In the late 70s I remember ground running a training aircraft (a Jet Provost Mk 3), with an oscilloscope perched precariously on my knee, taking notes on a range of vibration readings across a range of rpm. It was a scheduled performance check and, as I recall, the procedure called for analysis of the frequency chart generated — with particular attention to gearbox frequencies. At the time I had no idea that this was called Condition Monitoring (CM). In later years I discovered that a range of such techniques was available to help me manage and optimise maintenance, but I was (and still am) no specialist in the specific application of the techniques. As a one time user — and now promoter — of Condition Based Maintenance (CBM) I need to be an 'informed buyer'. To this end I set out to gain an appreciation of some of the mainstream techniques, the basic premise on which they work and where and how they might be usefully employed.

**ABOUT THIS GUIDE**

The introduction of technology that allows the condition or 'health' of machinery to be checked with the minimum of intrusion, or none at all, has provided us with one of the most cost-effective maintenance tools currently available. Official figures from the late 1980s indicated that companies with an effective CM programme were saving 25% on maintenance spend. With the advent of more compact and easy-to-use equipment the advantages of monitoring the health of machines via 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 principles of CM, a range of the more common vibration and associated techniques available and the kind of condition information you can expect to see. In addition, case studies will show how that information can be best used. The aim is to equip you with enough background knowledge to be able to ask the right questions, understand the options and identify the basic techniques that commercially available packages promote.

The main principle of CM is that it firstly determines 'normal' machine vibration levels, and then – accepting that (a) deterioration in mountings, rotating and related components and (b) imbalance will be reflected by a change in vibration characteristics — quantifies the degree and severity of subsequent degradation so that it may be dealt with by an appropriate maintenance response. This 'appropriate response' targets resources, improves plant reliability and availability and reduces overall maintenance intervention and spend. CM also provides the flexibility to determine and plan repair work 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?'

**VIBRATION**

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 that he ignores such warnings at his 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 measured vibration levels with established standards.
Vibration Analysis and Associated Techniques in Condition Monitoring  
Part 1 AN INTRODUCTION: VIBRATION THEORY AND MACHINE VIBRATION

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.

Vibration as a measure of machine health

The basic indicator of a machine's 'health' is the measured dynamic motion commonly called the 'whole machine', 'overall', or absolute value. Recording and trending of this, relative to the machine's normal value (i.e. 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 is now available. At the basic end of the market are whole machine devices which tend to operate in the 10 Hz to 1 kHz frequency range 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 best suits monitoring needs (and hence which measuring instruments are needed). Basically, if you monitor the wrong parameter you may miss the condition information you want.

It can be seen from the following diagram that at low frequencies (and low machine running speeds) displacement 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

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 (RMS) value.

Vibration as a measure of machine health

The basic indicator of a machine’s ‘health’ is the measured dynamic motion commonly called the ‘whole machine’, ‘overall’, or absolute value. Recording and trending of this, relative to the machine’s normal value (i.e. 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 is now available. At the basic end of the market are whole machine devices which tend to operate in the 10 Hz to 1 kHz frequency range 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 best suits monitoring needs (and hence which measuring instruments are needed). Basically, if you monitor the wrong parameter you may miss the condition information you want.

It can be seen from the following diagram that at low frequencies (and low machine running speeds) displacement or velocity values are of good quality, but at higher machine or component (e.g. bearing) operating speeds 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

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 (RMS) value.

Vibration as a measure of machine health

The basic indicator of a machine’s ‘health’ is the measured dynamic motion commonly called the ‘whole machine’, ‘overall’, or absolute value. Recording and trending of this, relative to the machine’s normal value (i.e. 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 is now available. At the basic end of the market are whole machine devices which tend to operate in the 10 Hz to 1 kHz frequency range 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 best suits monitoring needs (and hence which measuring instruments are needed). Basically, if you monitor the wrong parameter you may miss the condition information you want.

It can be seen from the following diagram that at low frequencies (and low machine running speeds) displacement or velocity values are of good quality, but at higher machine or component (e.g. bearing) operating speeds acceleration measures are better used. Note that across the entire range of operating speeds velocity will give a good representation of condition.
Note also that the energy of the signal generated by machine components tends to decrease with frequency. For example, low-speed vibration, such as can be caused by misalignment, generates a strong, high energy, high amplitude signal, while bearings typically generate low energy, low amplitude, and high frequency signals.

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

Some of the measurement devices available and the majority of the mid-size portable devices are capable of measuring high frequency repetitive vibration signals, and are useful for monitoring –
- 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, however, using acceleration enveloping techniques (which will be dealt with in some detail later) but, effectively, this filters out low frequency rotational signals and enhances high frequency repetitive signals in the 10 kHz to 30 kHz range.

### MACHINE VIBRATION

Even the simplest machine generates signals of far more complexity 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 their mass and stiffness) at which very high amplitudes can be excited by a force applied at the same frequency. This phenomenon, **resonance**, is a useful characteristic in its own right and one which we shall also explore later.

Vibration is one of the primary dynamic monitoring tools of CM. It is routinely used to measure ‘absolute’ vibration (i.e. of the whole machine relative to free space) –

- or, in specialist hands, vibration of meshing gears, or vibration caused by passing components (e.g. fan blades) –

### Overall values

Overall values measure the absolute or whole machine vibration level and tend to be dominated by the predominant amplitude of the whole machine, as indicated in the spectrum shown right.

These **overall measures usually lead to ‘Go/No Go’ or graduated (i.e. Good, Acceptable, Just Acceptable, Unacceptable) information. However, a spectrum can give 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 home in on specific components.
Vibration Analysis and Associated Techniques in Condition Monitoring

Part 1 AN INTRODUCTION: VIBRATION THEORY AND MACHINE VIBRATION

Frequency analysis

A gearbox spectrum will include primary frequencies generated from the rotation of shafts, while 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.

Vibration analysis can examine 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 sources of problems.

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 decomposition 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.

Spectrum outputs

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

FURTHER INFORMATION

- Moubray J, RCM II (2nd Ed), Butterworth-Heinemann 1999
- A PDF of the full guide from which this article has been derived is available at www.maintenanceconsultants.co.uk

ABOUT THE AUTHOR

Colin Sanders was an aeronautical engineering apprentice with the Royal Air Force and went on to spend over twenty years within the military aircraft maintenance environment. He served in Northern Ireland and the first Gulf War where he was a maintenance leader on the Buccaneer fleet. Since 1998 he has been engaged in management consulting, specialising in asset care issues. He has delivered consulting and training projects to a cross section of clients in Oil and Gas, Defence, Utilities, Manufacturing and FMCG environments.