A Maintenance Managers Guide to...
Vibration Analysis and Associated Techniques in Condition Monitoring

Part 3: USING MONITORING INFORMATION AND THE PRACTICALITIES OF CHOOSING AND USING VIBRATION ANALYSIS AND ASSOCIATED TECHNIQUES IN A CM PROGRAMME.

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

While 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 utilising studs or 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 the machine.
- Whole machine vibration readings are collected under consistent machine conditions (speed, loading etc.).
- The machine speed (in RPM) is noted.

Machine Classifications

For ease of reference the ISO and comparable standards classify machines. An example of the classification appears in Table 1.

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 in Table 2 opposite.

Example of Go/No Go formats

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 changes in condition.

Trending overall vibration (or noise levels for acoustic techniques)

In the example of Figure 1 the machine being monitored has overall readings (with rpm also recorded) taken every month and providing a ready indication of overall condition.

Colin Sanders, Managing Consultant, CSA

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

Table 1: Machine Classifications

Case Study — Introduction

The case study that follows uses a common combination of techniques, namely point amplitude and broadband frequency (FFT) analysis. This combination was chosen after criticality and cost-benefit analyses because of the degree of general and diagnostic information it 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 condition and change in that condition.

You will see from the case study that point vibration amplitudes are 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, manufacturer’s recommendations and vibration values taken on commissioning (i.e. 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 plot allows a historic trending of the particular frequency signal and provides an indication of its rate of deterioration and (post repair) the assurance that remedial action has addressed the problem.

If the machine 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 – 190KW 1750RPM VERTICALLY MOUNTED MOTOR AND TWO-STAGE CENTRIFUGAL PUMP COMBINATION**

Frequency vibration analysis was carried out using the broadband FFT technique (a refinement of the ‘whole/overall machine’ approach which allowed a wide range of information to be captured) at identified measurement points on motor and pump drive ends and non-drive ends. A portable data collector equipped with an accelerometer type transducer (chosen because of the operating conditions and parameters of the machine) was employed at permanently mounted (glued) mounts. Monitoring was carried out by a specialist third party who collected and processed the data, using proprietary software to generate spectral, trend and waterfall plots (see Figure 1), and submitted periodic reports (by exception) of the findings.

The report in this case identified ‘...an increase in vibration (1...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.’

**Table 2: Machine vibration severities**

<table>
<thead>
<tr>
<th>Vibration severity</th>
<th>Velocity Range Limits and Machinery Classes (after ISO Standard 2372)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM/VP40 In/s eq Peak</td>
<td>CM/VP50 Mm/s RMS</td>
</tr>
<tr>
<td>Class I</td>
<td>Class II</td>
</tr>
<tr>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>0.02</td>
<td>0.28</td>
</tr>
<tr>
<td>0.03</td>
<td>0.45</td>
</tr>
<tr>
<td>0.04</td>
<td>0.71</td>
</tr>
<tr>
<td>0.06</td>
<td>1.12</td>
</tr>
<tr>
<td>0.10</td>
<td>1.80</td>
</tr>
<tr>
<td>0.16</td>
<td>2.80</td>
</tr>
<tr>
<td>0.25</td>
<td>4.50</td>
</tr>
<tr>
<td>0.39</td>
<td>7.10</td>
</tr>
</tbody>
</table>

**Figure 1: Example of condition trending**

**Figure 2: Case study vibration analyses**
The spectral plot (see Figure 2) shows the predominant vibration frequencies, while 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 while 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 to have been two hours (with associated production losses in excess of £5k).

Note that Figure 2 shows the Trend plot with alert and alarm levels set, based on normal operating parameters determined at commissioning.

## DECIDING ON A VIBRATION ANALYSIS TECHNIQUE

Although referencing against the relevant ISO standard does give 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, incorrect belt tension, inadequate gearbox lubrication, etc.
- Bearing specifications, relevant RPMs.
- Manufacturer and CM engineer advice.

### 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)?
- whole machine vibration value give me the depth of information needed to allow intervention before catastrophic failure?

If whole-machine techniques are suitable, decide if

- Go/No Go indicators will do, or –
- Is it worth getting quantitative readings against industry standards,

### ANALYSIS TECHNIQUE

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
<th>WHAT IT DETECTS</th>
<th>HOW IT WORKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belt drives, compressors, engines, electric motors, gearboxes, pumps, roller &amp; journal bearings, shafts</td>
<td>Good for major imbalances in rotating machinery, results measured against acceptable levels.</td>
<td>Not much information on nature of fault, difficult to set alarm levels, insensitive.</td>
<td>Changes in vibration characteristics due to fatigue wear, imbalance, looseness, misalignment.</td>
<td>Point of measurement mounted transducer, converts mechanical vibration into electrical signal and feeds measuring/indicating ‘vibration meter’ (usually in a relative scale format)</td>
</tr>
<tr>
<td>Rolling element and anti-friction bearings, impact tools, (usually pneumatic) valve on combustion engines</td>
<td>Portable, easy to operate, very fast analysis, subtle changes apparent.</td>
<td>Data must be trended for maximum benefits, needs accurate bearing size and speed information for setting up.</td>
<td>Relatively advanced mechanical deterioration and poor lubrication that is causing mechanical shocks.</td>
<td>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.</td>
</tr>
<tr>
<td>Rolling element bearings and low speed machines (with care &amp; relevant expertise)</td>
<td>Early detection of bearing problems.</td>
<td>Incorporated within proprietary software packages.</td>
<td>Bearing faults.</td>
<td></td>
</tr>
<tr>
<td>Pumps (particularly sealless) gearboxes, roller element bearings</td>
<td>Good sensitivity to high frequency ranges Portable.</td>
<td>Numerical value only Difficult to identify source without specialist investigation.</td>
<td>Dry running &amp; cavitating pumps, valve noise, bearing lubrication problems loose bearings, metal to metal wear, surface flows.</td>
<td>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.</td>
</tr>
</tbody>
</table>

### Table 3 Summary table of popular techniques

- **Broadband Vibration (overall values only)**
  - **Shock Pulse Monitoring**
  - **Enveloping Techniques**
  - **Energy Spiking**
  - **Octave Band**
  - **Frequency Analysis**
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 vs. potential savings of each option (i.e. carry out a cost-benefit analysis)

A range of popular techniques

The range of techniques available that utilise vibration and associated techniques to determine condition is extensive. Here, 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 becoming 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 capability of technicians – with the right equipment and a minimum of training. The popular techniques fall into this category although specialist help may be needed in initial set up.

Broadband (overall) and frequency analysis

These were covered in some depth in Part 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 (i.e. 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) this 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

This is a derivative 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 proportional 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 transducer 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 the latest software developments help.

DIY or specialist help?

With the equipment and software available, the decision as to whether to go it alone or seek specialist advice or services is difficult. It 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.

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.

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, in Table 5, by ‘application’ rather than ‘analysis technique’, as this is the most likely trigger for their use.

**Glossary of Terms**

**Acoustic Emission.** Technique distinguishing the natural frequencies of a
machine’s components from those caused by deterioration in condition.

**Band.** The collection of data within a specific range of a machine’s operation (usually targeted at a narrow range of values equating to specific machine components (high speed bearings, gearboxes, 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 machine’s 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.

**Preventive Maintenance.** The scheduled (regardless of condition) restoration or discard of items with proven age-related failure characteristics or dominant modes of failure.

**Proactive Maintenance.** A generic term for Predictive and Preventive 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.

### Table 5 Analytical techniques for specific applications

<table>
<thead>
<tr>
<th>APPLICATION TECHNIQUE</th>
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<th>DISADVANTAGES</th>
<th>WHAT IT DETECTS</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Rotating machinery shafts, gearboxes etc.</td>
<td>Real Time Analysis</td>
<td>Analyses of all frequency bands simultaneously instant graphic display, constantly updated. Fixed or Portable</td>
<td>Time consuming</td>
<td>Acoustic &amp; vibration signals + shock and transient loads</td>
</tr>
<tr>
<td>As above + roller &amp; journal bearings, electric motors, pumps, turbines + diagnostic applications</td>
<td>Real Time Constant Bandwidth</td>
<td>Simple to use once set up, good range, good detail at high frequencies, Portable</td>
<td>Long analysis time high level of machine knowledge required to interpret results</td>
<td>As above + identification of multiple harmonics and sidebands</td>
</tr>
<tr>
<td>Gearteeth damage, pumps, roller bearings etc.</td>
<td>Time Waveform Analysis</td>
<td>Good for transient loads, slow pulses etc. Often used to analyse random noise, Portable</td>
<td>Multiple signals can be confusing and it is difficult to isolate source</td>
<td>Gear teeth damage, misalignment, pump cavitation, etc</td>
</tr>
<tr>
<td>Gearboxes, gear teeth, roller bearings, shafts, rotors, banks of fans</td>
<td>Time Synchronous Averaging Analysis</td>
<td>Good for individual gears analysis in gearbox or any machine with components rotating at similar speeds</td>
<td>Roller element bearings need care due to bearing tones</td>
<td>Wear, fatigue, stress waves, micro welding</td>
</tr>
</tbody>
</table>

**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.

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