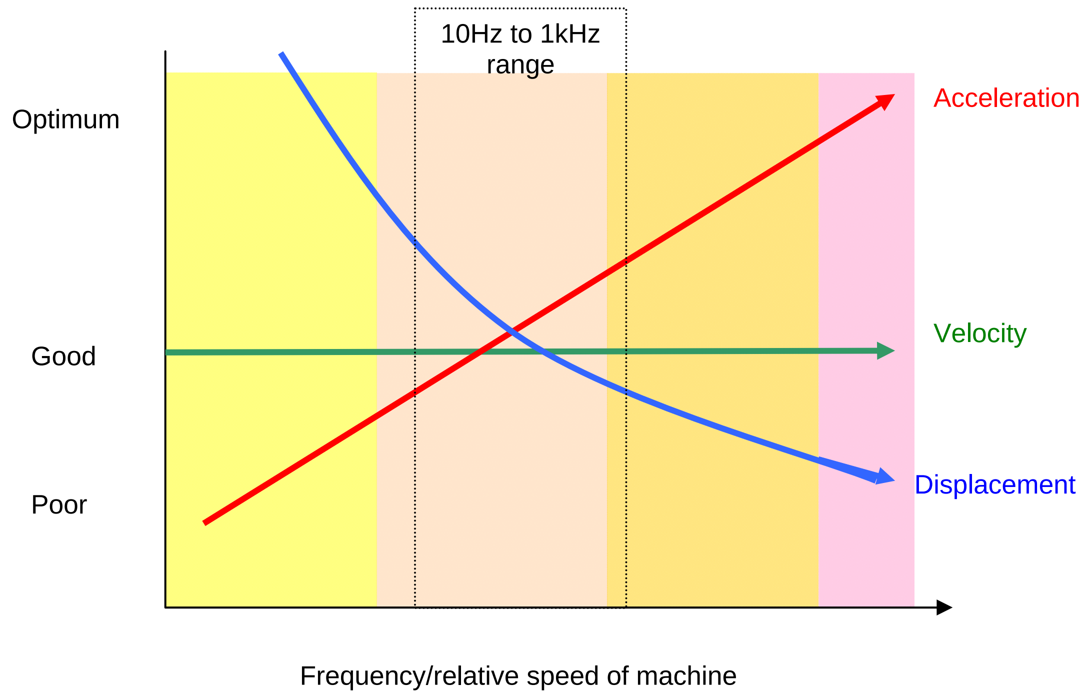
As frequency is related to RPM we can say that $\text{frequency} = \frac{RPM}{60}$

So that in a machine running at 1800 RPM we would expect to see the primary frequency (often referred to as fundamental or x1) at $\frac{1800}{60}$ or 30Hz

- Harmonics are sympathetic vibration signals generated at exact multiples of primary frequency (x2, x3, x4, etc.)

It can be seen from the diagram below that at low frequencies (and machine running speeds) displacement or velocity values are of good quality, but at higher machine/component operating speeds (typically bearings) acceleration measures are better used. Note that across the entire range of operating speeds velocity will give a good representation of condition.

Choosing the appropriate parameter to measure



It should also be noted that the energy of the signal generated by machine components tends to decrease with frequency. For example low speed vibration such as misalignment generates a strong, high energy, high amplitude signal, whilst bearings typically generate low energy, low amplitude, high frequency signals.

Some of the measurement devices available and the majority of the mid-size portable devices are capable of measuring high frequency repetative vibration signals and this

Acceleration is the rate of change of velocity measured in terms of gravitational force (g).

Displacement is the measure (in thousands of an inch[mil] or microns) of movement of the vibrating surface.

Velocity is the speed at which displacement takes place and is measured in mm/sec RMS or inches /sec RMS.

is useful for:

- Rolling element bearings
- Gearmesh analysis

High frequency signals would not normally be captured in the frequency range of overall readings because their low amplitude will not show against the machine's dominating (high magnitude primary) rotational and structurally generated signals.

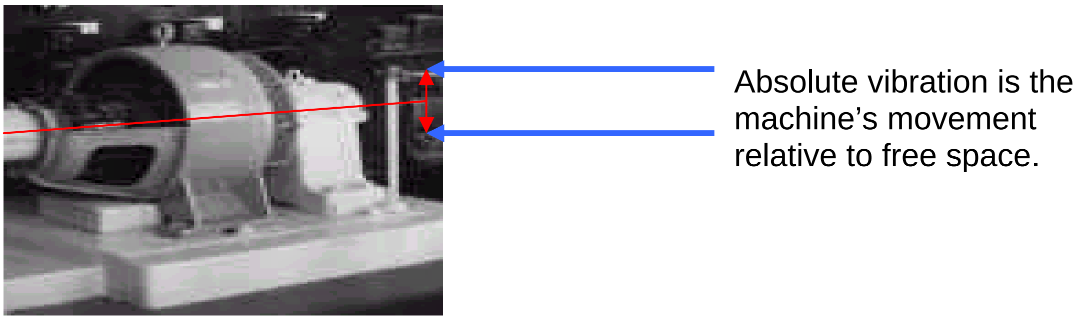
These low amplitude frequencies can be electronically enhanced and amplified using acceleration enveloping techniques, (this is dealt with in some detail later) but effectively this filters out low frequency rotational signals and enhances high frequency repetitive signals in the 10kHz to 30 kHz range).

2.3 Machine vibration

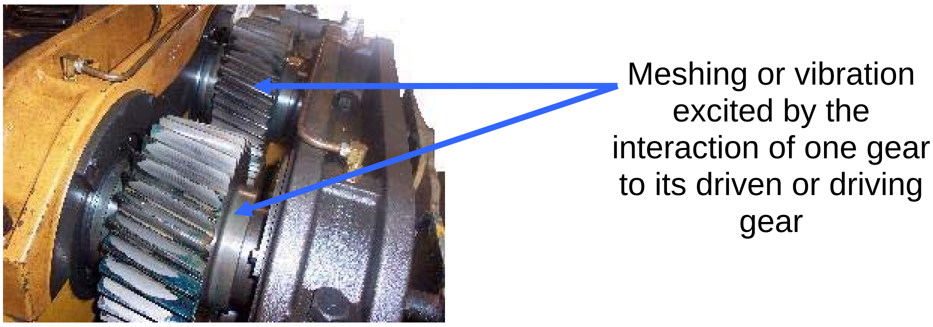
Even the simplest machine generates far more complex signals than the simple sine wave. The vibrations come from the primary frequency (which will usually be at the rotating speed of the machine), its harmonics and from a number of sources within the machine. This generates a wide range of signals at different frequencies, known collectively as a **spectrum**.

Additionally, all vibrating systems have natural frequencies (a function of mass and stiffness) at which very high amplitudes can be excited by a force applied at the same frequency. This phenomenon is known as resonance, which is a useful characteristic in its own right and one we shall explore later.

Vibration is one of the primary dynamic monitoring tools used in condition monitoring (CM). It is routinely used to measure 'absolute' vibration (the whole machine relative to free space);

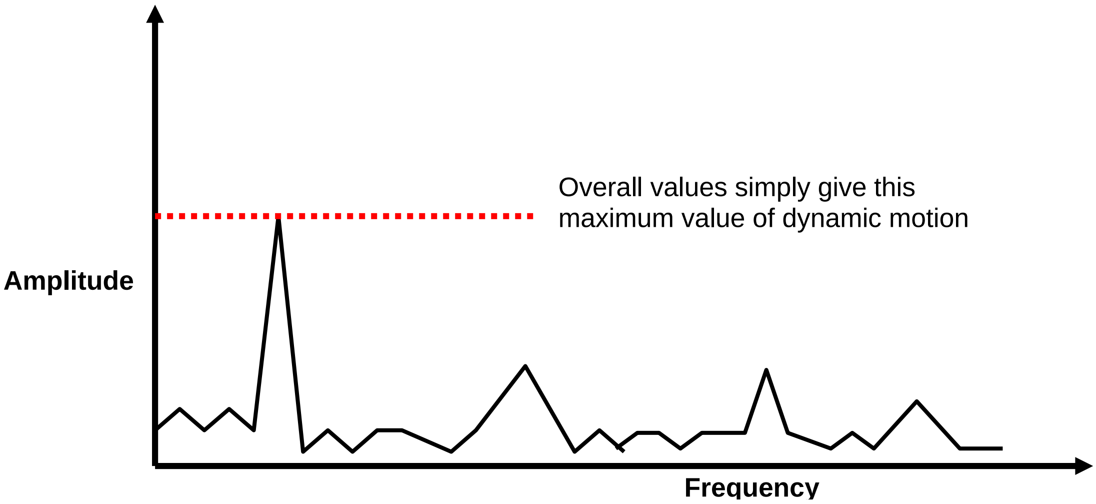


Or friction induced excitation caused by the vibration of meshing gears or vibration caused by passing components (typically fan blades)



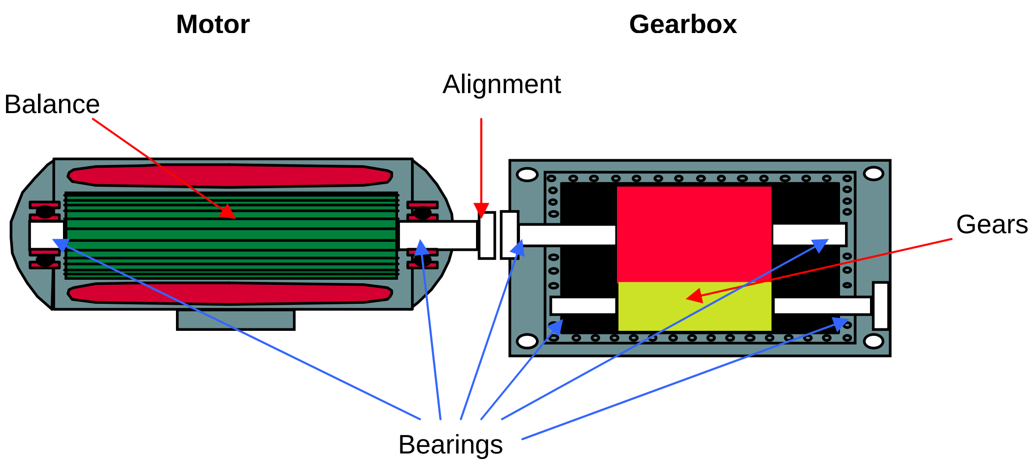
2.3.1 Overall values

Overall values measure the absolute or whole machine vibration level and tend to be dominated by predominant amplitude of the whole machine as reflected in the spectrum below.

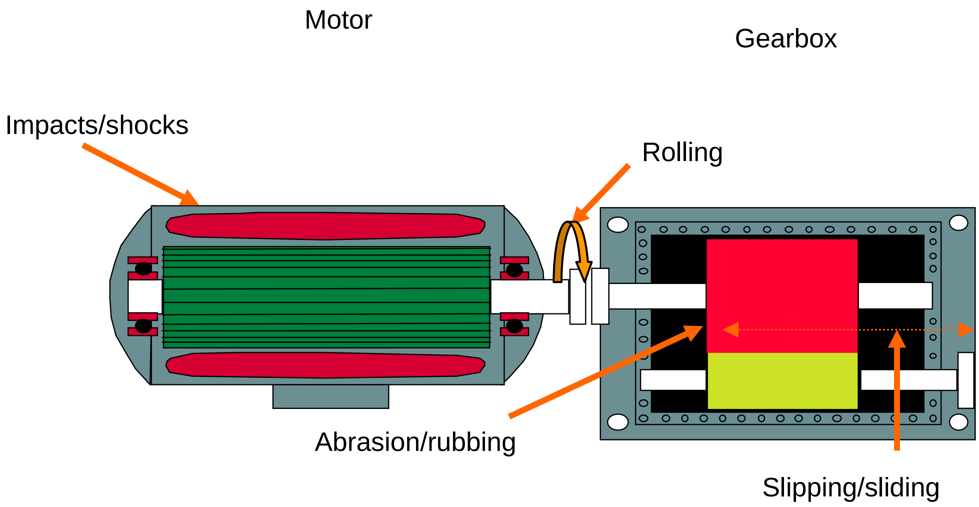


These overall measures usually give us go/no go or graduated (good, acceptable, just acceptable, unacceptable) information based on the overall amplitude reading.

However, a spectrum can give us far more information. In a motor gearbox combination we would normally take overall machine vibration levels on the motor and gearbox separately.

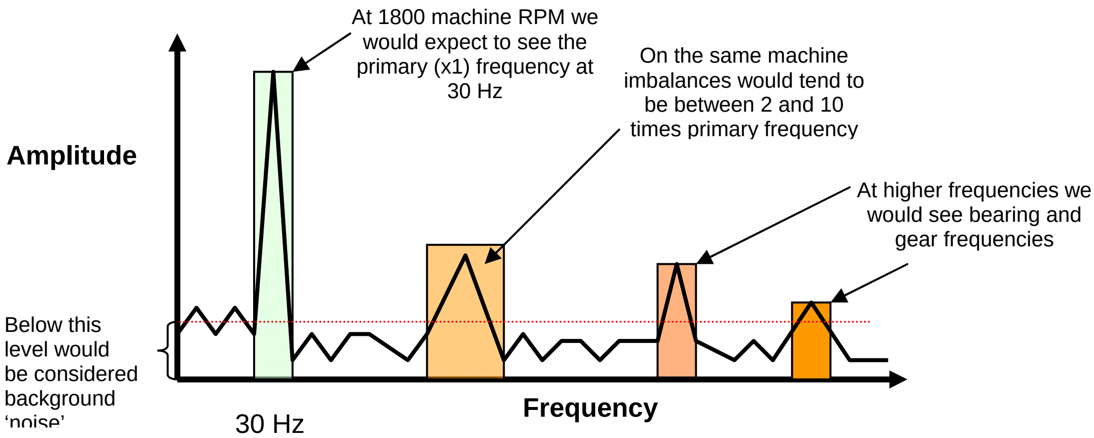


We can measure overall vibration and get go/no go type information but more specific techniques will allow us to hone in on specific components.



2.3.2 Frequency Analysis

A gearbox spectrum will include primary frequencies generated from the rotation of shafts, whilst other frequencies will be generated by harmonics of these primary sources and such things as the tooth contact of different gear sets and in bearings the ball passing frequencies.

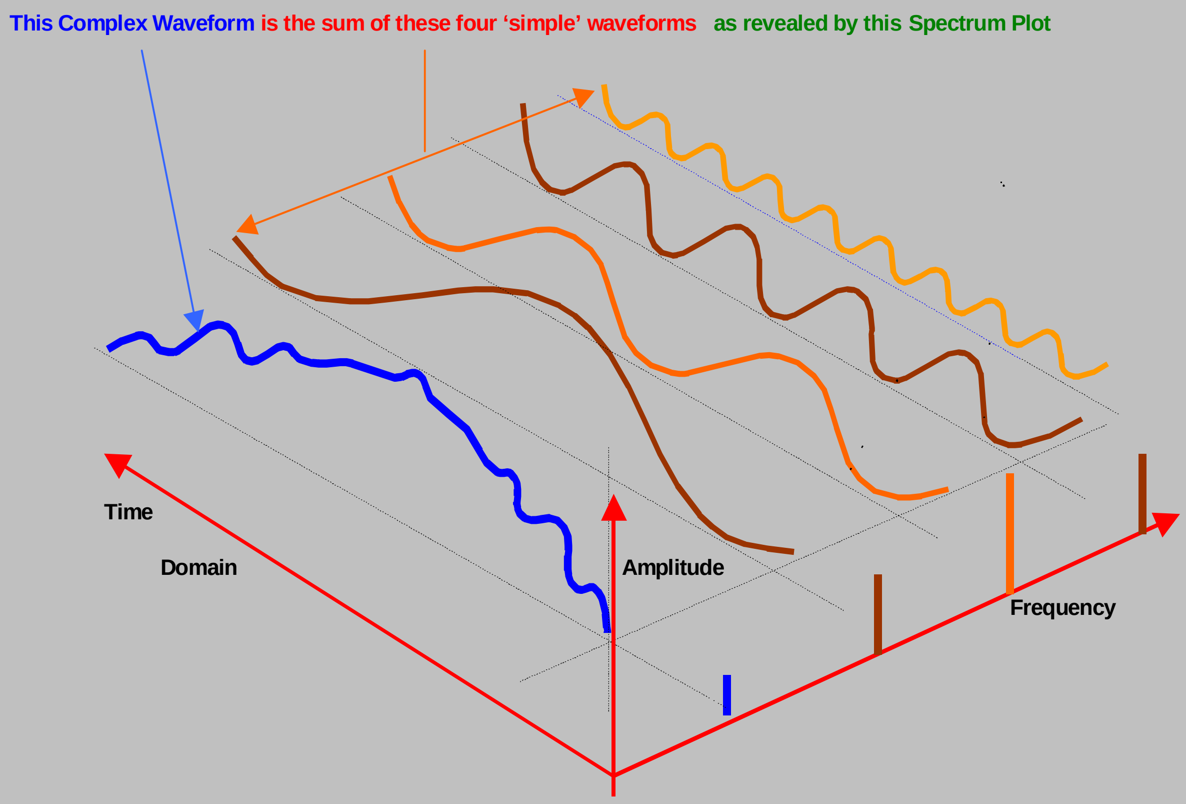


Overall or whole machine vibration level monitoring relies on any change in any one of these component's vibration characteristics affecting the 'whole machine' signal (it will not be detected until it influences the maximum amplitude).

Spectrum Outputs

The more specialised techniques will give a spectrum output as well as overall vibration levels and this gives a more complex and detailed output and so enables you to examine the state of individual components. A plotted history of frequency is commonly known as a **'waterfall'** and is a useful trending tool.

Fast Fourier Transform - Machines have many sources of vibration and generate complex vibration curves of limited value in unfiltered form. Fourier found that any finite; time-ordered set of data can be approximated by decomposed into a set of sine waves. Each sine wave has a specific frequency, amplitude, and phase relationship to the other sine waves, so that the variation level against time is transformed into a constantly changing display of amplitude against frequency.



FFT sacrifices phase relationships and concentrates on frequency and amplitude and has the following benefits.

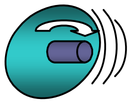
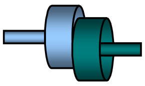
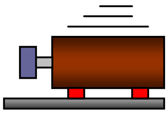
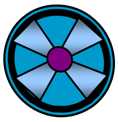
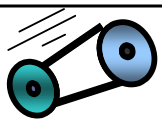
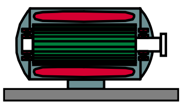
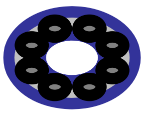
Its ability to extract the predominate cycle(s) from a series of data (e.g., complex machine outputs).

The entire time record is sampled and then processed at the same instant and the effect of random or one off events is minimised.

Vibration analysis can analyse changes in machine condition in a number of ways;

- At 'first pass' level as an increase in 'Whole machine' vibration magnitude
- By using more refined frequency analysis techniques to pinpoint the source of problems

2.3.3 A Guide to Fault / Frequency Relationships

Typical Fault & Dominant Frequency		Details	Comments
 IMBALANCE	x 1	Imbalance occurs at rotational frequency equal to 1 x rpm of the out of balance part. Usually radial (horizontal or vertical) Sometimes dynamic (axial)	Amplitude is direct indication of degree of imbalance
 MISALIGNMENT	x 2	Typically angular and/or offset problems in couplings Radial + Axial	In both radial and axial directions also apparent at x1rpm because of imbalance inherent to misalignment
 LOOSENESS	X 2 Natural X 1	Mechanical - caused by loose rotating parts or excessive play in machine mountings	Typically a machine will vibrate as it hits a natural resonant frequency during run up or run down - once the associated rpm is passed vibration amplitude decreases
 PASSING	X 1 and (x1)x(No of blades/vanes)	Usually cause a x1 frequency component and a multiple related to the number of vanes/blades	Also referred to as blade pass frequency
 MESHING	No. of teeth x rotational frequency of associated gear	Defects cause low amplitude high frequency vibration and show imbalance, misalignment and tooth damage associated with Gear Mesh Frequencies	Gear Mesh Frequency = output gear rpm x No. teeth in output gear. e.g. 32 tooth gear operating at 300 rpm [300/60 =5Hz] GMF = 32x5 = 160Hz
 BELTS	Related to rotational speed and multiples of rotational speed	Vibration analysis will identify rubbing and misalignment	Use strobe techniques to identify slipping belts
 ELECTRICAL	At supply frequency and multiple of	50Hz(UK)	Vibration will stop when power is turned off!
 BEARINGS	3-10 x rpm & Higher	Bearings indicate problems at high frequency 2- 60KHz (in the early stages of deterioration) and at low amplitude	Range of techniques available with bearing cabability

3. MACHINE VIBRATION - TOOLS AND TECHNIQUES

As we have seen whole machine measurements are the entry level techniques for vibration and acoustic condition monitoring. They can be thought of as a highly sensitive development of the human dynamic senses of hearing and touch. The majority of commercial packages at this level offer 'add ons' and these are examined later.

Whole machine measures of vibration are taken as either the sole source of condition information or as a first level indicator in more advanced techniques. The measurement devices all use a pick up (transducer) of some kind . At its simplest the measurement device will be **hand held** with an integral transducer and readout display. Alternatively some whole machine (and the majority of the more advanced techniques) use a **portable** unit (or data collecter) with an attached probe. Most of these have both integral displays and the capability of downloading data to relevant software package on a standard computer.

Whatever the technique it's value depends on it being able to detect the relevant potential failure early enough to meet your needs economically as well as technically.

Other packages promoted as whole machine techniques tend to concentrate on bearings and depending on the characteristics of the machine(s) being monitored and their reliance on efficient bearing operation this might readily equate to your perception of the whole machine's condition.

The whole machine vibration broadband analysis technique uses a transducer either mounted or held at a suitable measurement point, which converts mechanical vibrations into an electrical signal and through a measuring device (vibration meter) shows the overall reading of the vibration signature at that point on the machine. The equipment is usually cheap and compact, gives primarily go/no go or pidgeonholed (against various standards) type outputs and requires little expertise. However, it does need care in application to deliver consistent measurements.

3.1 Tools of the trade

Overall vibration or broadband (FFT) amplitude using accelerometer transducers is the parameter usually monitored, with the more sophisticated apparatus being able to offer more focused fault detection.

Hand Held Devices

Simple portable monitoring is predominantly used for overall vibration readings and uses hand held direct reading devices with built in transducer.

Hand held 'Vibration pens' read overall vibration giving an instantaneous readout.

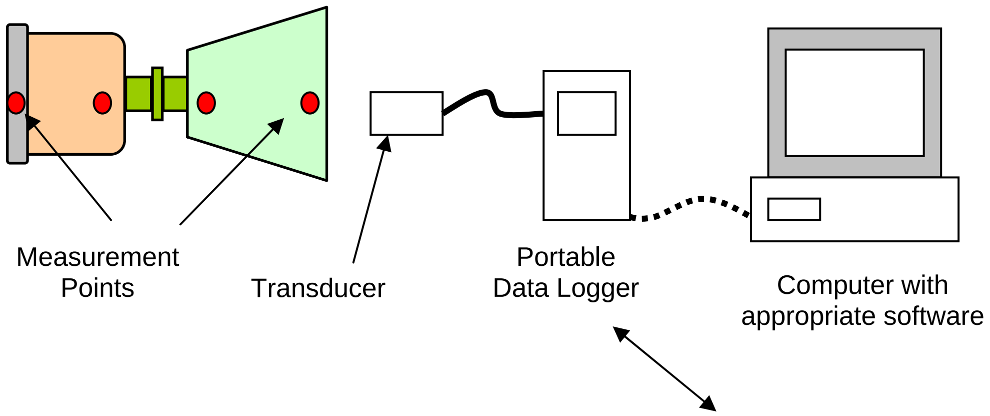
Some units have an additional high frequency capability for bearing and gear mesh monitoring (acceleration enveloping).

Other units consist of a transducer probe (accelerometer) connected to a processing unit with a direct readout and optional headphones

Hand held devices must be used with care because of their susceptibility to erratic readings. This is due to the pressure and angle of contact with the target machine, which can affect the transducer accuracy.

Portable Systems

Portable systems most commonly use data collection equipment, are a little more sophisticated and allow individual machine and machine point history data to be recorded (in the order they are collected), trended and analysed. Alarm levels can also be set on these devices.

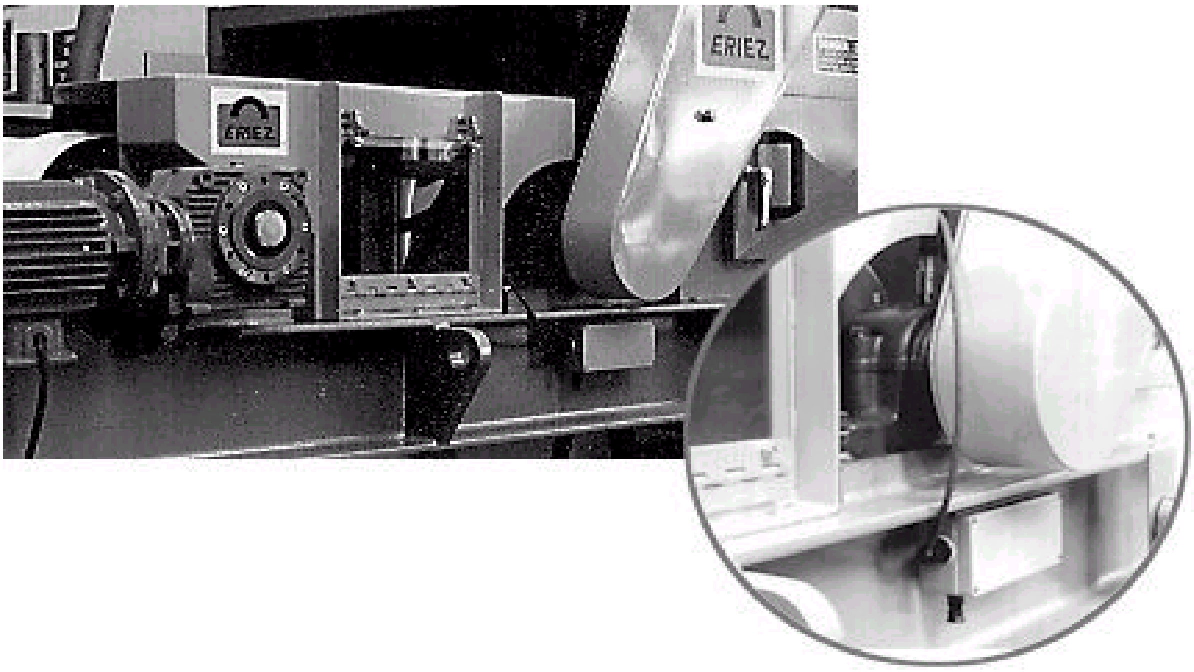


Data loggers often have a direct reading capability (mainly for whole machine or broadband applications) and/or downloaded to a computer with supporting software

The main advantage of portable devices is that they can be used for frequency analysis techniques and when combined with diagnostic and analytical software packages also provide component specific data. (This may require the use of a standard PC).

Permanent (hard wired) Systems

‘Hard wired’ (utilising permanently fitted transducers) systems are at the expensive end of the market and usually only the most critical of machines are considered for this method.



These systems allow short period remote (i.e. control room) monitoring of the machine and can carry a range of vibrational information including alarm, trend and peak information.

Some techniques in vibration analysis are designated ‘real time’ (see Specialist techniques) but they actually capture a ‘snapshot’ (at a fixed moment in time) or an averaged value over a fixed period, analyse them and then play them back. They may do this in a cyclic way so that continuously changing displays are achieved.

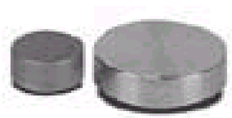
We have seen that vibration has three primary (and measurable) parameters…displacement, velocity, and acceleration and that each parameter is of some value, but it depends on the type and operating speed of the machine and the characteristic to be monitored as to which will be the most appropriate. These parameters are measured using transducers, which convert physical vibration into an electrical signal. The signal is processed giving a direct read-out or output to a data logging device and then via a standard computer (with supporting software package) condition information.

3.2 Transducers

The type of transducer used is dictated not only by the frequency range to be captured, but also by the design specification and the limitations of its mode of operation. The design characteristics of transducers give them a dynamic operating range (a frequency range in which they will perform optimally).

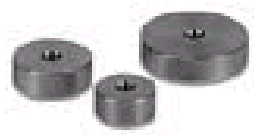
Whilst displacement transducers are used for proximity analysis and use an eddy current technique (detailed later) velocity and acceleration transducers are designed to measure perpendicular forces relative to their moving parts (usually at right angles to their base). Any deviation on this angle will result in an inaccurate reading of the movement they are measuring. This is largely overcome by the mounting method used i.e. the stiffer the mount the greater the frequency range and the more accurate the reading. Ideally the transducer is permanently mounted but this is not always possible, or desirable. It is common practice to fix mounts (or studs) to the machine/machine points to be monitored and these can be welded, screw-in, glued, bayonet fitting or magnetic plate devices (dependent on access and the hardware manufacturer).

A range of Mounts and Studs



Magnetic

Threaded



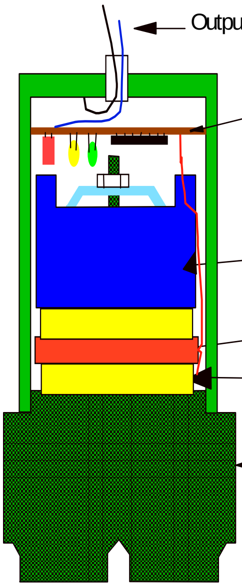
Screw in

All transducers measure the magnitude of dynamic motion; however, monitoring equipment manufacturers predominantly utilise accelerometers, which have a broad dynamic range.

Note: ***The terms acceleration and velocity applied to transducers describes the way they operate and <u>not</u> necessarily the vibration parameter they measure.***

3.2.1 Acceleration Transducers

The most common and widely used form of transducer for 'general health' and 'quick checks' (hand held and portable instruments tend to use accelerometers).



How it works

When force is applied to the piezoelectric material a charge is produced that is proportional to the force applied. Force is directly proportional to acceleration therefore any change in acceleration will produce a change in the charge emitted. The charge is amplified and the output voltage used to drive a meter or analyser.

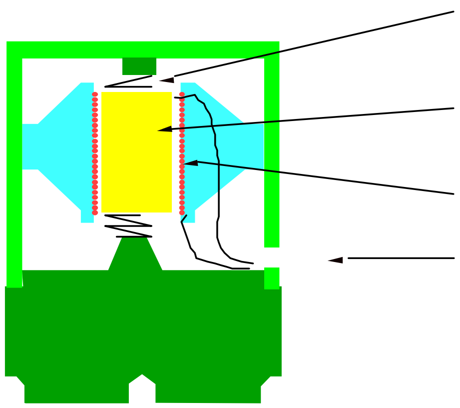
Frequency Range and typical uses

Frequency range is typically 10Hz to 30kHz, transducers have a wide dynamic range, (although range can be affected by mounting method, see above) can be surface or internally mounted. Insensitive to signals <5Hz they are robust, compact, and portable.

It has already been mentioned that vibration transmission paths are a key factor of transducer performance and affected by how rigidly the accelerometer is mounted. Manufacturers issue data showing the degree of accuracy and any range restrictions dictated by different mounting methods (the effective dynamic range).

3.2.2 Velocity Transducers

A common machine monitoring parameter and useful for general machine condition, imbalance, misalignment and general looseness.



How it works

Velocity transducers are usually surface mounted moving coil devices. As the surface vibrates the magnet moves in the coil producing a voltage proportional to the velocity of the vibration, this output then feeds a meter or analyser.

Frequency Range and typical uses

Frequency range is typically 1kHz, transducers are designed with a limited dynamic range, they are usually permanently fixed to the machine and used for monitoring of overall vibration levels on larger equipment. Relatively cheap but quite bulky.

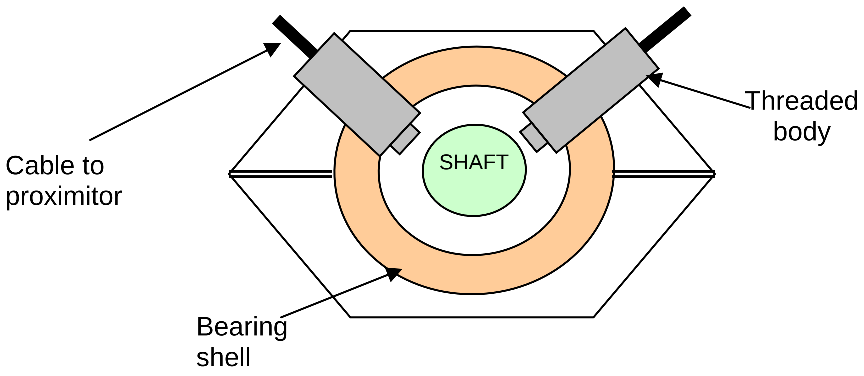
Velocity transducers are often used in stop gap or retrofit scenarios, they are easily installed (the transducers being surface mounted and self-generating) to produce a permanent system.

Velocity measurements are often a feature of simple hand held instruments but are not the ideal medium for detecting bearing defects, which are unlikely to be picked up by velocity instruments until significant damage has occurred.

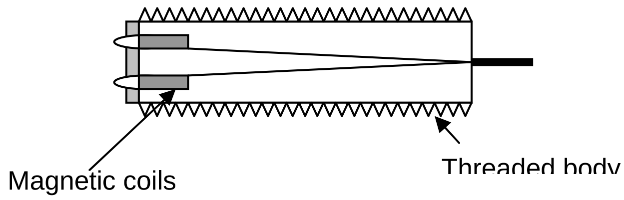
Trending of monitoring results is recommended for long term/ongoing machine condition evaluation, but “one-shot” assessments can be made against ISO 3945.

4 Displacement and Proximity Analysis

Displacement measures are almost exclusively used for proximity analysis and fitted by the machine manufacturer (very rarely retro-fitted). It can be useful for oil film bearings differential expansion, tachometers, rod drop and dynamic alignment.



Displacement is measured using eddy current probes. A change in readings indicates a change in position and hence signs of deterioration or defect.



The probe itself is a non-contact displacement type and this system is predominantly hard wired (fitted at manufacture). Systems are often specified to API 670 Standard measuring proximity limits (tolerances in mm, microns, thousands of an inch) for standard shaft/mounting combinations.

How it works

The probes are connected to a proximitor, which generates an excitation signal and produces an output proportional to position. The output voltage consists of a dc component, which corresponds to the gap (distance between probe and shaft) and an ac component, which corresponds to shaft vibration displacement about the mean position.

Frequency Range and typical uses

Low frequency range 0Hz to 10Hz, most displacement transducers can cover this range dynamically, must be permanently mounted to the machine. Used for monitoring of relative shaft movement and position within journal bearings on large prime movers.

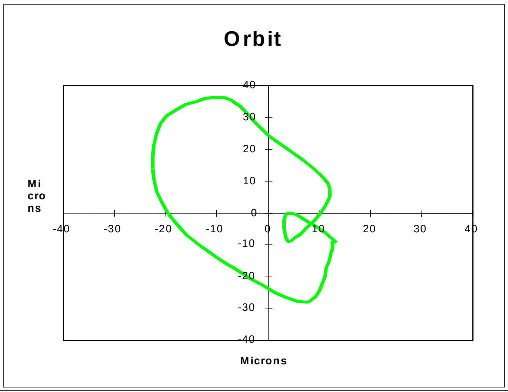
Proximity Analysis Application

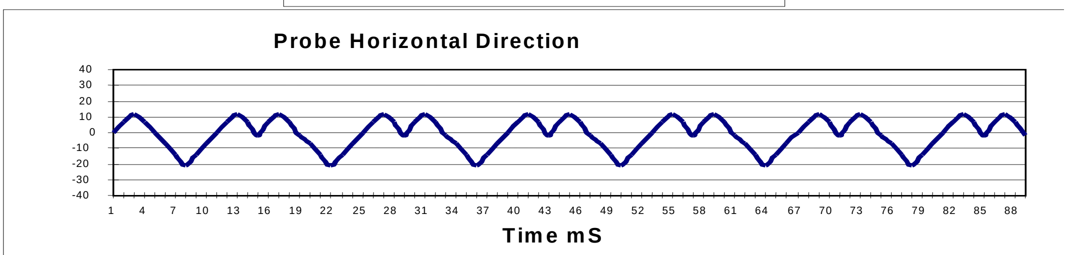
ANALYSIS TECHNIQUE	APPLICATION	ADVANTAGES	DISADVANTAGES	WHAT IT DETECTS	HOW IT WORKS
Proximity Analysis	Large Machines i.e. Motor assemblies, shafts, gearboxes, couplings, fans, etc. – Any motion of shaft centre within bearing	Identifies characteristics of rotation, good for balancing, portable data collector on fixed probes	Specialist diagnostic uses Relatively low frequency components Orbit analysis uses proximity probes (no retrospective fit)	Misalignment, interference, imbalance, eccentricity	Time waveform with option of orbit analysis (when shaft speed tachometer used) Generates sine wave on oscilloscope – in waveform offers repeating pattern equating to shaft displacement variation. When pulsed (orbit) can generate polar diagram showing shaft displacement around centre axis.

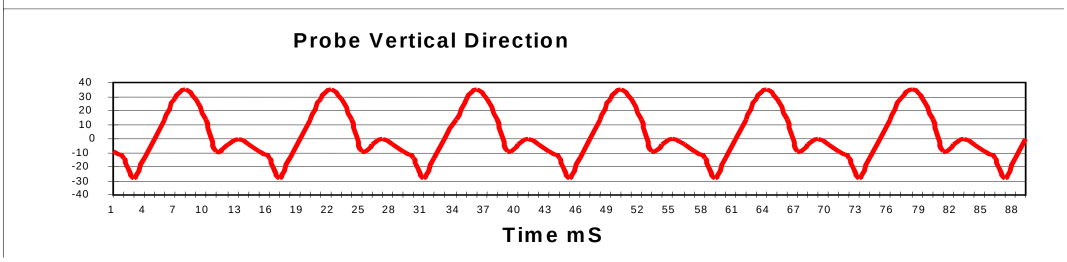
Proximity probes – Examples of Orbit Analysis and Time Waveform outputs

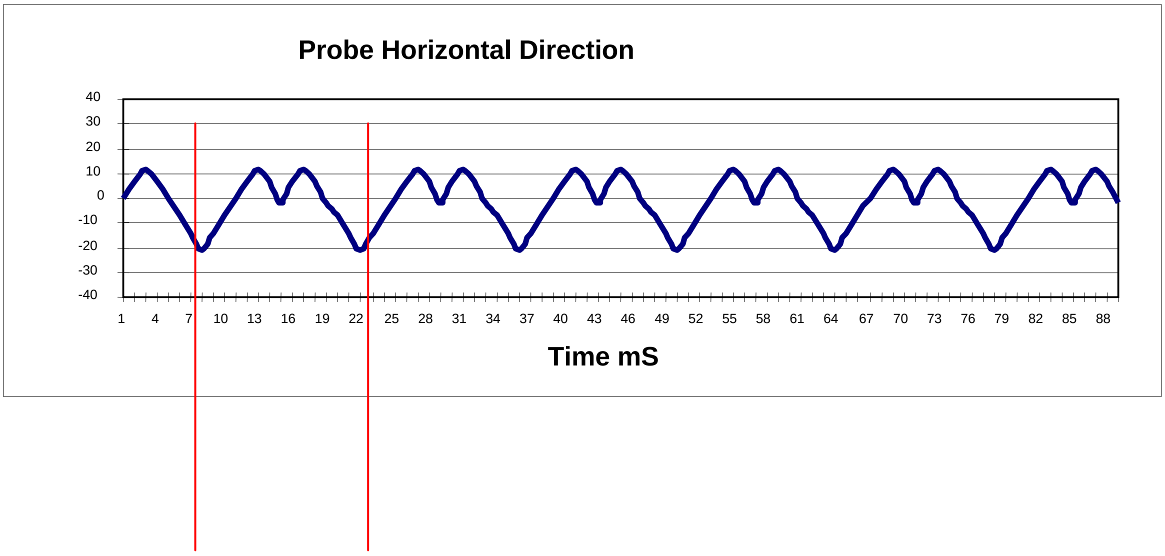
Time waveform plots are Microns v time in mS

The time waveform plots show the relative movement of the shaft in relation to the horizontal and vertical probes. The repetitive 'cycle' in each case can be clearly seen.









One cycle or complete rotation

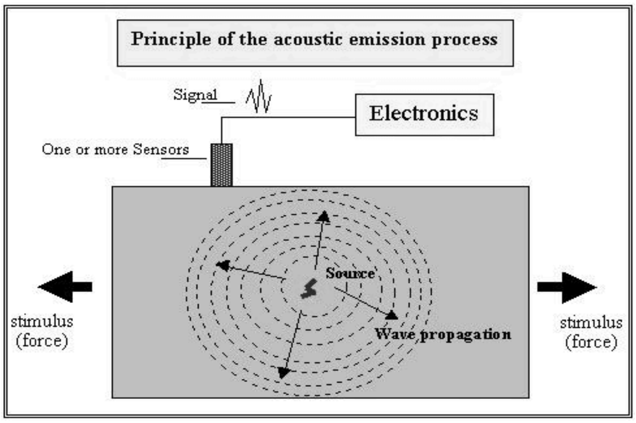
It can be seen that the shaft in relation to the horizontal probe moves between +12 and –22 microns from the central (0) position.

From the original plot on the previous page we can see that the vertical probe has recorded a movement of between +37 and –28 microns around 0.

The orbit diagram combines vertical and horizontal measures over (the time taken for) a complete rotation and provides a footprint of the movement of the shaft within its bearing or mount. By comparing this to the design tolerances of the machine we can determine whether it is working within its design parameters and identify major imbalance, misalignment and interference.

5. Acoustic Emission

In the engineering world modern resonance based AE techniques emanate from the practice of sorting good parts from 'clunkers' by hitting them and listening to them ring (hence other common names of ‘bump test’ and ‘hammer test’) AE uses a shock pulse. This works on the same principle…if an object is stimulated (bumped) the object’s natural or resonant frequencies are excited. AE identifies these natural frequencies and also captures additional signals generated by the object and takes them as an indication of machine condition (in a similar way to overall vibration measurements).



The signal obtained may be in audible or data format and is influenced by rotational speed, applied load and the presence of related defects that have led to metal to metal contacts (i.e. lubrication breakdown). The signal is subject to analysis but whereas vibration analysis monitors signals at low frequencies, which have to be ‘treated’ to eliminate background noise, AE uses higher frequency detection.

AE’s main advantages:

- allows a better signal to noise ratio and simpler processing.
- allows energy losses within the machine due to increased friction to be identified

The main disadvantages:

- a ‘first line’ indicator rather than advanced analysis technique (equating to whole machine vibration)
- will not detect low frequency defects until associated components (typically bearings) show signs of lubrication breakdown or metal to metal contact.
- usually only give relative (in decibels) or qualitative values of condition.

Earphones are still a common option of acoustic and vibrational equipment (a hang up of hearing ‘clunkers’) but latterly refinements mean that more useful, visual outputs are the most commonly used. Direct reading ‘go/no go’ scales use a relative value that can be thought of as filtering the recurring natural frequencies, highlighting the higher magnitude ‘defect’ elements.

6 USING MONITORING INFORMATION - REFERENCE LEVELS OF VIBRATION

Whole machine or overall vibration occurring in the 10Hz-10KHz band is considered the best parameter for monitoring structural problems like imbalance, looseness, etc. and many such problems will cause excessive whole machine vibration. Measurements can either be trended to produce an ongoing evaluation of condition or the values obtained compared to the machine's 'normal' value (ISO 2372). The latter is commonly accepted as a one-shot indication of the machine's 'Health'.

Getting consistent readings

Whilst internal transmission of vibration is a characteristic of the machine it is important that we monitor at the same point(s) in a consistent way. It is standard practice to mark the measurement point(s) on machines utilise studs/mounts to allow consistent contact of the pick up transducers. In all cases it is important that

- Readings are always taken from the same point(s) on a machine
- Whole machine vibration readings are collected under consistent machine conditions (speed, loading etc)
- The machine speed is noted (RPM)

Machine Classifications

The ISO and comparable standards classify machines for ease of reference an example of classification appears below.

Class	Description	Example
I	Individual parts of engines and machines integrally connected with the complete machine in its normal operating condition	Electrical motors up to 15 kW
II	Medium sized machines without special foundations Rigidly mounted engines Machines on special foundations	15-75kW machine up to 300kW
III	Large prime movers and large machines mounted on rigid and heavy foundations which are relatively stiff in the direction of vibration	E.g. Rolling machines
IV	Large prime movers and large machines with rotating masses mounted on relatively soft foundations in the direction of vibration	E.g. Turbo-generators

The Whole machine vibration value is then read off under the appropriate class of machine being valued and a graduated assessment of Good, Satisfactory, Unsatisfactory or Unacceptable obtained. The format of these tables generally being as below.

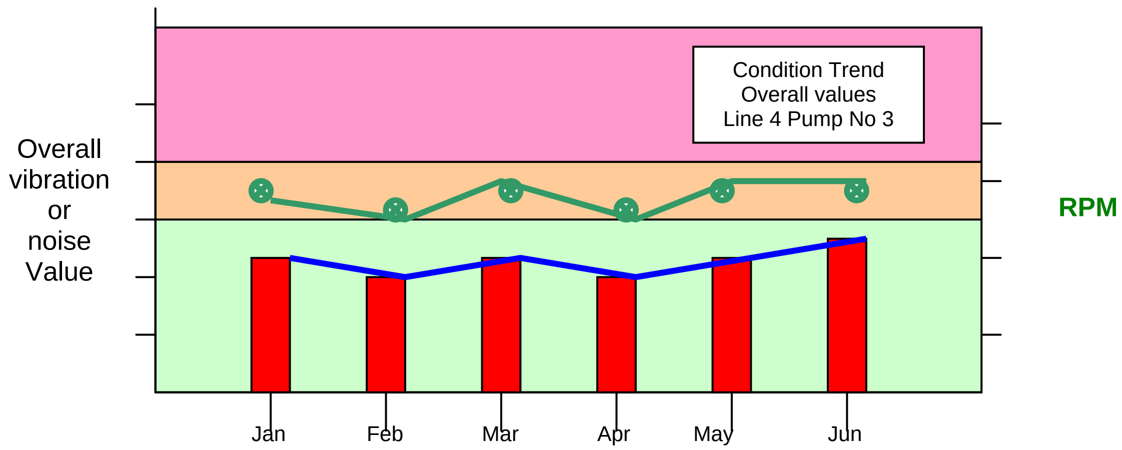
Example of Go/No Go formats

Vibration severity		Velocity Range Limits and Machinery Classes (after ISO Standard 2372)			
CMVP40 In/s eq Peak	CMVP50 Mm/s RMS	Small Machine	Medium Machines	Large Machines	
		Class I	Class II	Class III	Class IV
0.02	0.28				
0.03	0.45				Good
0.04	0.71				
0.06	1.12				Satisfactory
0.10	1.80				
0.16	2.80				Unsatisfactory
0.25	4.50				
0.39	7.10				Unacceptable

Overall vibration level and acoustic emission can give ‘go/no go’ information based on ISO standards but trended results give a more accurate indication of condition trends.

Trending overall vibration (noise levels for acoustic techniques)

In the example the machine being trended has overall readings (with rpm also recorded) taken every month and provide a ready indication of overall condition



6.1 Case Study A

Case Studies - introduction

The case studies that follow all use a common combination of techniques, namely point amplitude and broadband frequency (FFT) analysis. This combination of techniques was chosen after criticality and cost benefit analyses because of the degree of general and diagnostic information they offered.

We have already established whole machine vibration as a useful first measure of condition. When monitoring multiple points on a machine the vibration amplitude at each point is still a useful and common indicator of change and therefore condition.

You will see in the case studies that this point vibration amplitude is trended and that in each case increases in amplitude are apparent. You will also see that alert and alarm values appear on these trend plots and these were established with reference to industry standards, manufacturers recommendations and vibration values taken on commissioning (base readings).

The broadband frequency analysis technique allows us to identify the frequency at which increased vibration occurs and equate it to machine and component rpm, which aids any diagnosis (see Spectral plots). The waterfall plots allows a historic trending of the particular frequency signal and provides and indication of its rate of deterioration and (post repair) the assurance that remedial action has addressed the problem.

If the machines were subject to whole machine vibration monitoring this increase in amplitude would be apparent once it impacted on the whole machine value, but the diagnostic information available through the broadband FFT technique would not.

Case Study A

190kW, 1750rpm, vertically mounted motor and two stage centrifugal pump combination

Vibration method used
Frequency vibration analysis using broadband FFT technique at identified measurement points on motor and pump drive ends and non-drive ends. Monitored using portable equipment (data collector equipped with accelerometer type transducer) on permanently mounted (glued) mounts.

This machine was subjected to a refinement of the 'whole/overall machine' approach known as broadband FFT technique. This technique uses accelerometer type transducers (chosen because of the operating conditions and parameters of the machine) and allows a wide range of information to be captured. Monitoring was carried out by a specialist third party who collected and then processed the data using proprietary software to generate spectral, trend and waterfall plots. They submitted periodic reports (by exception) of their findings.

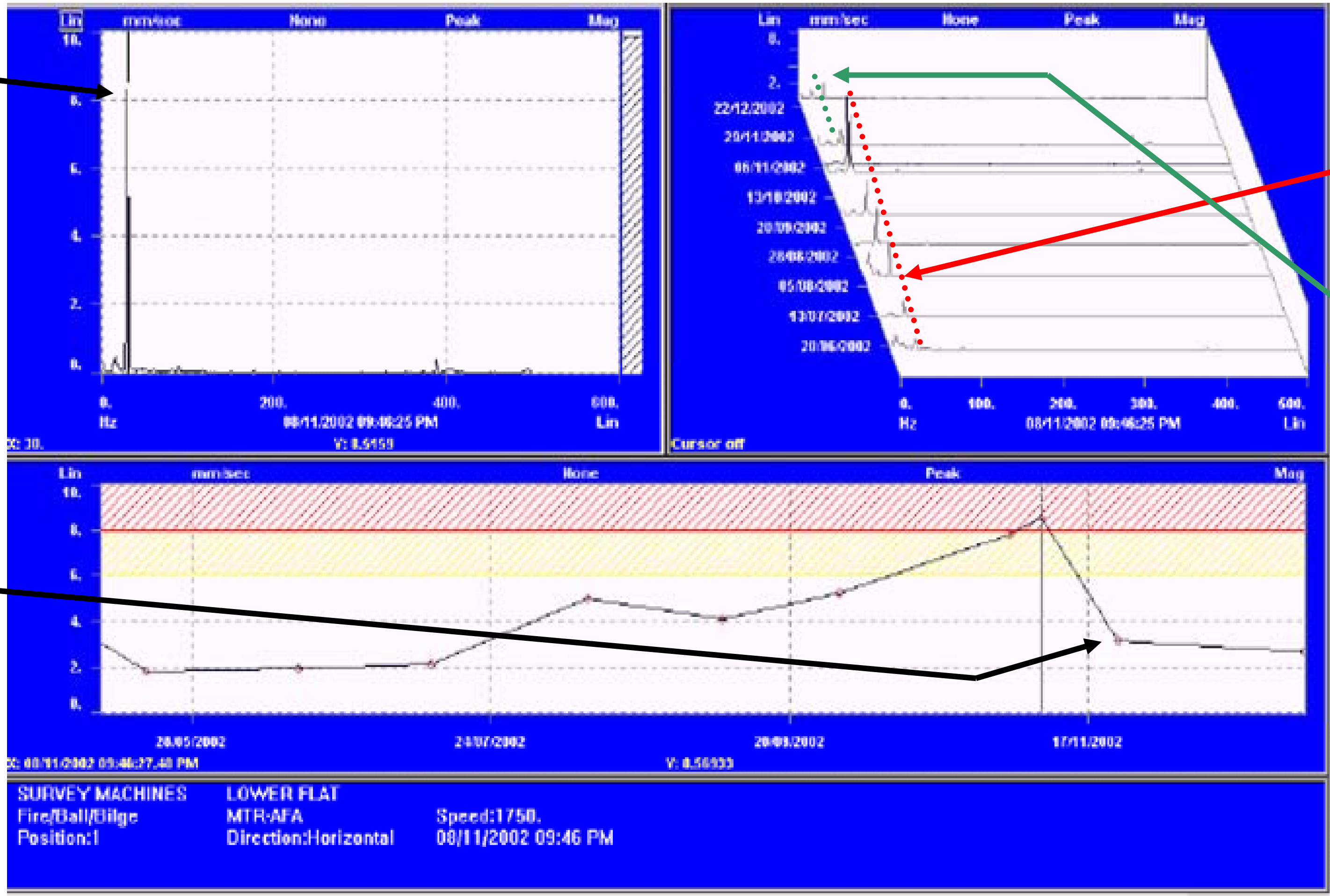
The report in this case identified *"…an increase in vibration (1 x motor/pump running speed [30 Hz]) at the motor non-drive end bearing position*," and "*overall amplitudes of vibration at the motor non-drive end increased from 2 mm.s to 8.5 mm.s over 4 subsequent surveys."*

The spectral plot shows the predominant vibration frequencies, whilst the waterfall shows the progressive, date ordered (trended) spectral plots displaying vibration levels across the whole frequency range being monitored.

The specialists advised that machines with this configuration characteristically show high vibration amplitudes at primary frequencies at the non-drive end of the prime mover whilst the fault actually lies within the driven unit. An inspection of the pump revealed the bottom bush and sealing ring to be excessively worn. Both components were replaced and this brought vibration amplitudes back to acceptable levels.

Benefits: Had the imminent failure gone undetected the unplanned shutdown until the spare unit could be brought on line was estimated at 2 hours with associated production losses in excess of £5k.

Spectral Plot
Shows range of frequencies generated and the 30Hz reading of concern
Note
Machine RPM is 1750
Primary frequency around 1750/60 (30Hz)



Waterfall Plot
Shows trended spectral plots

Note gradual increase at 30Hz reading indicating deterioration. And Drop in value post maintenance

Trend
Showing trend increase in overall value and subsequent drop post rectification

Note that this case study shows the Trend plot with alert and alarm levels set, based on normal operating parameters determined at commissioning.

6.2 Deciding on a Vibration Analysis technique

Whilst referencing against the relevant ISO standard gives an indication of condition when it comes to more specific information we must consider:

- The failure mode we want to monitor (normally established from the machine's historic failure mode(s) and identifying root cause, which may be;
  bearing failure
  belt tension
  gearbox lubrication
- Bearing specifications, relevant rpm's
- Manufacturer and CM engineer advice

6.2.1 Setting Monitoring specification

Ask

- What do I want to know (what failure mode do I want to detect and how early in the onset of deterioration)?
- Will whole machine vibration value give me the depth of information I want to allow intervention before catastrophic failure?

If whole machine techniques are suitable, decide if

- go/no go type indicators will do

or

- Is it worth getting quantitative readings against industry standards

or

- Setting up a recording and trending programme.

If more detailed information on the condition of the machine is needed make sure you know the failure mode you want to monitor.

- Look at more advanced techniques or the 'add ons' offered by some of the whole machine techniques.
- Know your machine - ensure you use a technique that can pick up the characteristics and frequency range of the machine(s)

In all cases

- Determine cost v potential savings of each option (do a cost benefit analysis)

6.2.2 A range of popular techniques

The range of techniques available that utilise vibration and associated techniques to determine condition is extensive. We have addressed overall techniques (those that measure the magnitude of dynamic motion) and identified the tools and options available at the ‘starter’ end of the market, but we have also seen some advantages (in the case studies) of the more specialised techniques.

The introduction of more and more sophisticated hardware and software continues to see more techniques become applicable by and available to maintenance personnel. This will certainly continue and means that techniques that once required trained and experienced vibration specialists are now within the ability of technicians with the right equipment and a minimum of training. The Popular techniques fall in to this category although specialist help may be needed in initial set up.

Broadband (overall) and Frequency analysis

Have been covered in some depth in Section 2 of this guide but are included here for completeness.

Enveloping Techniques

A variety of analysis techniques are available within commercial software packages to refine the detection of potential failures. Enveloping is such a technique whereby a shape is created around the spectrum plot that equates to alarm profile values set for each monitored component of the machine. These individual alarms are triggered even though the component signal may not be the highest amplitude signal within the spectrum (not of sufficient value to affect the whole machine or overall value).

Octave Band analysis

Despite its name (which comes from the type of filters it uses) it is a vibrational technique which has to be set up (usually by an expert) to determined measurement parameters relating to the frequency bands of interest on the machine being monitored (based on rpm frequency relationships). Once set up it is fairly simple to use for overall measurements but has a limited diagnostic ability.

Shock pulse

Is a derivation of acoustic techniques. Shock pulses are generated within a machine by the impacting of surfaces and the extent of this shock depends on the extent of damage, the rpm and the size of the components. The peak value of the amplitude picked up by the transducer is directly propotional to the impact velocity and as deterioration occurs shock pulse measurements increase significantly (up to 1000 times). It is a relatively quick and easy technique to use but needs information on bearing size and speeds and the trandsducer to be 'tuned'.

Energy spiking

Works on the principle that some faults excite the natural frequencies of components and structures within a machine. Repetitive impacts generate intense energy which can be sensed by a transducer (accelerometer) as periodic spikes of high frequency in a spectrum. Electronically processed and enhanced the fault frequency shows clearly. Diagnosis usually needs the services of an expert although latest software developments help.

Summary table of Popular Techniques

Analysis Technique	Application	Advantages	Disadvantages	What it detects	How it Works
Broadband Vibration (overall values only)	Belt drives, compressors turbines, engines, electric motors, gearboxes, pumps, roller & journal bearings, shafts	Good for major imbalances in rotating machinery, results measured against acceptable levels.	Not much information on nature of fault, difficult to set alarm levels, insensitive	Changes in vibration characteristics due to fatigue wear. Imbalance, looseness, misalignment.	Point of measurement mounted transducer, converts mechanical vibration into electrical signal and feeds measuring/indicating 'vibration meter'(usually in a relative scale format)
Shock Pulse Monitoring	Rolling element and anti-friction bearings, impact tools, (usually pneumatic) valves on combustion engines	Portable, easy to operate, very fast analysis, subtle changes apparent	Data must be trended for maximum benefits, needs accurate bearing size and speed information for setting up	Relatively advanced mechanical deterioration and poor lubrication that is causing mechanical shocks.	Piezoelectric accelerometer set up on bearing housing Picks up impact shock impulses- depend on surface condition and bearing velocity. Pulses make the transducer resonate at (resonant) frequency – shock pulses relate directly to bearing condition

Analysis Technique	Application	Advantages	Disadvantages	What it detects	How it Works
Enveloping Techniques	Rolling element bearings and low speed machines (with care & relevant expertise)	Early detection of bearing problems.	Incorporated within proprietary software packages	Bearing faults	In early stages of bearing failure high frequency resonant components are excited. Acceleration signal (time) is filtered at high frequency and then resulting signal undergoes low frequency range spectrum analysis. (FFT) Shows fundamental low frequency source of detected high frequency signals.
Energy Spiking	Pumps (particularly seal-less) gearboxes, roller element bearings	Good sensitivity to high frequency ranges Portable	Numerical value only Difficult to identify source without specialist investigation	Dry running & cavitating pumps, valve noise, bearing lubrication problems loose bearings, metal to metal wear, surface flaws	Works on 'resonance' principle – faults may excite natural frequency of components / structures. Similar to Enveloping but gives numerical value rather than spectrum. High frequency energy generated as periodic spikes in spectrum (measured by accelerometer). Low frequencies filtered out, and remaining signal peak to peak 'fixes' and holds high repeat and amplitude values
Octave Band	Shafts, gearboxes, compressors, engines, bearings (journal and roller) mechanical looseness and wear - primarily noise measurements	Simple to use good detection levels, Recorder provides permanent record. Portable	Long analysis time – frequency bands must be set up by engineer	Changes in machine characteristics, caused by fatigue, wear imbalance etc.	Frequency spectrum split into 'bands ' of interest – results plotted on recorder or displayed by meter (fixed band widths histogram type read out)
Frequency Analysis	Shafts, gearboxes, belt drives, compressors, journal bearings, motors, pumps and similar	Data collector is portable and easy to use. Waterfall plots allow early fault detection through trending.	Random noise and impact spectrum can look similar to early stage faults	Changes in vibration caused by fatigue, imbalance / alignment, turbulence etc.	Data collected from fixed points using data collector or computer. Readings generate obtained spectrum, which is compared with 'Baseline' spectrum. Used to identify machine faults through the analysis of discrete vibration components (FFT)

6.3 Case study B Water Service Pump

45 kW, 1750 rpm, vertical in line single stage centrifugal pump

Vibration method used

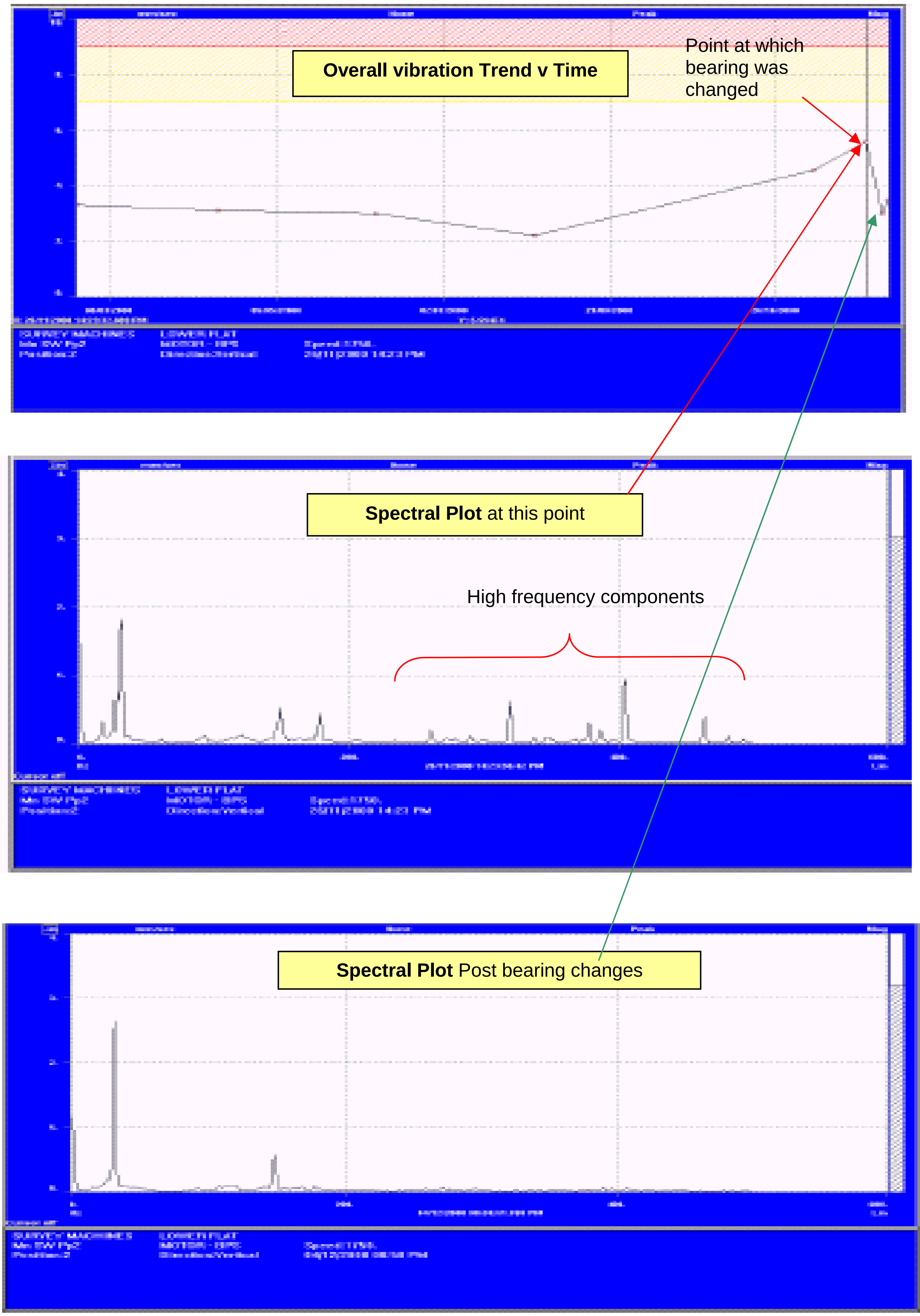
Frequency analysis FFT technique at set measurement points on motor and pump drive ends and non-drive ends. Monitored using portable equipment (data collector equipped with accelerometer type transducer) on permanently mounted (glued) mounts.

During routine monitoring an increase in vibration (overall and high frequency components) was identified at the motor drive end bearing position shown. The motor bearings were suspected as being faulty given the discrete high frequency components identified on the spectra the motor was therefore withdrawn from service and both bearings replaced.

It can be seen that data taken after reinstatement of the machine does not contain any of the high frequency components identified pre repair. When the bearing was changed vibration and performance returned to optimum operating parameters.

Benefits A highly critical machine due to its safety role, in service failure would have required production shutdown and the contravention of safety case compliance. The cost of such an incident would be in excess of £20k.

Bearing replacement cost approximately 1% of equipment capital cost, on investigation parallel performance monitoring indicated a history of increasing current demand for this unit peaking at 10% above normal; associated energy savings (if problem had not been identified) estimated at £1.5k per annum.

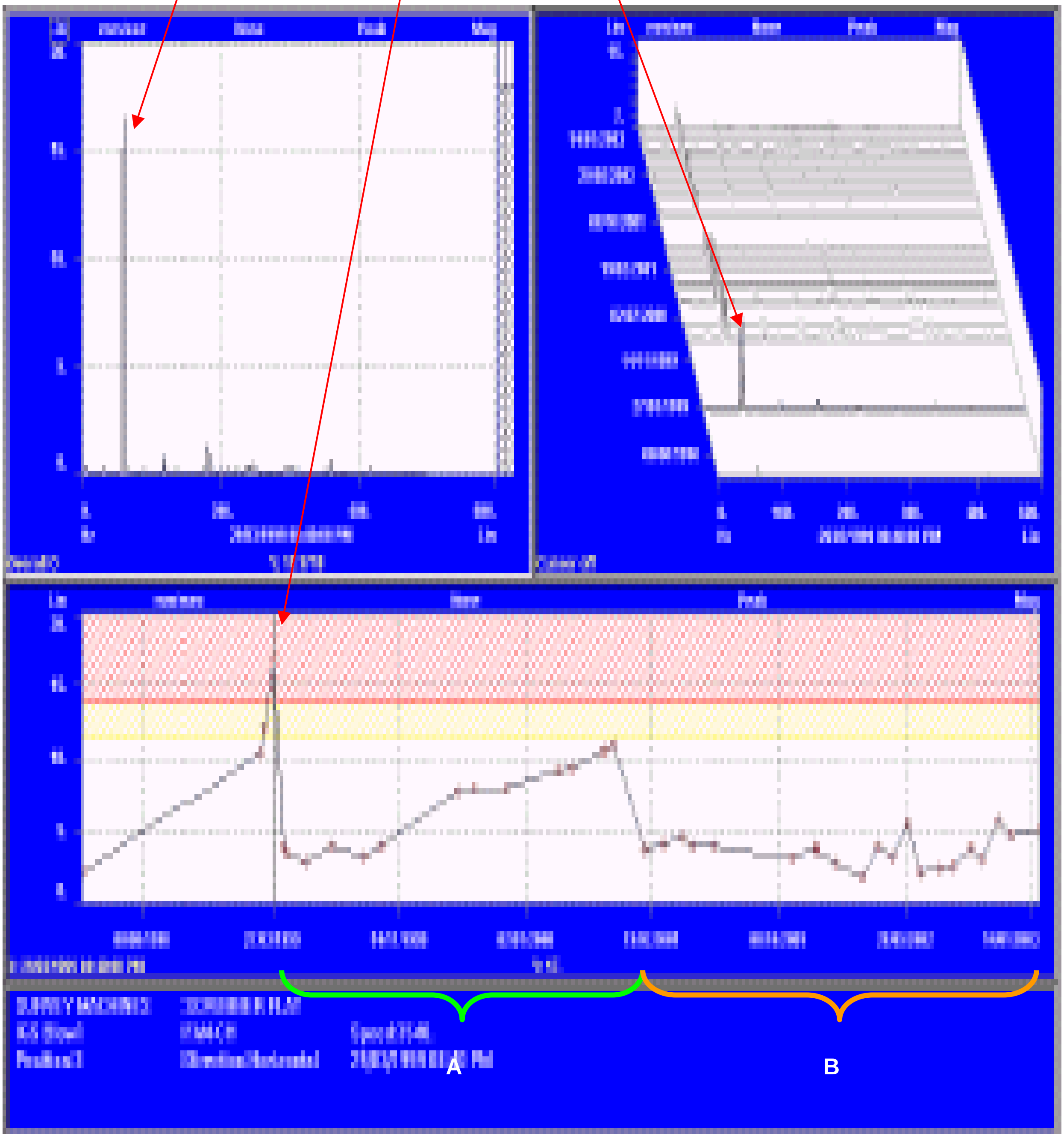

Overall vibration Trend v Time
Point at which
bearing was
changed
Spectral Plot at this point
High frequency components
Spectral Plot Post bearing changes

6.4 Case Study C Inert Gas Fan

75Kw motor with centre hung impeller, horizontally mounted, 3600 rpm.

Vibration Method used: Broadband FFT, Portable data collector, accelerometers (frequency analysis), commercial software package, skilled engineer interpretation.

High overall amplitudes of vibration were identified at the fan drive end bearing that was attributed to 1x running speed of the fan/motor (16 mm.s at 60 Hz).



In case 'C' the initial maintenance action was to replace the fan bearings and this initially decreased the vibration. When amplitudes started increasing again (as can be seen over period A) a dominant component of 1 motor/fan speed was evident. However, the root cause of the problem was fan imbalance, the rotating assembly was returned to the manufacturer and a replacement impeller fan installed and balanced (shown by the step change between period A and B) reducing vibration amplitudes to an acceptable level.

Benefits Despite the engineer's diagnosis the maintenance manager decided initially to treat the symptoms (bearing deterioration), rather than the cause (fan imbalance) although it would be wise to change the bearings in conjunction with fitting a properly balanced fan. Upon investigation it was found that the decision had been made consciously as an interim maintenance solution to meet production demand. The line downtime required for a fan change having been deemed prohibitive. The fan assembly was changed at the earliest opportunity. The ability to interpret the condition of the equipment accurately allowed maintenance to 'manage the risk' resulting in production targets being met, customers satisfied and downtime optimised.

7. DIY or Specialist help?

With the equipment and software available the decision as to whether to go it alone or seek specialist advice/services is difficult. The decision depends largely on the in house time, resources and budget available.

If you are using vibration or acoustic analysis for the first time you have to consider:

- Buying the equipment
- Training
- Learning how to do the job
- Learning how to recognise problems (usually a recognised course of training)
- Managing the whole thing

Alternatives

Alternative	What it involves	Advantages	Disadvantages
In House	You collect and analyse the data relying on vibration or acoustic equipment manufacturer for basic training (which may be a very minor requirement if you go for acoustic emission or overall vibration monitoring). Possible use of a third party for occasional specialist support.	Relatively cheap Quick response to suspected and identified problems Ownership in house	Commitment of time and resources Steep learning curve Initial lack of experience
Combined Service	Where the system is set up jointly, you collect the data and pass it on to a third party for analysis and reporting.	Experience on tap Specialist knowledge available from the outset	More expensive Response time to suspected and identified problems Lack of ownership Those collecting data are still a commitment of time and resources and training would normally be required
Outsourced to Third Party	Where specialists set up system, collect data, carry out analysis and send you periodic reports on machine condition.	No equipment costs Limited commitment of time and resources Experience on tap Specialist knowledge available from the outset	Relatively expensive Response time to problems Lack of ownership

The recommended route is to use simplified techniques such as Whole Machine vibration or acoustic emission level monitoring for regular, routine measurements. Record and trend the results and bring in the analytical power of frequency analysis when problems are suspected.

8. Specialist Techniques

We have examined the more common techniques available in vibration and acoustic analysis, but there are a number of specialised techniques, for which you would normally call in a specialist, that are useful for diagnosis or in specific circumstances. A range of such techniques is listed by 'application' rather than 'analysis technique', as this is the most likely trigger for their use.

Technique by Application

Application	Analysis Technique	Advantages	Disadvantages	What it detects	How it Works
Rotating machinery shafts gearboxes etc.	***Real Time Analysis***	Analyses of all frequency bands simultaneously instant graphic display, constantly updated. Fixed or Portable	Time consuming	Acoustic & vibration signals + shock and transient loads	Signal recorded and played back through real time analyser – transformed into frequency – operates through 0-10Hz and 0-20kHz. High resolution and slow motion capability
As above + roller & journal bearings, electric motors pumps turbines + diagnostic applications	***Real Time Constant Bandwidth***	Simple to use once set up, good range, good detail at high frequencies, Portable	Long analysis time high level of machine knowledge required to interpret results	As above + identification of multiple harmonics and sidebands	Vibration detected by accelerometer, signal amplified, filtered and analysed. Bandwidths & frequency can be changed to suit diagnostic needs (Function option with most FFT analysers)
Gearteeth damage pumps roller bearings etc.	***Time Waveform Analysis***	Good for transient loads, slow pulses etc. Often used to analyse random noise. Portable	Multiple signals can be confusing and it is difficult to isolate source	Gear teeth damage, misalignment, pump cavitation, etc	Oscilloscope via vibration meter or real time analyser, measures peak to peak amplitude against time – needs band filters to deal with complex signals (FFT)
Gearboxes gearteeth, roller bearings, shafts Rollers banks of fans	***Time Synchronous Averaging Analysis***	Good for individual gears analysis in gearbox or any machine with components rotating at similar speeds	Roller element bearings need care due to bearing tones	Wear, fatigue, stress waves, micro welding	Tachometer triggered pulse cleans signal so you see mainly running speed related components Signals not related to the RPM are averaged out leaving only those related to a single rotating speed

9. Glossary of Terms

Acoustic Emission *– technique distinguishing the natural frequencies of a machine's components from those associated with deterioration in condition.*

Band *- the collection of data within a specific range of a machines operation (usually targeted at a narrow range of values equating to specific machine components {high speed bearings, gearwheels, etc.])*

Baseline values *– the range of monitored data values obtained at the adoption of condition monitoring that identify the subject machine's normal operating range (variation) and allow alert and alarm values to be predicted.*

Broadband *– the collection of data throughout the normal range of a machines operating parameters*

Bump Test *– the inducing of an acoustic signal into a subject machine, exciting its natural or resonant frequencies and through processing of the signals emitted determining the condition of the machine.*

Condition Based Maintenance (CBM) *– maintenance carried out according to the need indicated by condition monitoring*

Condition Monitoring (CM) *– the continuous or periodic measurement of data (during operation) to indicate the condition of an item to determine the need for maintenance*

CM routes *– condition monitoring machine measurement tasks arranged into a logical data collection sequence*

CM Routines *– a collection of scheduled CM routes raised as a scheduled job within a planned maintenance programme*

Criticality analysis *– a quantitative analysis of events or faults and the ranking of these in order of the seriousness of their consequences*

Fast Fourier Transform *– a mathematical transformation technique applied to vibration signal data that allows the display of amplitude against frequency.*

Monitoring *– activity performed either manually or automatically intended to observe the state of an item*

p-f interval*- the period between which a defect becomes detectable and the point where failure occurs*

Planned Maintenance *– downtime due to the programmed or scheduled taking out of an item from service*

Predictive Maintenance *– tasks carried out to gain evidence of the condition of an item and whether it is deteriorating towards failure*

Preventative Maintenance *– the scheduled (regardless of condition) restoration or discard of items with proven age related failure characteristics or dominant modes of failure*

Pro-active Maintenance *– a generic term for Predictive and Preventative Maintenance*

Opportunity Maintenance *– the taking of an item out of service for maintenance when time and resources allow, i.e. during other scheduled or unscheduled production downtime*

Resonance *– a condition in which an object or system is subjected to an oscillating force with a frequency close to its own natural frequency*

Run to Failure (breakdown) *– the deliberate decision not to carry out any form of maintenance other than replacement or refurbishment upon failure*

Shutdown maintenance *– maintenance that can be carried out only when the item is out of service (or the planned shutting down of an operation solely to perform maintenance)*

Swept Filter Frequency Analysis *an analogue system where a fixed frequency range of the subject machine is swept*

Vibration*- the act or an instance of oscillation*