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CONDITION BASED MAINTENANCE

- An evaluation guide for building services

A Seaman



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PREFACE

Building services maintenance is predominantly based on a breakdown or time-based strategy, which do not always provide the plant reliability required in critical business environments. Building services are becoming an increasingly vital component of business activity and thus require more sophisticated methods of preventing down-time.

Condition Based Maintenance (CBM) has been widely used in the process industry for many years, but has been slow to mature in building services. CBM provides a means of improving the conventional maintenance regime by evaluating indicative parameters of plant condition such as temperature, vibration, oil condition and power quality.

CBM can enhance fault detection in many plant items, thus potentially reducing failure rates. In addition, potential benefits are gained by providing a greater understanding of plant performance, reduced labour time and repair budgets it can also improve the energy efficiency of many items of plant.

BSRIA has developed this application guide to aid facility managers and maintenance personnel in understanding the basic concepts of each CBM method, indicating the potential applications, capital costs and benefits associated with each method.

The CBM methods covered in this application guide are:

1. Vibration analysis
2. Acoustic emissions monitoring
3. Thermography
4. Wear and oil analysis
5. Power quality monitoring
6. Monitoring via building management systems.

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BSRIA'S CONDITION BASED MAINTENANCE SERVICES

BSRIA provides a wide range of condition based maintenance services.

Surveys

BSRIA offers surveys based upon several different condition monitoring techniques. These are provided as either a single survey or as part of an on-going program of monitoring. Surveys offered include:

- Thermography
- Power quality
- Electromagnetic field
- Acoustic emission monitoring
- Vibration monitoring.

Demonstration days

The demonstration days are aimed at introducing CBM instrumentation and methods to maintenance personnel from an independent organisation. This can be done at the client's preferred location. The demonstration days can include:

- Demonstration of various CBM instrumentation to maintenance personnel
- Demonstration of the types of plant item applicable to different types of CBM instruments.

Training days

Training days can be arranged at BSRIA's or the client's offices to suit the client's requirements. A range of courses is available including:

- Introduction to CBM techniques
- Training in specific techniques: thermography, power quality, vibration, acoustic emissions, etc.

Complete CBM programmes

BSRIA can provide a complete CBM monitoring service to:

- Identify your business-critical machines and equipment
- Set up a CBM programme to cover business-critical machinery and other plant items
- Collect and analyse data and produce reports for the maintenance team.

For more information about how BSRIA can help you contact;
Andrew Martin, Engineering Services Business Manager on Tel: 01344 426511 Fax: 01344 487575 Email: andrew.martin@bsria.co.uk

1 INTRODUCTION

Traditionally, building services maintenance is based on either a breakdown maintenance strategy (BM) where plant is run to failure, or a time-based maintenance strategy (TBM) where plant is maintained at periodic intervals. Both of these methods can be inappropriate in the modern business environment particularly, where building services plant is critical to the business activity. BM does not prevent plant components from failure, which can cause high repair costs. While TBM can prevent a proportion of failures, it can result in maintenance work being carried out when none is necessary. It can even induce failures.

A third type of maintenance - Condition Based Maintenance (CBM) - is increasingly being used. This provides a reliable, cost effective method of monitoring selected working characteristics of plant items, thus reducing failure rates and costs. It also potentially simplifies identification of faults and hence reduces the need for skills.

CBM is a strategy in which a parameter indicative of the machine's condition is monitored. This can be in the form of an on-the-spot assessment, which can give an instantaneous indication of the machine's condition, or in the form of trending (comparing previous plots of vibration with the current plot). Trending requires information to be gathered from the plant item over its operating life at sampling rates that are established from known failure rates, based on manufacturers' data, British and European standards and experience from conventional maintenance strategies. The gathered information is trended over time to establish changes in the selected monitoring parameter, which indicates when a potential failure will occur.

There are many CBM techniques that can be used for building services plant, and understanding their strengths and weaknesses is critical if the correct technique is to be applied. Almost all building services maintenance employees rely on their senses to monitor the condition of plant. Understanding how a particular plant item operates is critical for preventive maintenance. The noises and heat given off while plant is running give an experienced maintenance engineer a good indication of the plant condition. CBM uses these basic indicative parameters, and others, and expands upon selected elements. These may include the vibrations that are produced, the variations in temperatures, the quality of the power supply and the condition of lubricating fluids within plant items to establish changing condition, thus minimising failures.

Used effectively CBM can be an excellent preventative breakdown tool as well as a training aid for understanding the individual behaviour of plant items. This understanding allows preventative measures to be taken when conditions indicating degradation appear, allowing problems to be solved before costly faults and even failures occur. With increasing pressure on maintenance staff, CBM allows more effective use of maintenance resources.

An important part of CBM is record keeping, which allows a history to be built up of plant item condition. This is invaluable in predicting plant behaviour under site conditions.

The frequency at which monitoring takes place, and the implications for time required for maintenance personnel to perform these tasks, is dependent on a number of site-specific factors. These include:

- Type of machine
- Age & condition of machine
- Type of CBM method used
- Operating conditions
- Criticality of machine.

In general, the frequency can be established once the first set of condition monitoring data has been analysed. If the plant item is in very good condition, then this can be as infrequent as once a year. However, if the plant item shows signs of degradation then the frequency should be increased to pick up the rate of change. In general, knowing the condition of the plant item reduces the need for conventional maintenance, as the maintenance requirement can be predicted.

Many techniques can be used to detect changing conditions within similar plant items, as shown below:

Example:

The bearing within a pump is suffering from gradual degradation of its surface, which can be detected in many ways. A thermal imaging camera can be used to detect the rise in temperature around the bearing casing, indicating a problem. Vibration or acoustic emission analysis can be used to detect the change in vibration levels throughout the pump. Alternatively, wear and oil analysis can be carried out at a laboratory to detect changes in the oil and to identify bearing particles.

However, although each of these CBM techniques can identify that there is a problem within the pump, the accuracy of predicting the severity and precise location of the problem varies from technique to technique. All the CBM techniques have the potential to improve the effectiveness of the maintenance regime, regardless of the type used. Understanding and using the strengths of each CBM method will allow an effective CBM strategy to be implemented. Possibly using a combination of techniques.

The principal benefits of implementing CBM include:

1. Expensive and labour-intensive routine maintenance activities are reduced and maintenance scheduling can be improved. This is due to a greater understanding of the operating characteristics of plant items through trending, and quicker assessment of plant condition
2. CBM allows preventive measures to be taken before costly breakdowns occur, allowing a reduction in unscheduled downtime
3. CBM can increase reliability of systems through remote inspection and assessment
4. Energy savings can be achieved through improved operating conditions of plant
5. Machine life can be extended by preventing degradation of internal components
6. Plant items can be tested before handover in the commissioning process.

Table 1 shows some of the main faults detectable with CBM, along with the effectiveness of the different methods. Further information and case studies will be published in BSRIA's *Application of Non-destructive Testing (NDT) in Condition Based Maintenance (CBM) of Building Service*, due out in 2002.

***	Highly effective method, can detect the severity, location and rate of degradation
**	Has a high detection ability, but may have a limited ability to evaluate severity and rate of degradation
*	Can detect fault, but can not evaluate severity and rate of degradation

Table 1
CBM method evaluation

Plant item	CBM method	Faults indicated	Effectiveness
Mechanical			
Pumps & fans	Acoustic emissions	Bearing degradation	***
		Lubricant degradation	**
		Misalignment & imbalance	*
	Thermography	Bearing degradation	*
		Lubricant degradation	*
	Vibration	Bearing degradation	***
		Lubricant degradation	**
		Misalignment & imbalance	***
	Wear & oil analysis	Bearing & lubricant degradation	***
	Shafts & rotors	Vibration	Misalignment & imbalance
Bent shafts			**
Loose components			**
Acoustic emissions		Misalignment & imbalance	*
Belt drives	Vibration	Misalignment & imbalance	***
		Mismatched belts	**
	Thermography	Misalignment & imbalance	*
		Belt tension	*
Compressors	Vibration	Misalignment & imbalance	***
	Wear & oil analysis	Bearing & lubricant degradation	***
Valves	Thermography	Valves, blockage, wear, leakage	**
	Acoustic emissions	Valves, blockage, wear, leakage	*
Pipework	Thermography	Insulation	***
		Sludge build-up	***
	Acoustic emissions	Leaks (air, vacuums, steam)	**

Table 1 *continued*
CBM method evaluation

Plant item	CBM method	Faults indicated	Effectiveness
Chilled ceilings	Thermography	Blockage	***
		Poor heat transfer	***
Building fabric	Thermography	Faulty insulation	***
		Poor air tightness	***
Boilers	Thermography	Blockage & scaling	***
		Poor circulation	***
Underfloor heating & cooling	Thermography	Poor pipe layout	***
		Blockage	***
Electrical			
Circuit breakers	Power quality	High crest-factors	***
Cables	Power quality	Harmonic current	***
Electrical	Thermography	Faulty switchgear, undersized conductors	***
Transformers	Power quality	Harmonic current	***
	Wear & oil analysis	Fluid leakage	*
		Contamination	***
Variable speed drives	Power quality	High frequency noise	***
UPS	Power quality	Low-crest factor	***
Standby generators	Wear & oil analysis	Fluid leakage	*
Motors	Acoustic emissions	Bearing degradation	***
	Power quality	Harmonic voltage	***
	Vibration	Stator & armature damage	**
		Coupling damage	**
	Thermography	Bearing degradation	*

2 VIBRATION & ACOUSTIC EMISSIONS INTRODUCTION

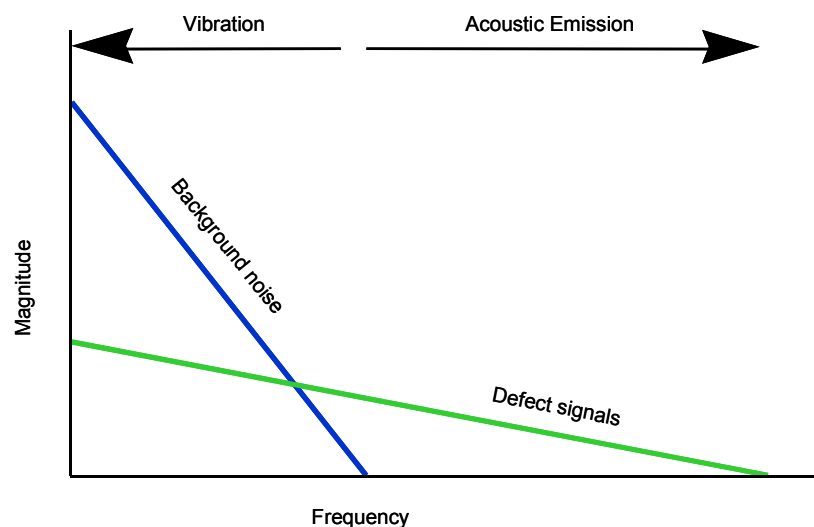
The various CBM techniques generally measure quite different parameters to detect changes within machinery condition. However, vibration analysis and acoustic emission condition monitoring use a similar approach. On a basic level, the two techniques rely upon the vibration signals generated within machinery when stress is applied to components of the machinery.

As both these techniques rely on variation in vibration frequencies, there can be confusion and misunderstanding as to when to use one method rather than the other. This section distinguishes between the two methods and provides advice on the most suitable technique for different applications. Chapters 3 and 4 provide detail on application of each technique.

The main difference between the two methods is the frequencies at which signals are generated and picked up by the appropriate monitoring instrument. Generally, vibration signals are low frequencies ranging from below 1 Hz to 25 kHz whereas acoustic emissions are high frequencies ranging from 20 kHz to 1 MHz.

Figure 1 indicates the difference in frequency measurement used for the two methods.

Figure 1
Indication of frequency and magnitude of vibration & acoustic emissions



(Source: Holroyd Instruments)

The differences between the two methods can appear to be minor, but they are very significant in regard to their ability to detect particular faults. The effectiveness in identifying the location, severity and rate of change of the particular faults is dependent on using the most appropriate method.

- Acoustic emissions have higher signal-to-noise ratio than vibration, which reduces the amount of background signals picked up by the measuring device. This means that vibration signals can require a greater deal of signal processing for the information to be analysed and used to identify faults.
- Early detection of bearing, gear and lubrication problems with low frequency vibration monitoring creates the need for frequency domain analysis, and detailed information regarding the components within the plant and its operational speeds. Acoustic processing can be done with no machinery information and in real time this requires less sophisticated processing and is less time consuming. Acoustic emission monitoring is therefore an ideal technique for a quick and effective assessment of this type of fault.
- Vibration monitoring instruments can detect early bearing damage by using a technique involving shock analysis. This method measures the high-frequency impact signals normally associated with acoustic emissions.
- Detecting signals from acoustic emissions usually requires a narrow frequency band to be adopted, while vibration generally adopts a broadband approach.
- The mounting methods and sensor locations on machinery are of paramount importance for vibration analysis but these aspects vary for acoustic emission. The position, coupling method and orientation are critical when dealing with the low frequencies of vibration. Acoustic emissions have a lower restriction on these parameters. A viscous coupling rather than a dry coupling is essential.
- Imbalance and minor machine misalignments at an early stage generate low frequency signals most suited to vibration monitoring. However, once the fault has progressed to allow the lubricating film to break down, metal-to-metal contact occurs and generates the higher frequencies that make acoustic emission monitoring an effective option. Therefore, vibration analysis is the most suitable method for early detection of these types of fault.
- Condition monitoring of non-rotating machinery is very difficult using either method. However, due to the better signal-to-noise-ratio of acoustic emissions, there is potential for acoustic emission monitoring in these types of applications.

3 VIBRATION ANALYSIS

Vibration analysis is one of the most widely used tools in CBM. Vibration analysis can potentially benefit most machines with moving parts since all rotating machinery has a degree of vibration due to the difficulty of balancing moving parts. Vibration analysis uses the vibrations within machinery, from sources such as bearing degradation and misalignment, to assess the plant's condition. When faults begin to appear in plant items, the normal vibrations within begin to show signs of change. By taking periodic vibration measurements of the plant item an assessment can be made of the current operating conditions. When these vibration measurements are trended over a period of time, the change in the plant conditions can be seen clearly in simple data sheets or as a graphical representation. By knowing the level of vibration that normal operating conditions produce, and by imposing levels at which action should be taken to prevent faults from becoming failures, an effective preventative maintenance programme can be built up.

The vibration monitoring equipment on the market can be simple to use and cost effective such, as hand-held devices, but more sophisticated and comprehensive approaches to vibration monitoring are available at an increased cost.

The information below will provide a good understanding of the different types of equipment, capital costs, different vibration techniques, potential benefits, and potential problem areas. This will allow the correct vibration-monitoring programme to be established.

3.1 DETECTABLE/ PREVENTABLE FAULTS

Vibration analysis allows many types of faults to be detected using the vibrations produced within plant items. Table 2 shows the variety of faults detected on different plant items.

Table 2
Detectable/preventable
vibration faults

Plant item	Fault type
Pumps	Bearing degradation/lubrication degradation/imbalance
Fans	Bearing degradation/lubrication degradation/misalignment/imbalance
Shafts and rotors	Misalignment/imbalance/bent shafts/loose components
Belt drives	Misalignment/imbalance/mismatched belts/pulley damage
Motor drives/electrical	Bearing degradation/lubrication degradation/stator damage/armature damage/coupling damage/misalignment/imbalance/castings/burnout/thermal trip
Compressors	Misalignment/imbalance/loose components

3.2 INSTRUMENTATION COSTS

The vital component of a vibration monitoring strategy is the measuring device. Table 3 shows typical capital and hire costs for such instrumentation.

Table 3
Vibration instrumentation

Monitoring instrumentation	Price	
General-purpose meters and analysers	£300 - £2000	
Portable data acquisition and analysers	£600 - £8000	
Continuous on-line monitoring	£1000 - £dependent	
Equipment accessories	Price	
Analysis software	£200-£2000	
Transducers	£200-£700	
Mounting studs	£15-£100	
Instrumentation hire	1 week	4 weeks
General-purpose meters and analysers	£150-£175	£450-£500
Portable data acquisition and analysers	£300-£600	£1000-£2000
Analysis software	£30	£90

General-purpose meters and analysers come in a variety of sizes and have either an analogue or digital readout. Most give a single reading of vibration level, while others can offer limited data-storage capacity that can be connected to a personal computer for trending purposes.

The measurements that are obtainable from the various meters range from rms acceleration and velocity, to analysers that can also measure temperature, machine speed and cavitation.

Portable data acquisition equipment and analysers collect and record data on vibration of machinery, with the ability to display vibration analysis plots. While these plots can be used to evaluate and diagnose the cause of vibration, they do require a certain knowledge of vibration frequency for on-the-spot diagnostic analysis. The meters can be attached to portable computers with vibration analysing software for trending and more sophisticated diagnostic purposes. These types of meters are ideal for performing periodic condition monitoring. They also have the ability for additional information to be entered into the meter such as temperature, flow rate and visual clues to the condition of the plant for future analysis.

Continuous on-line monitoring is the most sophisticated method of vibration analysis. Permanent or on-line systems use general-purpose or portable data acquisition analysers, but have sensors permanently attached to strategic measurement points on machines. These sensors are attached to data collectors, which in turn are attached to local monitoring units. The whole system is linked into a computer with vibration analysis and diagnostic software, which automatically obtains readings and performs analysis. The software can generate alarms, which indicate when certain parameters have been reached, this can indicate potential faults, and allow maintenance before a failure occurs.

3.2.1 Advantages and disadvantages of vibration analysis instrumentation

Instrumentation	Advantages	Disadvantages
General-purpose meters and analysers	Low cost, simple to use, small, lightweight and portable.	Limited data storage, poor repeatability of readings, limited or no analysis capabilities, limited measurement types.
Portable data acquisition and analysers	A wide variety of data is easily collected, can interface with condition monitoring software, can display vibration analysis plot for problem solving, and has the ability to automatically report irregular data.	Requires a walk-around survey.
Continuous on-line monitoring	Provides continuous monitoring, high detection rate of potential failures, reduced survey time.	High capital cost, requires training to use and analyse data.

The following section examines the key factors that require a basic understanding for an effective vibration-monitoring programme to be implemented.

3.3 INSTRUMENTATION SELECTION

Many vibration instrument manufacturers offer a diverse range of instrumentation, which have variable detection abilities.

- Different manufacturers produce instruments, which differ in their capacity to detect faults in identical machinery
- Sensor characteristics (sensitivity, frequency response) are determined by the manufacturers. Different instruments may have variations in these parameters, which equate to sensitivity to different frequencies
- Vibration instrument manufacturers tend to have different techniques for bearing evaluation such, as shock pulse and spike energy.

3.4 TYPES OF SENSORS

It is important to select the vibration measurement sensor type that is most likely to detect the expected faults. These devices provide a means of transferring the vibration signal into a measuring device for analysis.

Accelerometer

- Good reliability
- Wide frequency range (0 to 400 kHz)
- Good high frequency response.

Displacement probe

- Frequency range 0 to 1000 Hz
- Measures relative distance between two surfaces, only when two surfaces are moving separately, such as misalignment
- Limited high-frequency sensitivity
- Require external power supply
- The sensor that can measure shaft vibration relative to a bearing housing.

Velocity sensor

- Often used to measure bearing housing or machine casing vibration
- Low to mid frequency range (10 to 1500 Hz)
- Electro mechanical device seldom used due to high failure rate.

3.5 VIBRATION SIGNAL PROCESSING

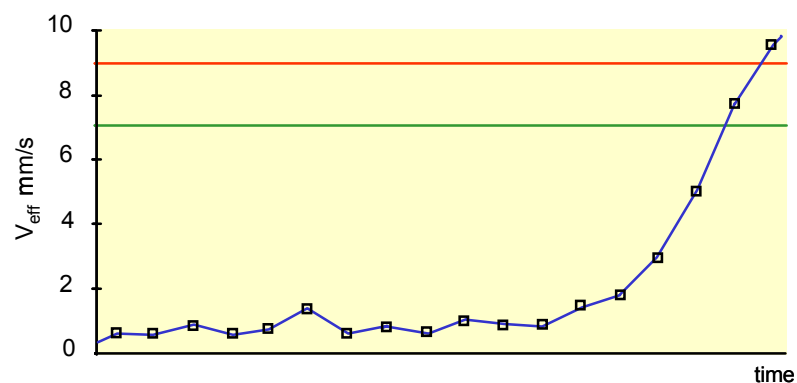
There are three main generic types of vibration measurement analysis within the field of CBM:

- Overall vibration
- Spectral analysis
- High frequency impact.

3.5.1 Overall vibration

The general vibration emanating from a machine and its components can give a good indication of its overall condition. Figure 2 shows a vibration plot with an increasing severity in the signal, indicating increasing degradation of internal components.

Figure 2
Overall vibration analysis



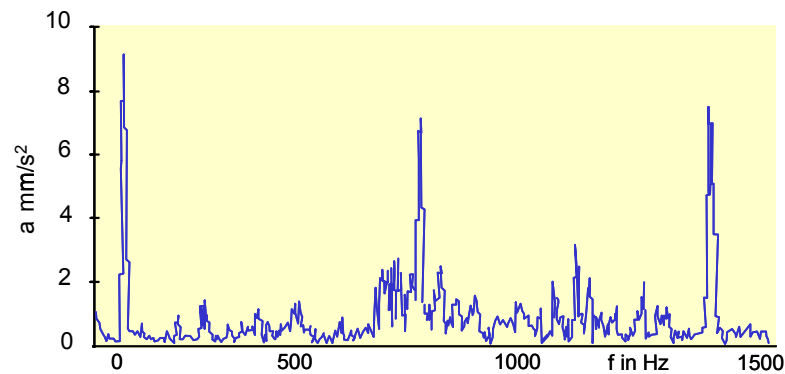
(Source: Prüftechnik)

The signal produced by the instrument has not been broken down into its constituent parts, so the plot only indicates a general fault with the plant item. By trending one can determine vibration severity and change. To indicate the location of faults within the vibration signal, the waveform needs breaking down and analysing.

3.5.2 Spectral analysis

Different faults cause vibration at different frequencies, so by using a spectrum analyser to convert the overall signal into individual amplitudes at component frequencies the source of fault can be established. Figure 3 shows how a general signal can be broken down into its component frequencies. The vibration measurement is transformed from a time domain to a frequency domain by a Fast Fourier Transform (FFT). This detects the frequency at which the faulty component is vibrating, thus giving an indication of the location and cause of the faults.

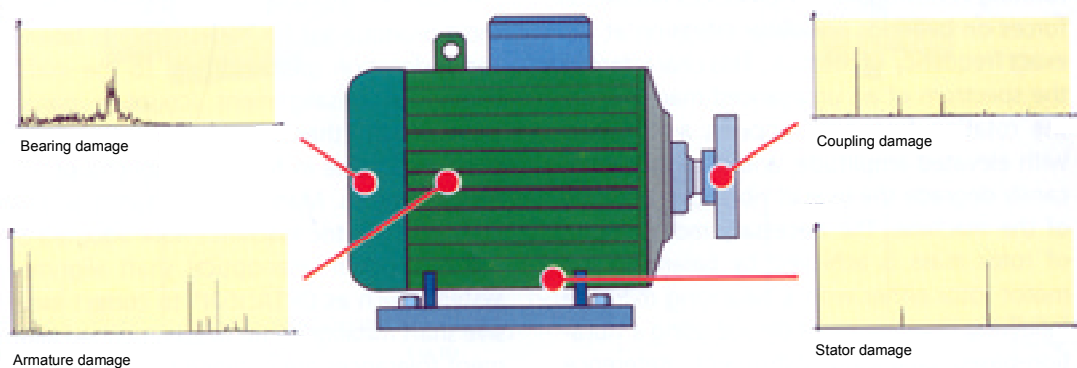
Figure 3
Frequency analysis



(Source: Pruftechnik)

Figure 4 shows how frequency analysis carried out on a motor can break down the vibration signal into its constituent parts, thus showing the condition of different components within the motor

Figure 4 Vibration frequencies of a motor



(Source: Pruftechnik)

3.5.3 High frequency

High frequency impacts between damaged surfaces produce impulse shocks, mainly within bearings. These shocks provide an assessment of the bearing's condition, identify potential faults, and assess the likely failure rate. Many manufacturers incorporate such high frequency measuring facilities in a range of instrumentation. The various manufacturers have developed variations in this type of analysis, with

differences in the detecting abilities, but all provide a similar analysis technique using the high frequency range associated with acoustic emissions. These include:

Shock pulse

- A method of monitoring by means of detecting pulses, generated by defect impacts
- Effective for early detection of bearing wear.

Spike-energy

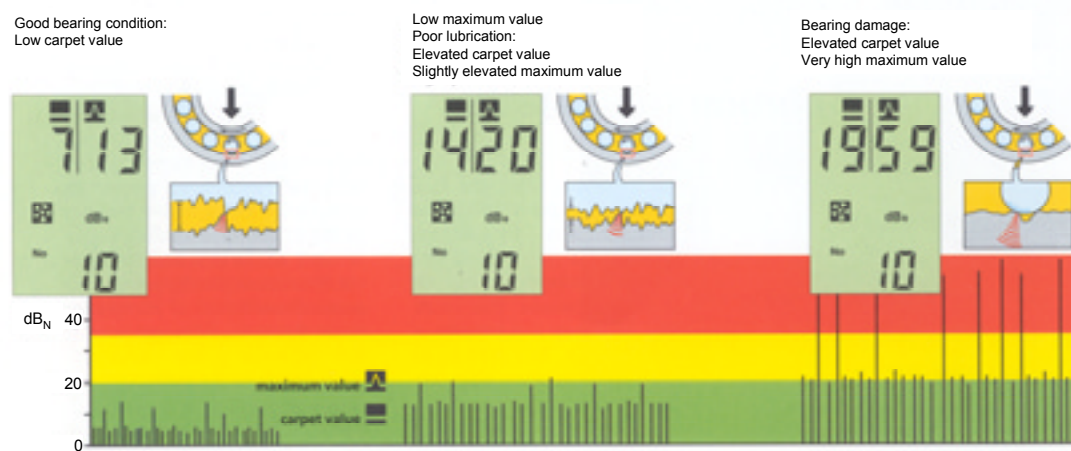
- A method of monitoring which combines shock pulsing, the rate of occurrence of pulses and the broadband rms acceleration over the frequency range 5 kHz to 45 kHz.

Spectral emitted energy

- A method of detecting early bearing and gearmesh faults
- Detects lubricant problems, allowing early corrective measures.

Figure 5 shows a high-frequency method of determining the bearing condition, by using the signals from impacts and shocks. The instrument produces an arbitrary figure, which can be used as an on-the-spot assessment of the bearing condition, or can be trended.

Figure 5 High-frequency vibration signals



(Source: Prüftechnik)

3.6 PLACEMENT OF SENSORS

The method of mounting sensors is of primary importance to the successful application of vibration monitoring. It has a direct effect on vibration signal frequencies, which can result in misleading measurements.

Various mounting methods are available. Magnetic bases are a temporary method of mounting sensors. It is a quick and easy method, but does suffer from errors in the frequency response, which can lead to misleading results.

Adhesive cement and stud mounting are the best methods for permanently mounting sensors. They are stable sensing platforms, which reduce potential errors in signal detection.

Hand-held probes are convenient, but they are prone to errors induced by the amount of pressure applied by the operator, the angle of the sensor to the surface and the way in which the probe is placed on the surface.

The orientation of the sensor to the machinery is again of primary importance for successful monitoring. The locations (are shown in Figure 6):

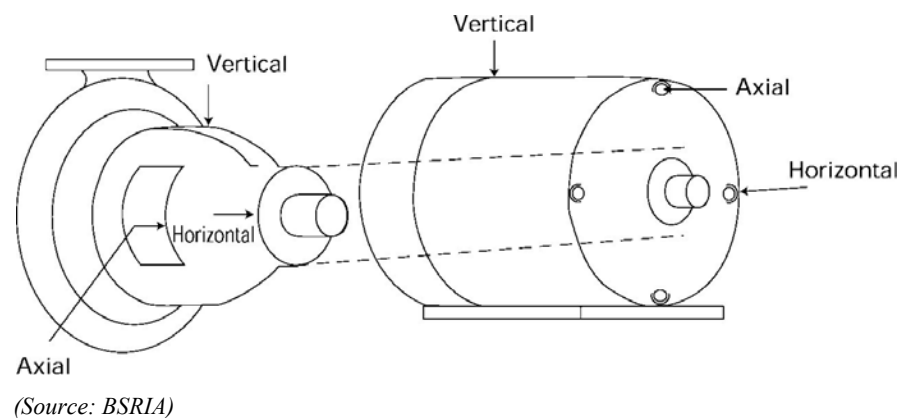
- radial
- axial
- bearing housing
- casing.

Vertical or horizontal positioning is also important as this is related to the direction of the vibration signal. The sensor placement should ensure that the direction of acceleration is monitored correctly.

ISO 10816-1 states “Measurements should be taken on the bearings, bearing support housing, or other structural parts which significantly respond to the dynamic forces and characterise the overall vibration of the machine”

Ensure that sensor mounting complies with *BS ISO 5348*. The location depends on the components to be measured and the application. Not all of the above locations need sensors, but a certain degree of assessment will have to be done to establish the most suitable location for the particular parameter being measured.

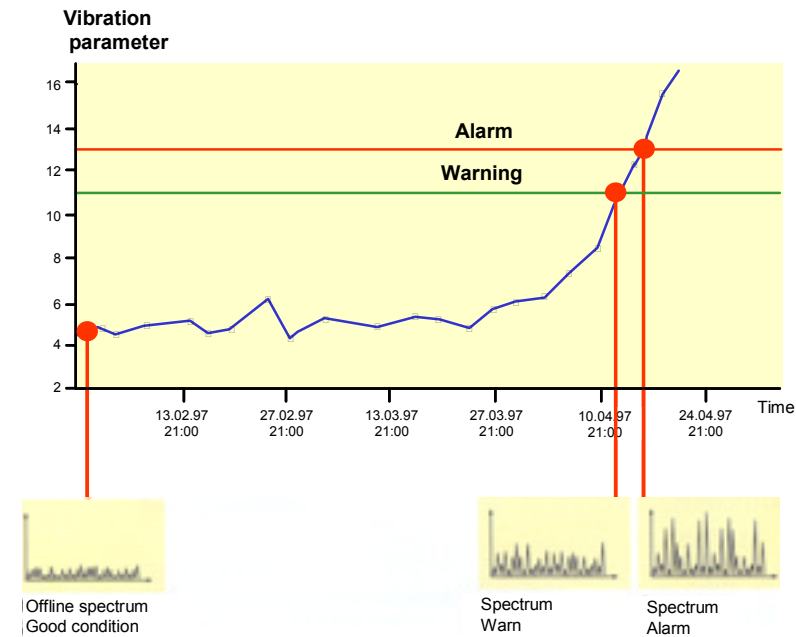
Figure 6
Vibration sensor
placement



3.7 DATA CAPTURE

The data that is obtained from the vibration measurement often needs to be compared with previous data so that trending can be done, as shown in Figure 7. To achieve consistent, reliable trending the conditions under which the monitoring is taking place must be the same. By using vibration data processing techniques, the amount of data stored is greatly reduced. It is also much more relevant for trending purposes. However, not all vibration signals require trending, as is the case with the high frequency signal generated by impacts and shocks, which can attribute a figure to the condition of bearings on the spot.

Figure 7
Trending vibration data



(Source: Pruftechnik)

3.8 BENEFITS AND PROBLEMS

3.8.1 Potential benefits

Monitoring vibration within machinery can have many benefits to the effectiveness of a maintenance regime including:

- Detect bearing degradation
- Increase operating life of components
- Detect misalignment and imbalance of shafts and rotors
- Detect looseness of components such as drive belts
- Allow effectiveness of oil changes to be evaluated
- Detect armature, coupling and stator damage in electric motors.

3.8.2 Potential problems

3.8.2.1 Non-repeatability

One of the major possible faults in vibration measurement is from background vibration noise, from other plant items or from a different component within the plant item. Possible problems to watch out for are:

- Vibration from nearby plant
- Vibration along connection pipework

- Vibration from loose components, with no direct effect on performance of plant but which generates a vibration signal
- Vibration along bedplates.

If problems are encountered, there are a number of methods for removing the unwanted signals.

- Take vibration measurement with the plant item on normal load and while shut down. This gives an indication of the background vibration
- Consider the other vibration within the machine and try to eliminate it from the analysis by filtering.

3.8.2.2 Variable loads and speeds

Consistent measurement results can become difficult with variable speeds and loads. To ensure the vibration signals received are an accurate representation of the plant's condition, the load upon the machine should always be the same when taking measurements.

3.8.2.3 Reciprocating machinery

Vibration analysis of reciprocating machinery is a difficult process. The signals generated are complicated, with many different components producing signals within the machine. It is very difficult to separate the normal operating vibration signal from those that indicate faults within the machine. It is possible to achieve this by comparing a signal of a machine in perfect operating order with subsequent signals. However, this is a time consuming and complicated process, which would require extensive experience, so has limited usage at present. This type of analysis is achievable from specialist vibration companies.

3.9 TRAINING REQUIREMENTS

Use of basic hand-held vibration instruments requires limited training, as they are simple to operate and the data they produce is easy to interpret. Becoming proficient in analysing vibration signals on a time domain basis (overall vibration) and high frequency shock methods would, on average require a half-day to a day's training. However, when more detailed frequency analysis (spectral analysis) is required training of between 3-5 days would be necessary. With on-the-job experience most maintenance staff could become proficient with this type of condition monitoring.

3.10 REGULATIONS AND STANDARDS

There are many British, European and international standards available that will aid a vibration monitoring strategy. Some are aimed at the processes involved in sensor mounting methods and suggest strategies, while others deal with suggested acceptable vibration levels of particular plant. These should only be used as a guide, as different plant operating under diverse circumstances will have individual vibration characteristics. A selection of standards is shown below:

1. **BS 4675** (ISO 2372, 1974). *Mechanical vibration in rotating and reciprocating machinery. Part 1: Basis for specifying evaluation standards for rotating machines with operating speeds from 10 to 200 revolutions per second.* 1976.

2. **BS 4675** (ISO 2954). Part 2: *Requirements for instruments for measuring vibration severity*. BSI 1978.
3. **BS 7854** (ISO 10816-1). *Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts. Part 1: General guidelines*. 1995.
4. **BS 7854** (ISO 10816-6). Part 6: *Reciprocating machines with power ratings above 100KW*. 1995.
5. **BS ISO 7919-1**. *Mechanical vibration of non-reciprocating machines – Measurements on rotating shafts and evaluation criteria. Part 1: General guidelines*. 1996.
6. **BS 4999**. Part 142: *General requirements for rotating electrical machines. Specification for mechanical performance: Vibration*. 1987.
7. **BS ISO 5348**. *Mechanical vibration and shock. Mechanical mounting of accelerometers*. 1998.

3.11 USEFUL PUBLICATIONS

1. BSRIA, *Guidance to the standard specification for vibration testing of building services installations*. FMS 7. 2000. ISBN 0 86022 541 0.
2. BSRIA, *Vibration monitoring for building services*. TN 3/95. 1995. ISBN 0 86022 397 2.
3. REEVES C, *Machine & systems condition monitoring Series. Vibration*. Coxmoor 2000. ISBN 1 90189 200 X.

4 ACOUSTIC EMISSION

Acoustic emission condition monitoring is similar to vibration monitoring in that both use a transducer to convert mechanical energy into electrical energy. Through the use of associated hardware and software, this electrical energy can be converted into a quantifiable value for interpretation.

Acoustic emission detects the naturally occurring high frequency structure-borne elastic waves, which are produced in materials under some form of stress. Stresses produced from a number of sources can be detected, such as friction, impacts, cavitation and even turbulence.

Acoustic emission is concerned with the high frequency range from approximately 20 kHz to 1 MHz, which accounts for one of the main differences between vibration and acoustic condition monitoring. Acoustic emission has a good signal-to-noise-ratio which means background interference does not pose a problem when processing the signal to get meaningful information.

Traditionally, vibration monitoring has been the preferred CBM technique in machine stress monitoring for many years. However, research into the practical applications of acoustic emission and improvements in instrumentation in recent years has shown that acoustic emission is as practical and reliable as vibration monitoring for many different types of machinery and faults. Used effectively acoustic emission can be more sensitive to certain types of faults than conventional vibration monitoring, so it is no longer the case that vibration analysis takes priority in all areas where stress waves indicate the conditions of machinery.

Gaining an understanding of the different faults detectable using the various acoustic instruments, along with the benefits and problems that acoustic emission monitoring can provide, is vital in establishing a successful acoustic emission monitoring strategy

4.1 DETECTABLE/ PREVENTABLE FAULTS

There are many benefits of monitoring acoustic emissions for building services plant. These are similar to those of vibration monitoring, as they can detect similar faults. Table 4 shows some of the types of machinery and potential faults that are detectable using acoustic emission CBM.

Table 4
Detectable/preventable
acoustic emission faults

Plant item	Fault type
Pumps	Bearing degradation/lubrication degradation/cavitation
Fans	Bearing degradation/lubrication degradation
Seals	Leakage/abrasion
Gearing	Pitting & chipping
Valves	Blockage/wear/leakage
Motors	Bearing degradation/lubrication degradation
Shafts	Misalignment/imbalance

4.2 INSTRUMENTATION COSTS

The main component of an acoustic emission condition monitoring strategy is the measuring device itself. Table 5 shows typical capital and hire costs for such instrumentation.

Table 5

Acoustic emission instrumentation

Monitoring instrumentation (purchase)	Price
General-purpose meters and analysers	£300-£1500
Portable data acquisition and analysers	£1200-£4000
Continuous on-line monitoring	£1500-£dependent
Monitoring instrumentation (hire)	1 week
General-purpose meters and analysers	£150-£175
Portable data acquisition and analysers	£300-£600
Analysis software	£30

The most simple and inexpensive meters used for acoustic emission measurements are quick and easy to use, with little or no training required to operate effectively. These types of instruments range from a single button device that provides a magnitude of the signal (dB), to instruments that display the magnitude of the signal as a bar graph.

These types of instruments provide a cost effective method of collecting acoustic emission data from numerous machines when repeated measurements are desired. The instruments can be pre-programmed to guide the operator around a set route for condition monitoring and have the ability to store the acquired data for future downloading for trending and analysis. These types of instruments range from data storage with little or no built-in analysis capability to frequency analysers that can provide diagnostic capabilities of the origin of the acoustic emission.

Systems that use on-line/permanent components consist of channel scanners that monitor the acoustic emission from a number of transducers. This type of set-up is the most expensive type of acoustic emission CBM, but does offer the greatest capacity to analyse many acoustic emission signals and detect faults. The systems will generate alarms which indicate when specified thresholds have been reached, indicating a potential fault, and allowing rectification before failure occurs.

As a general rule, acoustic emission instrumentation can be less expensive and simpler to operate than vibration analysis equipment. The acoustic signal can be processed in the time domain (on-the-spot) rather than frequency domain, which can require extensive processing to break the signals into their component frequencies. This can mean less-sophisticated processing components are needed, and generally less training and expertise are required to operate them and obtain useful condition monitoring data.

4.2.1 Advantages and disadvantages of acoustic emissions instrumentation

Instrumentation	Advantages	Disadvantages
General-purpose meters and analysers	Low cost, simple to use, small, lightweight and portable.	Limited data storage, poor repeatability of readings, limited or no analysis capabilities, limited measurement types.
Portable data acquisition and analysers	A wide variety of data is easily collected, can interface with condition monitoring software, can display vibration analysis plot for problem solving, and has the ability to automatically report irregular data.	Requires a walk-around survey.
Continuous on-line monitoring	Provides continuous monitoring, a high detection rate of potential failures, and reduced survey time.	High capital cost; requires training to use and analyse data.

4.3 INSTRUMENTATION SELECTION

There are many companies offering acoustic emission instrumentation, with different characteristics. The issue of selecting the correct equipment can become difficult if the differences between acoustic emission and vibration monitoring are not understood.

- Acoustic emission manufacturers tend to have different techniques for evaluating the defect growth, impacts, friction and turbulence, such as 'Distress[®]', a trade marked signal processing technique (see 4.5.1).
(*Distress[®] is a registered trademark of Holroyd Instruments Ltd*)
- Different manufacturers have a mix of signal detection and processing techniques. This means that the instruments do not all have the same capacity to detect faults in the same machinery
- The sensor characteristics (sensitivity, frequency response) are determined by the manufacturers. Different instruments may have variations in these parameters, which equate to sensitivity to different frequencies.

4.3.1 Types of acoustic sensors

Acoustic emission sensors need to be sensitive, robust, cost effective and be easy to use. Most acoustic emission transducers use piezo-electric elements, where an electrical charge is produced by stress in materials, which can be amplified and processed using a number of signal processing techniques.

Most sensors are designed to respond to frequencies in the range 20 kHz to 1 MHz. There are a number of different sensors that can be considered for acoustic emission measurement, but care must be taken in obtaining the correct one. Sensors can be sensitive in a particular frequency range, which affects their response to certain signals.

Broadband detection

- Responsive to a wide range of frequencies.
- Very susceptible to the effects of low frequency signals, such as background signals which can distort results.

Resonant (narrowband) detection

- Most common form of detecting acoustic emission signals
- Has a high sensitivity in a narrow bandwidth
- Minimal sensitivity to low frequency, i.e. vibration signals.

Accelerometer as an acoustic emission transducer

- Most common form used in vibration signal detection.
- Performance unreliable for narrowband detection
- Not suitable for acoustics.

4.4 ACOUSTIC SIGNAL PATTERNS

Three main signal patterns emerge from acoustic emission measurements that produce distinct waveforms with graphical representation of the signal:

- Burst – this type of signal will show up on an oscilloscope as a sudden surge in the signal level before returning to a normal level.
- Continuous – this type of signal shows up as an uninterrupted signal with a slightly varying magnitude.
- Mixed - this type produces a moderately constant signal with burst activity taking the signal magnitude beyond the steady state of the signal.

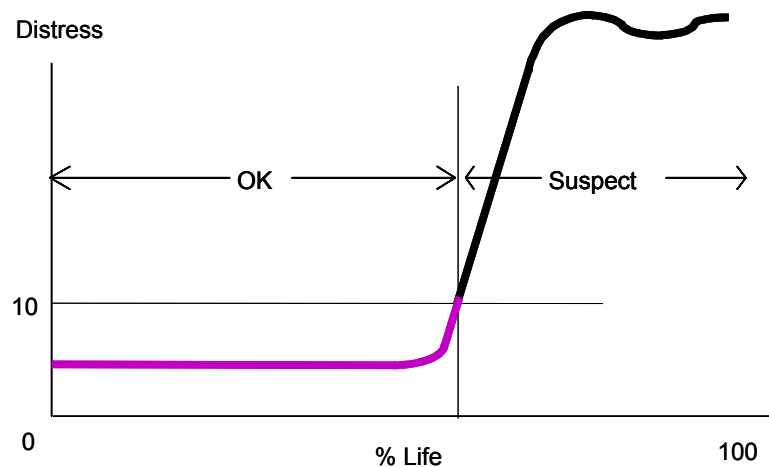
These three types of signal can give an indication of general conditions within machinery.

- Continuous signal = plant item operating at normal speed and load and in general good condition.
- Burst/mixed = where burst activity is evident, generally considered indicative of problems within machinery.

4.5 TYPES OF SIGNAL MONITORING**4.5.1 Distress[®]**

The acoustic emission instruments which provide a form of distress value, use techniques that transform the waveforms generated from impacts and rubbing of components such as bearings, into an arbitrary value. This value can be used to determine on the spot the amount of degradation to bearings, from loss of lubricant or contamination of the lubricant. Figure 8 shows how the figure generated by the acoustic emission instrument can be assessed against a preset value.

Figure 8
Distress®

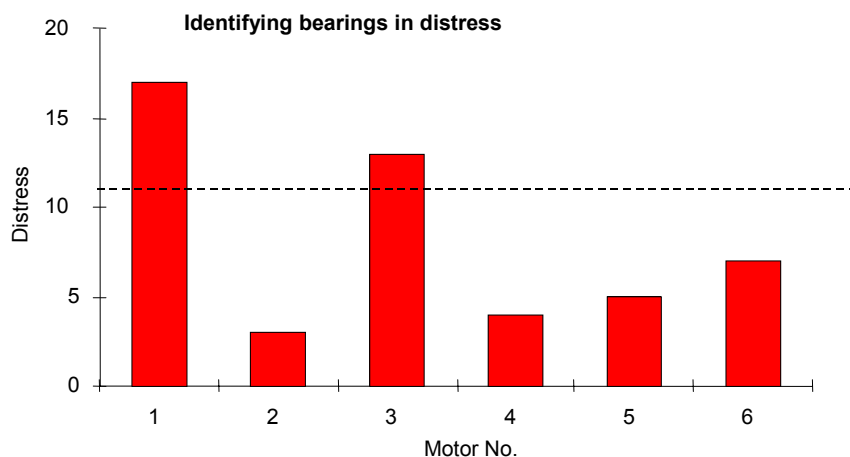


(Distress® is a registered trademark of Holroyd Instruments Ltd)

Most rotating machinery can be attributed the same or very similar distress value for various levels of degradation, thus enabling on-the-spot comparison.

Figure 9 shows the distress® levels of six similar pumps, and indicates that a number of the pumps are reaching a level where internal damage may be occurring.

Figure 9
Distress® to pump bearings



(Source: Holroyd Instruments)

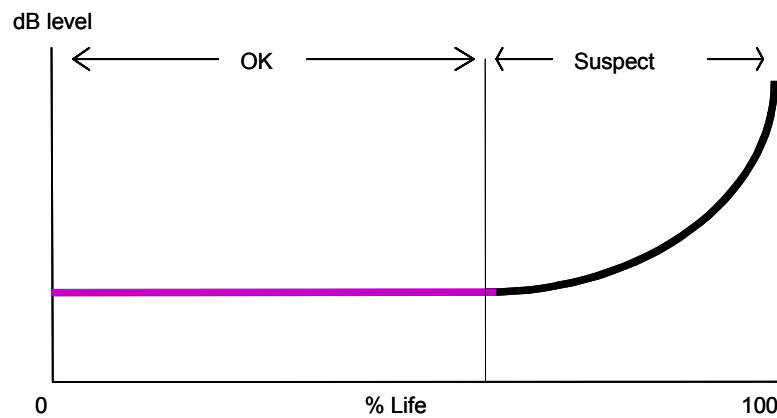
Distress can be used as a method of assessing condition and ranking dissimilar plant items, whereas the dB method cannot do this.

4.5.2 dB level

This type of measurement, unlike Distress®, requires that certain information be known about the machinery, such as the type, size, rotational speeds and design, as the dB level will vary for different machinery types. Therefore dB level cannot be applied to every item of rotating machinery without some form of comparison with identical machines operating under the same conditions, or by trending the dB levels of individual machines.

Figure 10 shows how the dB level (as with distress levels) changes over the operating life of an item of building services plant. This shows how the dB levels will gradually rise with increasing degradation of internal components.

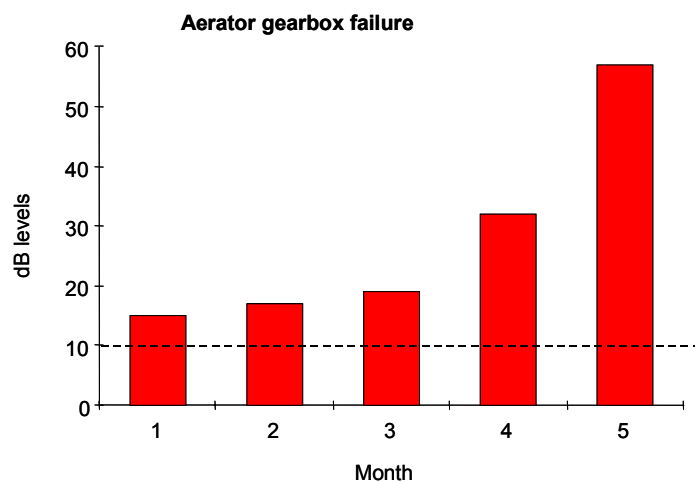
Figure 10
dB Level



(Source: Holroyd Instruments)

Figure 11 shows that by comparing the dB level against previous readings of the same machine or comparing similar machines, it is possible to determine the rate and severity of degradation. This provides a simple and easy to understand method of condition monitoring.

Figure 11
dB levels over time



(Source: Holroyd Instruments)

4.6 SIGNAL PROCESSING

The main objective of signal processing is to obtain and characterise the information that is required for analysis. There are a number of signal processing methods that need to be considered to establish the most suitable instrument for a particular application. Two types of signal processing methods that make the signal more manageable and meaningful are described below.

4.6.1 Threshold signal processing

A maximum limit can be set for the signal, with the section of signal exceeding the maximum being accepted for further processing. There are two main ways of evaluating the signal exceeding the threshold.

The simplest form is by counting the number of times the threshold is exceeded. This provides a simple means of detecting an increase in the average signal level. This greatly reduces the amount of data storage needed but does not allow much analysis of the signal, such as the characteristics of the signal, and limits the ability to pinpoint the cause of acoustic emission.

The next level of threshold processing provides a more comprehensive analysis of the signal. This type of processing is concerned with the burst signal characteristics, examining the rapid rise and gradual fall in magnitude, typical of acoustic emission bursts.

The threshold level, threshold limit transgression and the duration of burst are all examined. This gives scope for assessing the cause and severity of the plant fault.

As the continuous noise level changes so will the signal relationship, so care is needed to keep threshold levels in line with the continuous signal levels.

4.6.2 Frequency signal processing

This type of processing is concerned with pinpointing the type of frequency at which the fault is being generated.

Particular faults will generate signals at specific frequencies. By analysing these specific frequencies, a great deal of qualitative information can be obtained about the location and severity of the fault.

Recognising the different frequencies of signals generated within a plant item allows an effective indication of the precise nature of the plant condition. This type of processing has many benefits for the diagnostic capability of acoustic emission leading to remedial action before the fault deteriorates into a failure. Examining particular frequencies is only required when the general signal does not contain enough information to produce a definitive assessment of fault location and severity.

4.7 PLACEMENT OF SENSORS

The precise placement of sensors is generally not as important for acoustic monitoring as it is for vibration monitoring. This is related to the way in which the waves are generated and distributed throughout the materials of the plant item. The high frequency signals generated with acoustic emissions are not dependent on the directional (vertical, horizontal) relationship between sensor position and motion of component under investigation.

The general rules applied to vibration sensor positioning also apply to acoustic emissions.

These include:

- Positioning of the sensor directly on or adjacent to the component being monitored
- Where background noise interferes, the best signal-to-noise-ratio will be found adjacent to the component being monitored at the most distant point from the background noise
- Positioning of the sensor on a structural part of plant item.

Unlike the dry coupling for vibration sensors, acoustic emissions require a viscous medium such as oil or grease to maximise the acoustic transmission. One important item to ensure is:

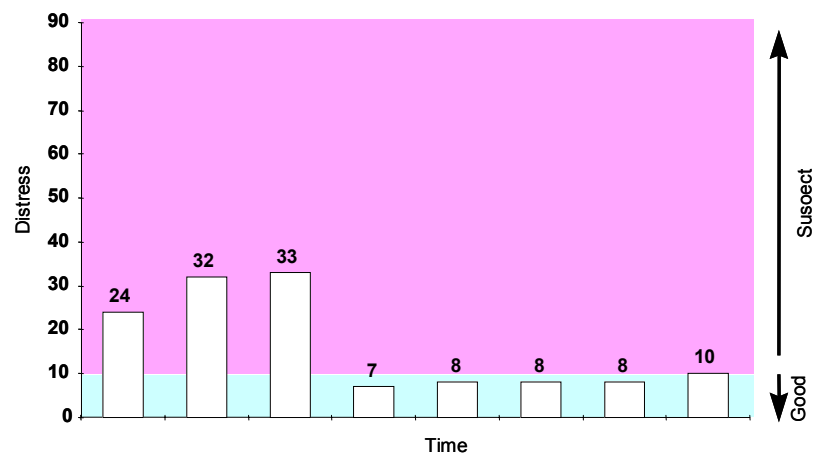
- Ensure the surface of both the sensor and the plant item is flat and clean, with no signs of rust or dirt, which would interfere with the sensor's contact point.

4.8 DATA CAPTURE

Once the appropriate signal processing has been achieved, an evaluation of the results will show whether there is an uncharacteristic signal from the monitored item of plant. Once the association between type of signal and different fault types is known an on-the-spot evaluation can be achieved. However, for a constructive appraisal of the plant condition over its operating life, it becomes beneficial to trend the gathered monitored data. This shows when changes occur and at what rate. When this is built up over the operating life, the gathered information can prove invaluable in understanding the behavioural characteristics of individual plant items.

Figure 12 shows how the degradation of the component has increased over time, while there is a clear sign of the maintenance having had a dramatic effect on the distress levels.

Figure 12
Trending showing
corrective measures



(Note: roller changed after 3rd reading)
(Distress® is a registered trademark of Holroyd Instruments Ltd)

4.9 BENEFITS AND PROBLEMS

4.9.1 Potential benefits

Acoustic emission CBM has the potential to be one of the most commonly used methods of CBM. Acoustic emission offers many advantages over conventional maintenance regimes, including:

- Instrumentation can be simple to operate
- Information produced by instrumentation is straightforward to interpret
- Can detect faults in motors, pumps, gearboxes, shafts
- Can detect faults in different types of bearings such as ball, roller and plain
- Can detect faults in fast and slow rotating machines
- Can provide an instant indication of machine condition without prior measurements or specific machine information such as speed and bearing diameter.

4.9.2 Potential problems

There are a number of areas to consider that will help prevent problems arising.

- Establish there is no interference to the signal from unwanted sources
- Always monitor the condition of plant at the same load to allow trending
- Be aware of the insensitivity to minor misalignment, imbalance and bent shaft problems until they have become quite severe
- Difficulty may be experienced in assessing the condition of very slow rotating machinery, such as a machine with a rotating speed of less than approx 40 rpm.

4.9.2.1 Reciprocating machinery

Monitoring conditions within reciprocating machinery is always difficult due to the natural vibrations produced when the machine is in operation, even when in good condition. It is possible to detect faults within reciprocating plant, but it requires extensive practical experience, and knowledge base of frequency analysis. For monitoring reciprocating plant, a specialist acoustic emission company should be contacted for advice and assistance.

4.10 TRAINING REQUIREMENTS

Training requirements for acoustic emission condition monitoring are similar for those of basic vibration monitoring. To be able to use the simple hand-held distress type instrument requires approximately half a day to a day. To become proficient in using acoustic emission in most of the potential building services applications requires between 2-5 days training as well as extensive practical experience.

4.11 REGULATIONS AND STANDARDS

There are only a few standards or regulations that deal specifically with acoustic emissions condition monitoring. The generic standards currently include:

1. **EN 1330-1** *Non-destructive testing terminology – Part 1: List of general terms.* 2000.
2. **EN 1330-2** *Non-destructive testing terminology – Part 2: Terms common to the non-destructive testing methods.* 2000.
3. **EN 1330-9** *Non-destructive testing terminology – Part 9: Definition of terms in acoustic emissions.* 2000.
4. **EN 13477-1** *Non-destructive testing- Acoustic emission – Part 1: Equipment characterization- Equipment description.* 2001.
5. **EN 13477-2** *Non-destructive testing- Acoustic emission – Part 2: Equipment characterization-Verification of operating characteristics.* 2001.

4.12 USEFUL PUBLICATIONS

The following publication aids understanding of the more complex nature of acoustic signals and their applications.

1. HOLROYD T, *Machine & systems condition monitoring series. acoustic emission & ultrasonics.* Coxmoor 2000. ISBN 1 9018 20 7

5 POWER QUALITY

Power quality depends on at least a dozen key features of the electrical supply including frequency and voltage variations, but the most critical factor is waveform distortion or harmonic content. Harmonic voltages can cause malfunctions in sensitive equipment, such as the sensing circuits of circuit breakers and uninterruptible power supply switches, while harmonic current can result in overheating of conductors, transformers, motor coils and capacitors. These are potentially disastrous and cases of building power supply failure and supply-related fires are increasing. Therefore, measuring power quality as part of a CBM regime can be very useful and effective

5.1 DETECTABLE/ PREVENTABLE FAULTS

Power quality measurement has great potential within the field of CBM. It is increasingly important to ensure continuity of power supply to buildings. Table 6 shows some typical plant items that can benefit from power quality condition monitoring, along with the types of faults detected and suggested devices for monitoring.

Table 6
Detectable/preventable
power quality faults

Plant item	Fault type	Instrument advice
Cables	Harmonic current overload, particularly in neutral of three-phase split supplies	Hand-held, but use power quality data recorder to find maximum load and time
Motors	Harmonic voltage causes overheating and low efficiency	Hand-held
Circuit breakers	High crest factor can cause nuisance tripping	Power quality data recorder can record voltage and current until tripping occurs
Transformers	Harmonic current circulates in windings, causing overheating	Hand-held, but use power quality data recorder to find maximum load and time. NOT the HIGH VOLTAGE SIDE.
PFC	Harmonic currents near the resonant frequency of the PFC unit cause excessive current and overheating	Possible with hand-held, but load and number of PFC modules online will affect resonant frequency.
Variable speed drives	Output of drive may include high frequency noise that causes overheating, particularly when long supply cables are used between a drive and its motor	Hand-held
UPS	Low crest factor of voltage can cause nuisance tripping	Hand-held, but use power quality data recorder to record at time of nuisance tripping

5.2 INSTRUMENTATION COSTS

There are a number of power quality monitoring devices available. Table 7 shows typical capital costs for such instrumentation. A brief outline of the implications of implementing the different power quality techniques is given below.

Table 7
Power quality
instrumentation costs

Measurement Instrument (Purchase)	Price range
Plug-in voltage disturbance logger	£300-£400
Hand-held power quality analyser	£1000-£2000
Power quality data recorder	£2000 to £10000
Measurement Instrument (Hire)	Price range per week
Single-phase hand-held power quality analyser	£100 - £200
3 or 4-channel power quality data recorder	£200 - £600
Current clamps, extra each	£25 - £65

The lowest-cost power analysers will only record voltage disturbances, although they can be left in position for long periods to record occasional disturbances. Hand-held instruments are useful for quick checks of a number of points, and should be capable of recording the distorted current and voltage waveforms and breaking them down into their individual harmonic components. Some may also be capable of recording transients and inrushes of current. Data output to a computer is essential so that high quality reports can be generated. The larger instruments are capable of collecting vast amounts of data over extended periods of several weeks or even months, and can be programmed with thresholds to record full waveform details and a history of all variations outside selected limits.

With some instruments, the analysis software supplied may not be sufficient for the location of distorting power quality loads. Power quality software is often expensive because of its limited market. However, some software can take the outputs from a variety of different power quality analysers, put it into a standard format, and perform comparisons.

5.2.1 Advantages and disadvantages of power quality instrumentation

Instrumentation	Advantages	Disadvantages
Single phase hand-held analysers	Low cost, simple to operate, lightweight and portable, ideal for preliminary surveys.	No phase comparisons, limited diagnostic capabilities, time consuming for complex installations, little or no storage facilities.
3 or 4-channel power quality data recorder	Improved detection, long-term monitoring, large data capacity, and high accuracy.	High capital cost, training may be required, analysis may be laborious.

5.3 INSTRUMENTATION SELECTION

Instrument selection must be appropriate to the information required. Harmonics, transients, flicker and long term trending are not available from all power quality instruments. Specification of instruments must be checked before selection.

- Frequency response of the instrument must be adequate to detect all the harmonics and transients expected
- Hand-held harmonic analysers should measure up to the 25th harmonic or higher, i.e. 1250 Hz
- Power quality analysers should measure up to the 50th harmonic, i.e. 2500 Hz
- Transient detection instruments must detect changes in voltage, with a possible duration of less than one millisecond
- Instruments that use thresholds can be very useful for determining compliance with standards or regulations.

5.4 POWER QUALITY DETECTION

Power quality monitoring results provide a means of reducing the following:

- Costs of harmonic mitigation measures (filters)
- Power and transmissions losses in conductors, transformers, motors, etc
- Engineering effort to diagnose problems
- Accelerated ageing of equipment due to heating and other harmonic effects
- Requirements for de-rating and oversizing of equipment to withstand harmonic duties.

The benefits of controlling/filtering harmonic levels are:

- Improved power factor and reduced MVA demand
- Reduced harmonic voltage distortion within plant and harmonic currents injected into power systems
- Lower susceptibility to transient voltage during switching of large capacitor banks on the utility system.

5.5 KEY CONSIDERATIONS

Many issues need to be considered prior to power quality assessments, to provide maximise effectiveness and safety including:

- Compliance with health and safety regulations
- Selecting correct instrument
- Selecting correct point of measurement
- Power factor correction
- Effect of unbalanced harmonic generation
- Evaluation of the time-varying characteristics of harmonics
- Possible costs involved in taking measurements and remedying problems.

5.6 BENEFITS AND PROBLEMS

5.6.1 Potential benefits

The information obtained from power quality monitoring of electrical systems allows many potential faults to be predicted and avoided. Some of the potential faults of these systems can have critical effects on a company's ability to perform. Benefits of using power quality as part of a CBM regime include:

- Reduction in breakdown of electrical systems
- Improved safety of electrical systems inspections
- Prevention of overheating of electrical systems
- Prevention of tripping by monitoring the crest factor
- Energy savings.

5.6.2 Potential problems

To avoid problems with the monitoring, the following points should be checked:

- Ensure all health & safety measures have been taken prior to a power quality assessment
- Ensure analysis software can perform the tasks required
- Ensure the detection response of the instrument is adequate.

5.7 TRAINING REQUIREMENTS

Electrical engineering or technician qualifications and experience along with health and safety training are required to be able to perform power quality assessments safely and effectively. A one-day basic introduction to power quality can be achieved, but this should be supplemented with practical electrical test and inspection training.

5.8 REGULATIONS AND STANDARDS

Safety is paramount when conducting power quality surveys, so compliance with certain regulations is obligatory. Power quality surveys must comply with:

1. *The Health and Safety at Work etc. Act 1974.*
2. *Electricity at Work Regulations, HSE*, in particular Reg.14, concerning working with live conductors.

Risk assessments must be undertaken before each activity.

Standards relating to power quality problems are.

1. EN 50160 or BS EN 50160 *Voltage characteristics of electricity supplied by public distribution systems*. Refers to the point of common coupling. Also used to set limits between which equipment will operate.
2. G5/4 *Limits for harmonics in the UK electricity supply system*.
3. IEEE standard 519-1992, *Recommended practices and requirements for harmonic control in electrical power systems*.
4. BSI BS 7821 Part 4 1995, *Determination of the power rating of a transformer loaded with non-sinusoidal currents*.
5. BSI BS 7671:1992, *Requirements for electrical installations*

6. IEEE standard 142-1982. *Recommended practice for grounding of industrial and commercial power systems.*
7. EN (IEC) 61000-1-1, Electromagnetic compatibility (EMC) – Part 1: General Section 1: *Application and interpretation of fundamental definitions and terms.*
8. Other IEC 61000 standards such as:
9. IEC 61000-4-7 & IEC 61000-3-2 & IEC 61000-3-4 & IEC 61000-3-3 & IEC 61000-2-2.

5.9 USEFUL PUBLICATIONS

Guidance for power quality assessment can be found in a number of publications. These include:

1. Pearson C, Uthayanan V. *The BSRIA power quality guide.* Application Guide AG 2/2000. BSRIA 2000, ISBN 0 86022 539 9.
2. Waller M. *Harmonics: A field handbook for the professional and novice.* ISBN 0 7906 1048 5.
3. Dranetz. *The Dranetz field handbook for power quality analysis.*

5.10 Power quality example

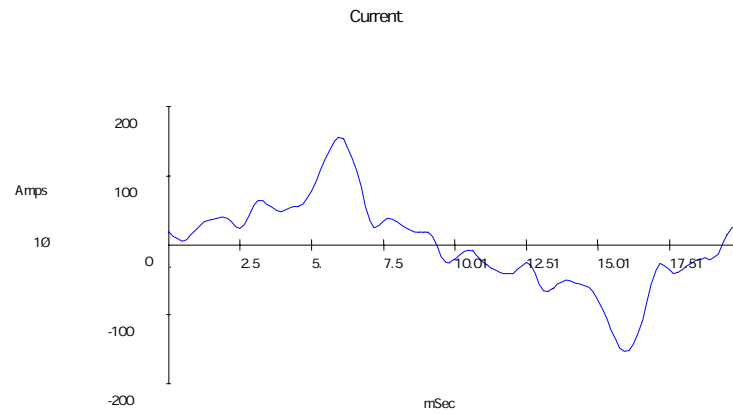
Examples of power quality problems from the BSRIA *Power quality guide* AG2/2000 included severe voltage distortion of up to 13%, high neutral currents often made up of mainly third harmonic, high neutral - earth voltage of nearly 7 V in one case and high earth currents of up to 48 A in one building.

One large office building had 3000 computers, 2 large uninterruptible power supply >675 kVA and high frequency lighting. It was built in the 1970s with half size neutral busbars. Much of the harmonic load was from the lighting; 28 A of harmonic current (as shown in Figure 13 and Table 8) for one floor and the large number of computers also generated significant levels of third harmonic. As with many buildings it was not possible to measure the harmonic current on the main low voltage feeder because it was not safely accessible. However, adding the harmonic current from all the non-linear loads gave a total of over 1000 A of harmonic current for the whole installation.

As much of the harmonic current was third harmonic from single-phase loads, the neutral feeders to the split-phase distribution boards were very highly loaded. With a balanced load, the neutral busbar would be carrying most of this harmonic current - which meant it was very near to its capacity. Any imbalance in the three phases might increase this over the limit. High levels of voltage distortion were measured, 10% in the plant room and 6.7% in the office. A decision was taken to urgently upgrade the neutral capacity by using the earth busbar in the same enclosure as well as installing an additional earth busbar and harmonic filter.

Figure 13

Current waveform drawn by high frequency fluorescent lighting on one floor of an office building

**Table 8**

Example summary - high frequency lighting load harmonic

	Voltage V	Current A
RMS	245.1	65.39
Peak	336.5	158.08
DC Offset	-0.4	-0.35
Crest	1.37	2.42
THD% Rms	5.98	43.54
THD% Fund	5.99	48.37
HRMS	14.7	28.42
Kfactor		8.77

6 WEAR & OIL ANALYSIS

Conventional oil maintenance regimes require oil changes based on a calendar or hours-run schedule. This can often lead to unnecessary oil changes. Conversely, it can also result in overdue oil changes and associated problems, such as a change in viscosity and a build-up of contaminants that result in inefficient performance of the oil. The benefits of using CBM techniques on oil can result in the avoidance of damage as the lubricant exceeds its ability to perform its task. It can also cost money.

Lubricants within machinery can indicate a great deal about the condition of different components within a plant item. By taking regular oil samples and submitting them to a number of pre-arranged tests the health of not just the oil, but also the components within can be established. Many tests are very simple, such as change in colour or smell that can indicate a potential problem. These can be performed on site with no testing equipment. However, the potential source may be more difficult to determine.

The analysis of oil samples can range from a simple and inexpensive visual indicator such as colour, or an expensive laboratory set-up, which uses spectrometry. The most appropriate type will depend greatly on a company's requirements.

Most analysis of the oil samples uses simple on-site testing, alongside a laboratory providing specialist analysis procedures. However, it is possible to carry out complex analysis on site requiring an extensive capital outlay for analytical equipment.

6.1 DETECTABLE/ PREVENTABLE FAULTS

Wear and oil analysis can provide information both on the condition of the oil and the condition of the equipment. Table 9 shows typical building services plant and the potential faults that oil and wear analysis can detect.

Table 9

Detectable/preventable wear & oil faults

Plant item	Fault source
Compressors (air conditioning)	Bearing degradation/lubricant degradation/glycol concentration/leakage of refrigeration fluid/additive depletion contamination
Refrigeration units	
Pumps & fans	Bearings & lubricant degradation
Transformers	Leakage of fluid/contamination
Standby generators	Bearing degradation/lubricant degradation/contamination

6.2 INSTRUMENTATION COSTS

To gain the most useful information from wear and oil analysis (W&OA) the correct tests are required. Table 10 shows the typical capital costs of a selection of sampling instrumentation. Table 11 shows typical tests that can be performed either with on-site test facilities or through an external laboratory, while Table 12 shows sample costs for these tests. A brief outline of the implications of implementing the different W&OA techniques is also given below.

Table 10

Wear & oil instrumentation and sampling tests

Simple test instruments	Price
Colour test	£10-£25
Chromatography	£24-£35 per sheet
Test and analytical kits	£250-£4000
Sampling & analysis instruments	Price
Ferrous wear debris monitor	£2000-£10,000
Soot analyser	£8,000-£10,000
Ruler - total acid number, total base number, contaminant analyser	£12,000- £15,000

Table 11

Wear & oil laboratory based tests

Laboratory based tests	Description
Viscosity	This is a measure of the resistance of a fluid to flow.
Water content	Typical water content in sample.
Total acid number	This is a measure of the amount of weak and strong acidity in the oil.
Total base number	This is a measure of the alkalinity of the oil.
Spectrometric analysis	This is used for trending the concentrations of wear metals.
Analytical ferrography	This identifies the composition of material present in a sample.
Oxidation	This determines the oxidation of the sample.
Particle count	This is the concentration of particles in a sample.

Table 12

Wear & oil sample cost of laboratory based test

Laboratory based tests	Cost
Viscosity/total acid number & total base number/power quality index/water content	£12-£15 per sample
Particle counts	£25-£35 per sample
Spectrographic analysis	£12-£20 per sample
Wear debris analysis by ferrography	£50-£70 per sample

Basic on-site testing comprises chromatography and colour tests, combined with taking an oil sample and sending it to a laboratory for analysis. However, companies with large amounts of plant or those responsible for large numbers of buildings may justify the cost of purchasing their own oil analysis equipment.

There are many different sampling methods available, ranging from tests that can be carried out by on-site staff with little training to those requiring expensive equipment to be used on site.

One of the simplest tests involves examining the colour or smell change within the oil sample. A change in colour or smell can indicate a change in the condition under which the oil is operating. Another simple test involves the evaluation of the oil sample by a form of chromatography. This involves spotting a sample of oil onto a chromatography substrate, resulting in bands or zones appearing on the plate. A change in the colour of the bands indicates a change in the oil condition such as oxidation. These types of test are simple and relatively inexpensive, but do lack sophistication in identifying the actual problem within a particular piece of machinery. Rather they identify that there is potentially a problem.

The more sophisticated methods in the on-site category not requiring expensive laboratory equipment are test kits that allow on-site analysis of oil samples. These test kits can range from single parameter kits such as acid indicator test kits, which give a simple pass or fail result, to kits that can analyse a multitude of parameters, including viscosity, water content, alkalinity/acidity, contaminants, ferrous and non-ferrous wear debris.

These kits may also provide trending capabilities.

Other on-site tests involve the purchase of analytical laboratory equipment that will analyse different characteristics of the oil, and pinpoint different faults.

6.2.1 Advantages and disadvantages of wear and oil analysis techniques

Testing technique	Advantages	Disadvantages
Simple on-site	Simple, low cost, gives a good indication of impending fault.	Cannot always determine the source of fault.
Complex on-site	Large sampling capacity	Expensive to set up a comprehensive laboratory, not practical for most small or medium companies
Laboratory based	Can determine the exact source of fault is a cost effective method of obtaining a sophisticated analysis.	Sample turnaround is reliant on laboratory efficiency.

6.3 INSTRUMENTATION SELECTION

The choice of whether to set up an in-house laboratory or to use the facilities offered by a commercial laboratory depends on the amount of sampling and analysis being done. Most small to medium building services applications will not need the capacity of laboratory equipment on site. Instead, they will use cost-effective indicative tests such as colour/smell and chromatography and will use commercial labs for trending the cause of the fault.

6.3.1 Sampling procedures

Taking a sample of oil is not a difficult operation; simple off-line sampling needs very little equipment. A typical sampling kit would consist of the following:

- A sample pump/suction device
- Bottles
- Tubing
- Labels
- Records.

When a sample has been taken, a few key identification parameters are needed for trending purposes and for sending the sample for analysis. These parameters are as follows:

- Machine or system identification
- Type of oil/fluid
- Hours since last oil change
- Hours since last filter change
- Sampling date

There could be specific data needed by an analysis laboratory.

Once the sample has been gathered, simple on-site tests can be performed to indicate whether there is a potential problem. Only if a fault is not identifiable from the simple testing methods should a sample be sent to a laboratory.

A laboratory's expertise can be very useful for a number of reasons:

- It can advise on sampling techniques
- It should have good analytical expertise
- It can provide detailed assessments of sample oils, and give a direct reason for the course of contamination.

6.4 BENEFITS AND PROBLEMS

6.4.1 Potential benefits

Oil and wear analysis can contribute to the successful operation of plant items by identifying the degradation and failure of components within machinery.

Benefits can include:

- A longer working life of an oil
- Indication when to change oil
- Identification of contamination within the oil

- Identification of any degradation of many components, such as bearings
- Where a working fluid is required for successful operation, analysis can assess the condition of new oil prior to acceptance and installation into the machinery
- Analysis can also evaluate the effect of maintenance tasks performed on plant items.

6.4.2 Potential problems

Although oil analysis used as a CBM tool can provide insights into potential faults, using incorrect procedures can result in inaccuracies.

The following should be borne in mind:

- Avoidance of cross-contamination is critical for meaningful interpretation
- Sample oil at same location, as variations in oil can be seen at different locations within the reservoir
- Sample while machine is operating, or if not possible as soon after shutdown as possible, to avoid separation of particles
- Avoid sampling from drain plugs, as this results in non-representative samples
- Use sample equipment that has been certified to meet specific cleanliness levels
- Be consistent in labelling and sample techniques
- Selection of the most suitable oil analysis laboratory is an important factor; make sure of the quality assurance, testing capabilities, customer service and turn around time. Look for an in-house quality assurance program with an ISO certification.

6.5 REGULATION AND STANDARDS

There are not many standards and regulations regarding oil analysis of building services plant but the following may assist:

1. BS 2000-168: 1995, Methods of test for petroleum and its products. *Determination of rolling bearing performance of lubricating grease.*
2. BS 2000-281:1993, *Determination of anti-wear properties of hydraulic fluids.*
3. BS 2000-48:1997, *Determination of oxidation characteristics of lubricating oils.*
4. BS 2000-182, *Determination of inorganic acidity of petroleum products. Colour indicator titration method.*

6.6 USEFUL PUBLICATIONS

The majority of analytical laboratories involved in this type of analysis will provide guides on how to make the most of their services. There are a number of publications that can aid in setting up a wear & oil analysis maintenance regime including:

1. ROYLANCE B, *Machine & systems condition monitoring series. Wear debris analysis.* Coxmoor 1999. ISBN 1 90189 202 6.
2. *Machine & systems condition monitoring series. Oil analysis.* Coxmoor 2001

7 THERMOGRAPHY

Thermography is an informative CBM tool for assessing the condition of many different types of building services plant. The deviation in temperature at which particular pieces of plant operate is often indicative of plant condition.

Although infrared cameras have adopted much of the technology of camcorders, the equipment is still costly because of the sophisticated materials required and the relatively small numbers in which they are produced.

7.1 DETECTABLE/ PREVENTABLE FAULTS

Table 13 outlines the potential components and faults that are detectable using thermography CBM

Table 13
Detectable/preventable
thermography faults

Plant item	Fault type	Instrument advice
Electrical	Poor connections/faulty switchgear/undersized conductors/excess loads/disconnected phases/contactors & relay faults/induced currents/harmonic currents.	Single point and thermal camera
Motors	Bearing degradation/windings overheating	Single point and thermal camera
Drives	Belt tension/misalignment/imbalance	Single point and thermal camera
Pipework	Scaling/fouling of heat exchangers. Sludge build-up/defective valves	Thermal camera only due to large survey areas. Single point for valves.
Chilled ceilings Underfloor heating/cooling	Blockage Poor heat transfer	Thermal camera only due to large survey areas.
Building fabric	Faulty insulation/poor air tightness	Thermal camera only due to large survey areas.
Boilers	Blockage/scaling/poor circulation	Thermal camera only due to large survey areas.

7.2 INSTRUMENTATION COSTS

Table 14 shows typical capital and hire costs. A brief explanatory note regarding the diversity of instrumentation is also shown below.

Table 14
Thermography
instrumentation

Measurement instrumentation (purchase)	Price range		
Non-contact temperature sensor	<£100		
Single point	£200-£1000		
Thermal imaging camera	£10000 to £40000		
Measurement instrumentation (hire)	1 Day	3 Days	1 Week
Thermal camera	£250	£650	£995
Thermographer + camera (survey)	£500- £1000	£1300- £2500	

Thermography is strictly the production of images from heat, but other methods also use heat via infrared radiation to produce an indication of an object's temperature.

Equipment used in condition monitoring comes in three distinct types, non-contact temperature sensors, simple hand-held devices that provide a single point of measurement and thermal cameras that provide a thermal image.

Single point devices provide a single temperature reading of the area being monitored, whereas the thermal camera constructs a thermal image of the field of view. The two distinct groups offer varying degrees of accuracy, and benefits to the field of CBM.

The single point device offers simplicity and ease of use at an affordable price but lacks the accuracy needed for extensive or complex situations. The thermal camera is a highly accurate and efficient device but comes at a considerable cost.

Thermal imaging cameras vary in their detection capabilities, the prime factor being their ability to detect temperature gradients. Cameras with a high sensitivity range of 0.1 K will be more accurate and expensive than those with 1 K sensitivity ranges. Resolution is also a key consideration; the lowest-cost cameras produce an image from an array of about 100 x 100 points or pixels. This can mean that the temperature of small objects is misrepresented if the surrounding area is a different temperature. Suppose a hot spot at 100°C was 5mm square in an area at 20°C when the camera was producing an image of an area 1000 x 1000 mm. The average temperature of the pixel containing this hot spot would be 40°C, which may not be critical. The more expensive cameras have a resolution of about 320 x 240 pixels. The more expensive thermal cameras also incorporate data storage facilities.

7.2.1 Advantages and disadvantages of thermography instrumentation

Instrumentation	Advantages	Disadvantages
Single Point	Low cost, simple to operate, ideal for low critical installations, lightweight and portable.	Fixed emissivity, limited diagnostic capabilities, time consuming for complex electrical panels, trending difficult, small or no data storage facilities.
Thermal Camera	Improved detection, reduced survey time, detailed quick analysis, trending can be done, high accuracy, graphic output.	High capital cost, training may be required.

This section aims to address some of the principal points for the successful implementation of thermography as a condition based maintenance tool.

7.3 INSTRUMENTATION SELECTION

Instrument selection must be appropriate to the information required. Specification of instrumentation must be checked before selection.

- Thermal resolution (typically ± 0.1 K)
- Accuracy (typically quoted as ± 2 K although nominally ± 1 K for thermal imaging camera, and single point instrument).
- Spatial resolution (typically 100 elements per line @ 50% SRF (spatial resolution factor) with 100 lines suitable for manual scanning)
- Video output
- Recording medium and format (should be suitable for further analysis, e.g. emissivity adjustment)
- Sun filters or long wavelength camera to reduce the effect of solar radiation when working outside.

7.4 POTENTIAL MODIFICATION REQUIRED FOR THERMAL IMAGING

Thermal imaging surveys of electrical panels require that the panel is suitable for thermal imaging, which would cost approximately 10-15% more than conventional panels. Panels can be modified to make them more suitable for thermography, but the cost will be variable. Information regarding the modification of electrical panels for effective thermal imaging can be obtained from *Guidance to the standard specification for thermal imaging of LV electrical installations*. FMS 5/99.

7.5 KEY CONSIDERATION FACTORS

There are a number of key factors, which need to be borne in mind before commencing a thermography survey, especially when dealing with electrical systems. These include:

- Always perform a risk assessment when working with electrical equipment
- Always adhere to health and safety regulations
- Training is required to make the potential thermographer proficient. Training courses in thermal imaging cost approximately £1000 for a 3-4 day course.

7.6 BENEFITS AND PROBLEMS

7.6.1 Potential benefits

The main benefits potentially achievable are as follows:

- The thermal camera has a wide diversity of applications, ranging from variations in temperature of pump bearings, electrical panels through to chilled ceilings and the heat loss from the building fabric
- Potentially reducing frequency of machine failure, thus reducing the repair budget
- Potentially increased reliability of all systems providing monitored results are used effectively

- Increased safety of employees working with electrical equipment, as remote monitoring techniques can be used
- Using a portable single point instrument and thermal imaging cameras does not necessarily reduce the maintenance hours required, the benefits come as the survey can be carried out when the system is live rather than requiring down-time as with conventional maintenance regimes.

7.6.2 Potential problems

There are a number of key areas to be considered if a thermography survey is to be effective. These relate to ensuring that preparation of the equipment under investigation has been performed including:

- Compliance with all electrical safety regulations
- Reflections – low emissivity materials will reflect a high proportion of radiant energy. Lights and the sun can cause difficulty in interpretation and achieving accurate determination of temperatures
- The same plant at different buildings may be at different temperatures. In addition, plant of different ages may also have different operating temperatures
- The operator of the single point instrument will have to be confident in the thermal survey's ability to replace intrusive maintenance, as trending is difficult
- Single point instruments may miss the hot spots that develop, and do not allow a visible representation of the variations in temperature of a whole component. Even without trending, the single point measurement would be a useful addition to the normal maintenance regime

If some kind of marker, such as a sticky label, is placed on the equipment (but not while live), it is possible to ensure measurements are made at the same point in each survey and a trend can be produced.

7.7 TRAINING REQUIREMENTS

Training is essential in thermography theory and practical applications. A course of between 3-4 days is usually sufficient. As there are potentially situations when working with live electrical panels is required, training and understanding of the health and safety and electrical regulations is mandatory.

7.8 REGULATIONS AND STANDARDS

Due to thermal imaging often requiring electrical installations to be operational, there are times when certain legislation must be complied with.

The *Health & Safety at Work etc. Act 1974* (HMSO. ISBN 0 10 543774 3) is the primary legislation, but there are number of other Acts and Regulations that need to be assessed for safe thermography.

1. Heath & Safety Executive. Memorandum of guidance on *The Electricity at Work Regulations*. HSE Books 1989. ISBN 0 7176 1602 9.

2. Management of Health & Safety at Work, *Management of Health & Safety at Work Regulations*. Health & Safety Commission 1992. HSE Books. ISBN 0 7176 0412 8. (Approved Code of Practice)
3. *Safe Use of Work Equipment - Provision and Use of Work Equipment Regulations 1998*. HSE Books. ISBN 0 7176 1626 6. (Approved Code of Practice & Guidance)
4. *Construction (Design and Management) Regulations*. The Stationery Office 1994. ISBN 0 110 438 45 0.

There are also a number of standards and recommendations for particular plant items or areas of work, such as below:

1. **BS EN 13187**. *Thermal Performance of Buildings – Qualitative Detection of Irregularities in Building Envelopes Infrared Method*.
2. **BSI 7671**. *IEE wiring requirements. Requirements for Electrical Installations*. 16th ed 1993. ISBN 0 85296 927 9.

7.9 USEFUL PUBLICATIONS

There are a number of publications which can aid in setting up and running a thermography maintenance strategy. The following is a sample of publications.

1. Pearson C. *Safe Thermal Imaging of Electrical Panels ($\leq 100\text{V a.c.}$)*. Application Guide AG 17/97. BSRIA 1997. ISBN 086022 470 8.
2. BSRIA, *Infrared condition based maintenance for building services*. Technical Note 2/95. BSRIA 1995. ISBN 0 86022 397 3.
3. Barnard N, Pearson C C. *Guidance to the standard specification for thermal imaging of non-electrical building services installations*. FMS 6/2000. BSRIA 2000. ISBN 0 86022 540 2.
4. Barnard N, Pearson C C. *Guidance to the standard specification for thermal imaging of LV electrical installations*. FMS 5/99. BSRIA 1999. ISBN 0 86022 526 X.
5. Thomas R A. *Machine & systems condition monitoring series. The thermography monitoring handbook*. Coxmoor. 1999. ISBN 1 90189 201 8.

7.10 THERMOGRAPHY EXAMPLE

Figure 14 shows a sample thermal image of a motor in operation, showing how the image can aid in evaluating the condition of internal components.

Figure 14

A thermal image of a motor

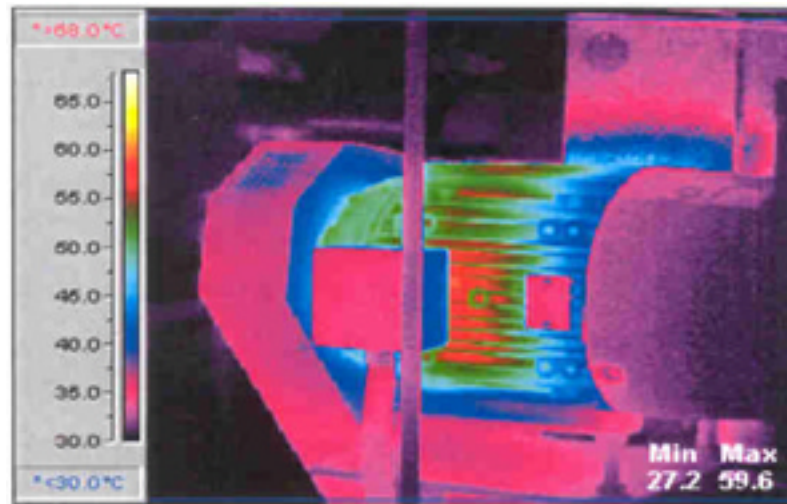
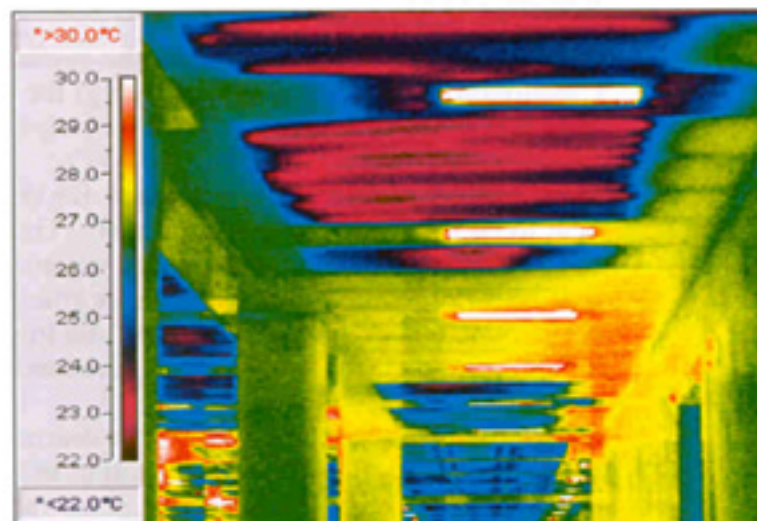


Figure 15 shows a sample thermal image of a chilled ceiling. The image shows the flow dynamics of the refrigerant fluid, thus demonstrating simple interruption of operating performance.

Figure 15

A thermal image of a chilled ceiling



8 BUILDING MANAGEMENT SYSTEMS

Building management systems (BMS) are a useful CBM tool. Many parameters are monitored in order to control the various building services applications. This data can also be used for condition-based maintenance at little extra cost. There may be the need for extra sensors for specific CBM for a small investment. BMS can also provide the facilities for the integration of other CBM techniques such as vibration and acoustic emission sensors, allowing various CBM methods to be monitored and evaluated in one system. While BMS monitoring is frequently carried out, it is rarely done as part of a CBM regime

8.1 DETECTABLE/ PREVENTABLE FAULTS

Table 15 shows building services plant that can potentially be monitored by a BMS.

Table 15 Potential BMS monitoring

Plant item	Source of fault	Monitoring technique
Pipelines	Leakage Waterside fouling	Level/flow detector/moisture detector/gas detector/metering/pressure Velocity/differential pressure
Pumps	Bearings/lubrication Belt Misalignment/imbalance Scaling	Speed/temperature Differential pressure/velocity/motor current Speed Flow/differential pressure/temperature
Fans	Bearings/lubrication Belt Misalignment/imbalance Air-side fouling	Speed/temperature Differential pressure/flow/motor current monitoring Speed Differential pressure/flow/motor current monitoring/speed
Air filtration	Air-side fouling	Differential pressure/flow/motor current monitoring/speed
Heating/cooling coils	Air-side fouling Condensate system Leakage Scaling Waterside fouling	Temperature/differential pressure/flow Level/moisture detector Level/moisture detection/flow detection/metering Temperature/differential pressure Temperature/pressure
Humidifiers	Scaling Heating element Integral controls Drainage system Waterside fouling	Temperature/humidity/flow Temperature/humidity/flow/electric current Temperature/humidity/flow Level Temperature/humidity/flow
Motor Drives - Electric	Bearings/lubrication Burnout/thermal trip Misalignment/imbalance Windings/castings	Speed/temperature Temperature/electric current/speed Speed Electrical current
Centrifugal Chillers	Compressor motor Air purge device Condenser waterside fouling Expansion device Integral controls Misalignment/imbalance Condenser waterside scaling Refrigerant leakage	see Motor Drives - Electric Temperature/pressure Differential pressure/temperature/pressure Pressure Temperature/pressure Speed Temperature/pressure Level/pressure/gas detector
Reciprocating Chillers	Valves Compressor motor Condenser fan motor Expansion device Integral controls Refrigerant leakage Condenser air-side fouling Evaporator waterside fouling Evaporator waterside scaling	Pressure/ultrasonics see Motor Drives - Electric see Motor Drives - Electric Pressure Temperature/pressure Level/pressure/gas detector Pressure/temperature Temperature/pressure/differential pressure Temperature/pressure

Plant item	Source of fault	Monitoring technique
Screw chillers	Compressor motor Integral controls Compressor seals Expansion device Refrigerant leakage Condenser waterside fouling Evaporator waterside fouling	see Motor Drives - Electric Temperature/pressure Temperature/pressure Pressure Level/pressure/gas detector Differential pressure/temperature/pressure Differential pressure/temperature
Absorption chillers	Integral controls Pump Pump motor Heat source Solution crystallising Condenser waterside fouling Refrigerant leakage Evaporator waterside fouling	Temperature/pressure see Pumps see Motor Drives - Electric Temperature Temperature Differential pressure/temperature Level/pressure Differential pressure/temperature
Cooling towers	Waterside microbiological growth Fan motor Waterside fouling Air-side fouling	PH/TDS/turbidity/biocide level/consumption/discharge/microbiological activity/temperature/Flow see Fans Temperature/flow/differential pressure Temperature/pressure
Evaporative condensers	Waterside microbiological growth Fan motor Air-side microbiological growth Fan Waterside fouling Air-side fouling Refrigerant leakage	see Cooling towers see Motor Drives - Electric see Cooling towers see Fans see Cooling towers see Cooling towers Level/pressure
Air-blast coolers	Fan motor Fan Heating/cooling coils Integral controls Fouling	see Motor Drives - Electric see Fans see Heating/cooling coils Temperature Temperature
Heat exchangers	Scaling Waterside fouling	Temperature/pressure Temperature/differential pressure
Gas/oil fired boilers	Burner Draft fan Fan motor Flue Scaling Waterside fouling	Pressure/temperature/oxygen/carbon dioxide/smoke see Fans see Motor Drives - Electric Differential pressure/temperature/oxygen/carbon dioxide/smoke Temperature/differential pressure/flow Temperature/differential pressure/flow
Electrical distribution	Overload equipment failure Excessive demand	Current voltage Power factor/current

There are certain factors to consider when installing sensors, whether they are temperature, pressure or flow. Table 16 summarises some of the requirements for sensor installation. (Ref *Control Sensor Installation*. Building Controls Group.1995 (available from BSRIA))

Table 16 Sensor application considerations

Type of sensor	Considerations
Immersion sensors for water - general	Ensure that the full active length of the sensor/sensor pockets is immersed in the water
Immersion sensors for chilled water and refrigeration pipes	- Install sensor/sensor pockets against the direction of flow - Install at the correct angle - The sensor should be installed diagonally in a bypass pipe or in a bend if the active length of the sensor probe is longer than the diameter of the pipe - A binder test point or an additional immersion pocket, adjacent to the sensor, should be provided for test purposes - An adequate distance (10 x pipe Ø) between the mixing point and the sensor should be provided when mixing water at different temperatures to take account of stratification
Surface temperature sensor - water/refrigerant	Ensure a smooth clean surface and fill the space between the sensor and the pipe with a heat conductive compound to improve thermal conductivity
Pressure - general	- Pressure sensors may be affected by orientation - The pressure tubes must be provided with a binder point near the device head for test purposes - The connection must be fitted with a bypass and stop valve to avoid overload on one side when manipulating the sensors. Isolating valves should also be fitted - The sensor should be installed on a vibration-free surface or vibration-proof base - The pressure-tapping point must not be located in turbulent airflow. Provide 6 x Ø/Dg upstream and 6 x Ø/Dg downstream of straight duct without obstructions
Pressure - air	- Probes for measuring static pressure should be installed parallel to the flow - The differential pressure measuring tube should be correctly sized - The tapping point should not be located where it will be affected by obstructions to the flow

8.2 THE ROLE OF BUILDING MANAGEMENT SYSTEMS IN CBM

BMS regularly monitor many of the parameters highlighted in Table 15 without them necessarily being used actively for condition monitoring. BMS can also incorporate many CBM methods such as vibration, acoustic and even remote thermography into their regular monitoring regimes.

Alarms can be set up to notify when thresholds are crossed such as reaching a critical vibration level on a pump, or an excessive rise in temperature.

BMS could be used more actively to assist in assessing the need for and scheduling of maintenance.

BMS offer much potential for CBM as many installations prefer to have fixed monitoring rather than periodic visits to measure vibration, acoustic emissions and thermal images. It is BSRIA's experience that this happening in some financial services sector buildings where plant failure potentially has a large impact.

8.3 BENEFITS AND PROBLEMS

8.3.1 Potential benefits

Some of the potential benefits to be gained from using the BMS for CBM include:

- Current BMS data can be collected for condition monitoring at little extra cost
- Automated analysis of monitored data is possible
- Easily managed record keeping of condition data, providing database for future maintenance requirement of individual plant items
- On-line CBM systems greatly reduce the maintenance hours required to perform periodic checks on plant condition.

8.3.2 Potential problems

Although using BMS as a means of CBM can be simple and very cost effective there are certain issues that need to be addressed if the data analysis is to be effective. These include:

- Ensure that the BMS does not get overloaded with data from monitoring and analysis
- Ensure that operational procedures for critical systems initiated by the BMS take priority over CBM monitoring if the BMS has limited capacity
- Incorporating on-line systems can entail a higher cost than for off-line instrumentation, due to the amount of cabling, sensors and instrumentation required for extensive sites.

8.4 BMS EXAMPLES

8.4.1 Filters

One of the most common applications of BMS CBM is the condition monitoring of air filters. The pressure differential is measured across the filter to give an indication of the filter's condition. Sensor purchase and installation costs for this purpose are approximately £80-£150 per filter bank. In one application this resulted in a reduction in inspection frequency, giving an estimated £350/annum saving together with an extension of the filter life, giving a further saving of £10 per filter. These savings are multiplied by the number of filters in the bank.

8.4.2 Cylinders/calorifiers

CBM aimed at detecting the scaling experienced by calorifiers has been performed by measuring the heat transfer effectiveness of the calorifiers during the early morning heat-up period. The heat transfer effectiveness was calculated from temperature measurement. Scaling causes a drop in its value.

The temperature sensors used were already installed for control purposes. The cost of implementing CBM in this instance was therefore very low. Operating cost increases were restricted to analysis of the data, which could be automated by the BMS. The potential benefits available include reduction in the inspection and cleaning expenditure. For two calorifiers monitored, the annual inspection and chemical cleaning cost was of the order of £1000. The monitoring indicated that cleaning was unnecessary, and this was verified when the calorifiers were inspected. Negligible scaling was seen.

8.4.3 Heat exchangers

CBM is applicable to large and/or critical heat exchangers which are exposed to a reasonably high rate of degradation of heat transfer effectiveness. Monitoring of heating or cooling coils in small air handling units which are protected by filters is unlikely to produce significant benefits.

The approach adopted is similar to that for monitoring calorifiers. Temperature measurements are used to calculate heat transfer effectiveness. Scaling and/or fouling cause it to drop.

An air blast cooler system was monitored. The temperature sensors were already installed for control purpose, and therefore set-up costs for CBM were minimal. Failure of the heat exchangers could occur if the heat transfer effectiveness dropped too low. The data collected for CBM purposes could be used to initiate an alarm to provide early warning before this occurs.

Operational costs were restricted to analysis of the data, much of which could be automated by the BMS. It was estimated that £4000 could be saved from the energy and cleaning costs for the system by optimising the cleaning frequency. This was out of a total cost of £50000 for all energy usage and maintenance tasks, equating to approximately 8%.

8.5 USEFUL PUBLICATIONS

There are a number of publications which will aid in understanding the potential of BMS for the application of CBM.

They include:

1. BSRIA. *Condition based maintenance for building services*. Technical Note TN 1/95. BSRIA 1995. ISBN 086022 396 5.
2. Barnard N. *BEMS as condition based maintenance tool*. Technical Note TN(s) 4/95. BSRIA 1995. ISBN 086022 399 X