Acoustic Emission as a Basis for the Condition Monitoring of Industrial Machinery

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1. INTRODUCTION

In the context of machine condition monitoring the AE technique provides a sensitive way of detecting energy loss processes (such as impacts and friction) which are associated with mechanical degradation. Whereas *machinery protection* devices detect these effects when they are macroscopic (eg by tripping on an increase of overall temperature or rms vibration level) the purpose of *condition monitoring* (CM) is to detect faults at a much earlier stage so that appropriate remedial action can be taken in good time so as to minimise the chances of an in-service failure or the occurrence of secondary damage. Leaving aside special cases such a *condition based maintenance* (CBM) approach generally represents the most cost effective maintenance strategy.

However, techniques suitable for CM must be sensitive enough to detect machine faults when they are at a very early stage. Ideally they should be applicable to a wide range of machine types, be easy and quick to use by available personnel and have a high success rate in detecting faults (without giving false alarms). No single CM technique meets all criteria in all applications and it is necessary to select a detection technology best suited to specific application types. It is in this context that the present paper puts forward AE as a CM technique having unique attributes which give direct practical benefits to the end user for monitoring rotating machinery.

2. THE AE APPROACH

Processes such as friction and impacts naturally give rise to broadband elastic wave activity (extending from DC to MHz frequencies) which propagates within most engineering structures. As a result there is much scope for variation in possible detection schemes. Audio frequency detection (as in the case of vibration monitoring) makes use of the high signal levels at low frequencies but is plagued by low signal to noise ratios which necessitate the use of complex signal enhancement techniques. Higher frequency detection requires more sensitive sensors (thereby explaining its later arrival on the CM scene) but has the distinct advantage on most rotating machinery of having a high signal to noise ratio.

This is simply illustrated in Figure 1 which shows the response of an accelerometer and an AE sensor (resonant around 100 kHz) to minor impacts of a small solder bead on a plate to which a running motor is attached. This clearly shows that the AE signal has a higher signal to noise ratio for the detection of minor impacts in a noisy background and the same applies in the case of a frictional source.

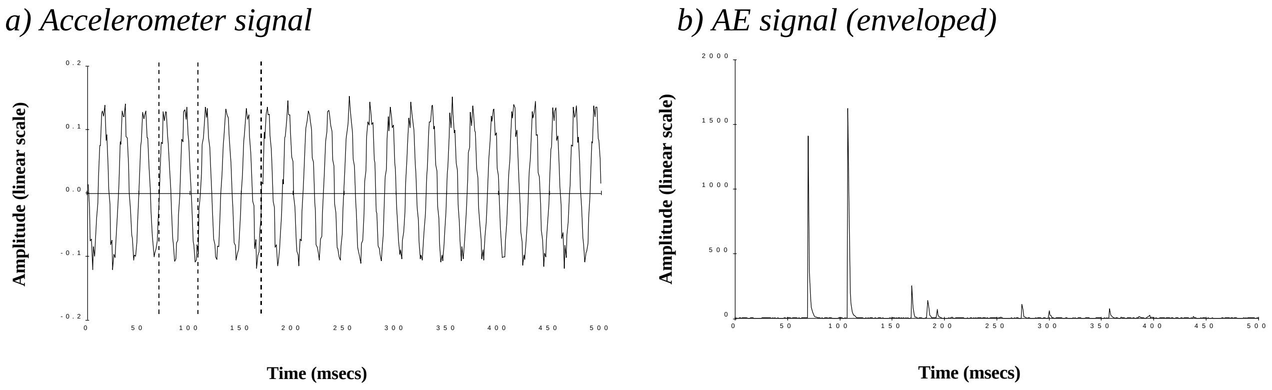


Fig 1 - Accelerometer and AE signals from impacts on a plate attached to a running motor.

In taking AE measurements the choice of detection frequency is relevant but not critical. If too low a detection frequency is chosen then background noise increases and resonances within the structure have an increasing effect on detected signal magnitudes. If however too high a detection frequency is chosen the lower source magnitudes and higher rate of attenuation may prevent detection of any signal at all. The output from the AE sensor can be processed in a number of ways and in this paper results will be presented which have been processed as (a) the signal envelope and (b) standard parameters.

3. LABORATORY STUDIES

Bearings were run in a test rig and the AE signals were processed in terms of their dynamic envelope (ie they were rectified and low pas filtered). Such signal processing retains much of the useful information contained in a narrow band signal and effects a dramatic reduction in the signal bandwidth making it much easier to digitise, further process and store (eg in a PC). The laboratory tests included seeded defects in various bearing types operating at different speeds and loads. In total AE envelope waveforms of 0.6 sec duration with 0.5 msec resolution were recorded for 1125 test conditions.

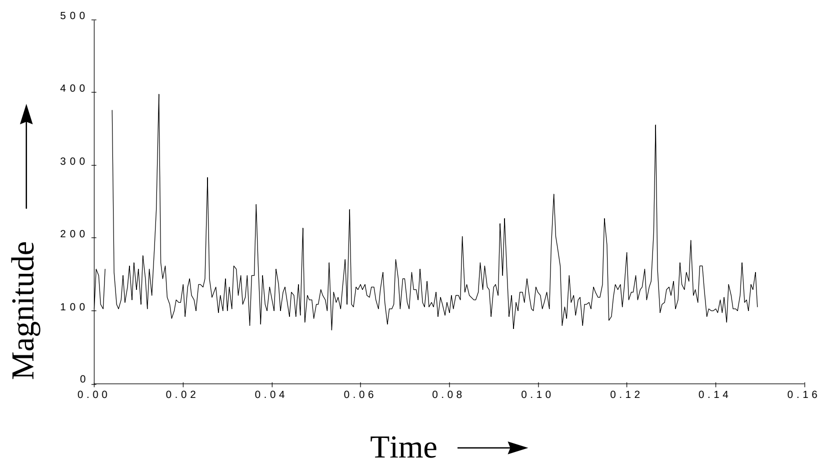


Fig 2 - AE signal with transients from impacts of roller on an inner race defect.

Singular defects in rolling element bearings give rise to isolated impacts as the defective surface comes into contact with another surface and each of these produces a single detectable AE pulse. This is illustrated in Figure 2 which shows a train of pulses separated by time intervals of 11 ms. This periodicity corresponds well with the calculated defect repetition frequency of 91 Hz for an inner race defect for this particular bearing test.

In addition to observing the time domain AE signal it is of course possible to view it in the frequency domain. Figure 3 (a) and (b) show waterfall plots of frequency spectra for a roller bearing with and without a roller defect at various rotational speeds. Comparison of Figure 3 (a) with Figure 3 (b) clearly demonstrates the absence of significant repetition frequencies for a bearing with no defect and the clarity with which a defect is detected. Analysis of the defect repetition frequency in Figure 3 (b) corresponds well with the calculated value for a roller defect in this bearing (indicated as BSF). Note also that the first harmonic is also clearly seen.

a) No defect *b) Roller defect*

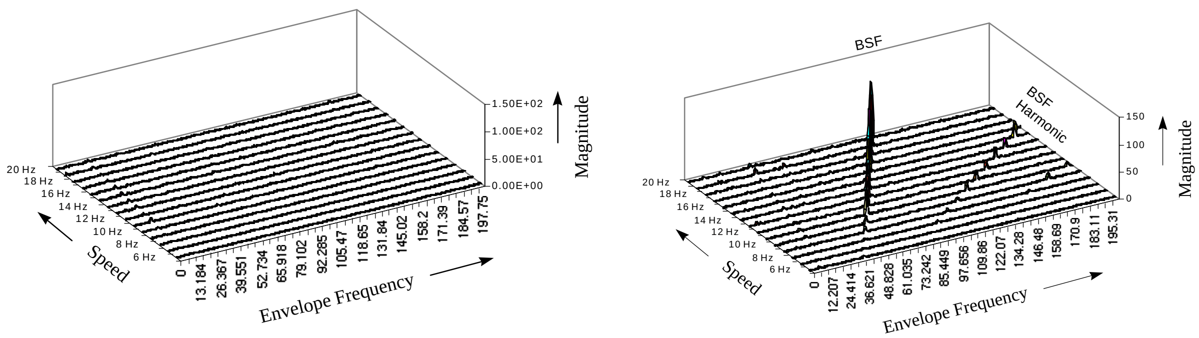


Fig 3 - Waterfall plots of AE envelope spectra for a roller bearing.

Clearly the knowledge and skill necessary to analyse such frequency spectra is similar to that for analysing vibration spectra. As an alternative to the extraction of such fine detail from the AE signal it is also possible to view the overall or mean AE signal level. To illustrate the speed and load dependency of the mean AE signal level Figures 4 (a) & (b) show carpet plots for a roller bearing with and without an inner race defect.

a) No defect *b) Inner race defect*

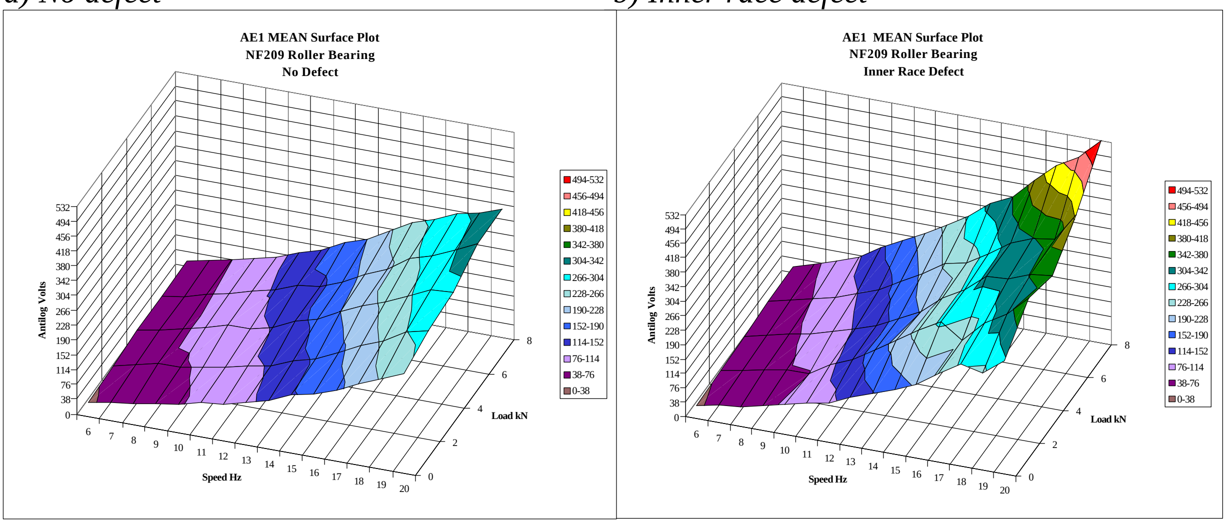


Fig 4 - Effect of speed and load on mean AE signal level from a roller bearing.

Figure 4 clearly shows that mean AE signal level is a well behaved parameter in that its value for any particular condition forms part of a fairly simple surface and the presence of a defect elevates that surface to higher values. It is also clear that mean signal level is insensitive to presence of the defect at low speed. It can further be inferred from Figure 2 that mean signal level will also be insensitive to the early stages of defect growth when impact pulses are of lower amplitude. On the other hand mean level is very responsive to continuous sources of activity such as rubbing. In practice mean signal level is most suited as a trending parameter where its current value can be compared with previous values taken under similar operational conditions.

However, to benefit most from the high sensitivity of AE to defects it is necessary to characterise the signal transients. The FFT approach is unnecessarily complicated for the simple task of detecting the presence of a fault and instead time domain signal analysis methods have been employed. A proprietary method of doing this produces a signal characterisation known as Distress®. In the industrial examples that follow the AE signal has been characterised as the standard parameters of Distress® and dB Level (which is a logarithmically scaled mean signal level).

4. INDUSTRIAL APPLICATION

Portable MHC (Machine Health Checker) instruments have been in use in UK industry since 1993. All variants of the instrument have identical calibration and require no operator set-up. The measurement procedure is simply to acoustically couple the AE sensor to the machine of interest (in the vicinity of its bearings) and switch on the instrument which will then directly display readings of dB Level and the proprietary parameter Distress®.

A useful feature of the Distress® parameter is that for most rotating machinery the action point is when it reaches a value of 10 or more. Because of this machines with problems can be quickly identified at an early stage. To illustrate its use Figure 5 shows the values of Distress® on four pump bearings taken at monthly intervals. Each month the values rise until the bearings are re-greased. In general the Distress® reading can be used to identify bearings in need of re-greasing at the time when they need it. Since bearings running with a low Distress® do not need re-greasing this can save on the cost of grease as well as minimising the likelihood of bearing and seal damage caused by over-greasing.

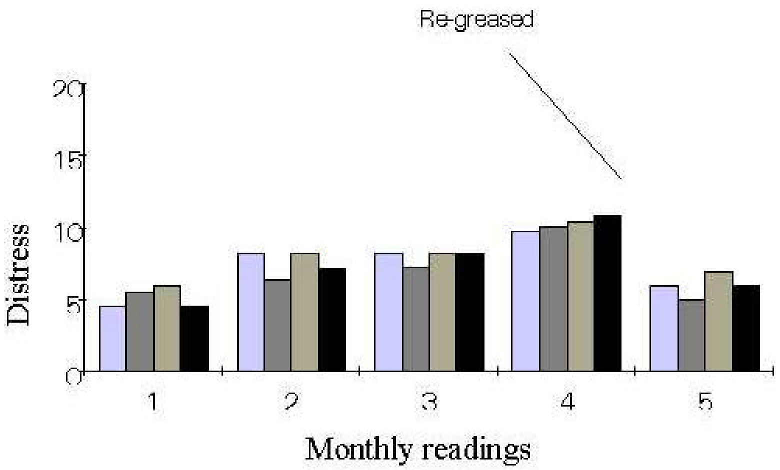


Fig 5 - Using AE measurements to identify when its time to re-grease pump bearings

It is usual for dB Level to increase as a machine deteriorates as multiple sources develop. This is illustrated in Figure 6 for the case of an Aerator gearbox used in the water treatment industry. Monthly measurements were made on a total of 80 Aerators which revealed an increasing value of dB Level on one of them giving a clear indication of impending failure. In month #5 the site engineer used his human senses to conclude that there was nothing wrong with the gearbox and chose to ignore the AE measurements. The gearbox was a total write off when it seized 2 weeks after the last measurement.

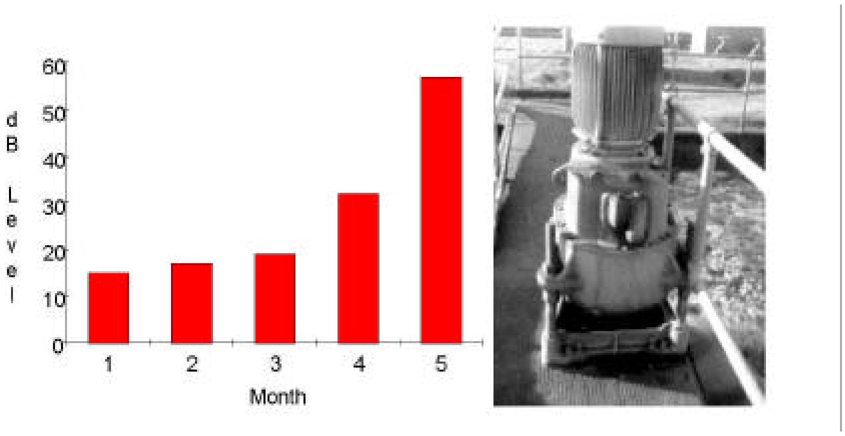


Fig 6 - Monthly AE readings taken on an Aerator gearbox

Since the interpretation of the Distress® reading is the same for different machinery and machinery rotating at different speeds it provides a very convenient way of assessing complete drive systems (motors, gearboxes and shaft support bearings). Simply by moving the position of the sensor it is possible to localise the fault position by directly comparing readings form different positions. This is illustrated for measurements taken on the drive systems of the 'Yankee' dryers of two paper-making machines in Figure 7.

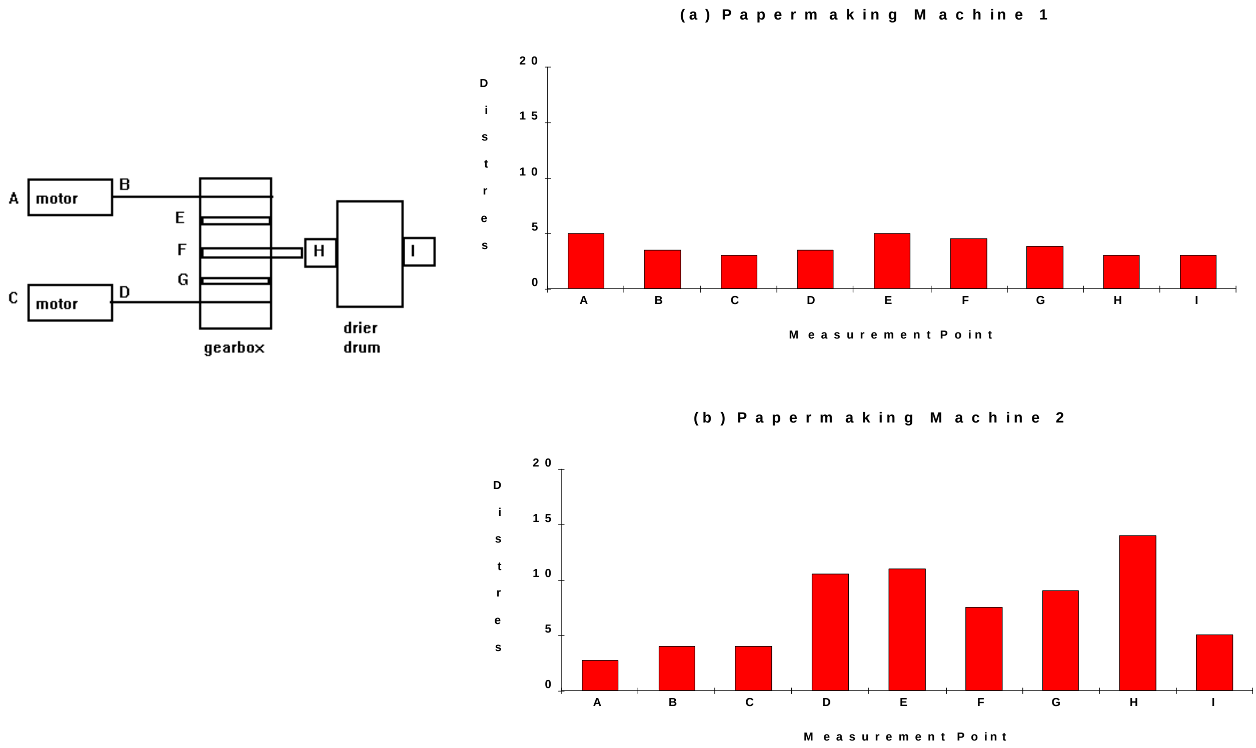
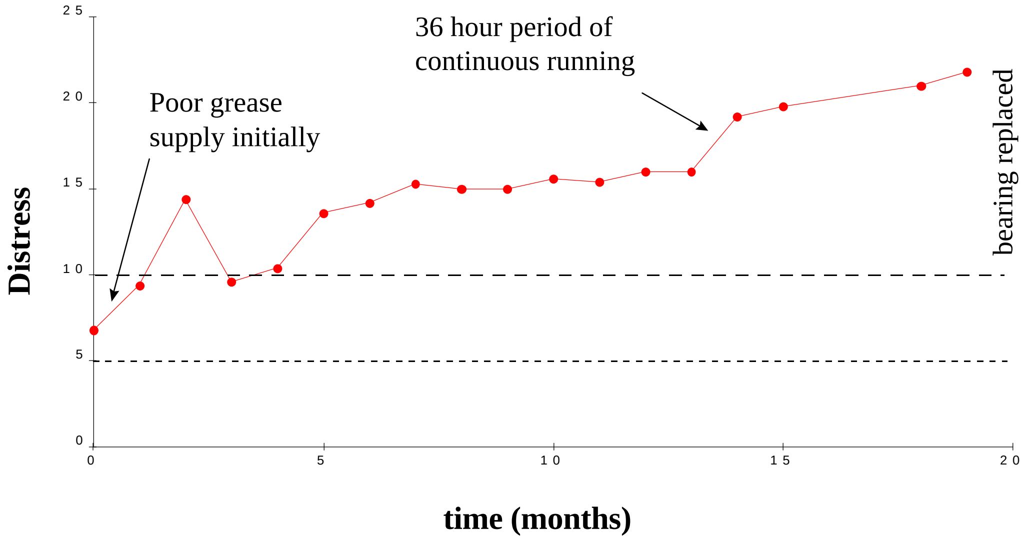


Fig 7 - Monthly readings of Distress® & dB Level on a centrifugal pump

The various measurement positions are indicated in the accompanying schematic diagram in Figure 7. Comparing Distress® readings on the two drives it is clear that PM1 (upper plot) is in good condition at all points since all values are less than 5 whereas PM2 has areas of concern (particularly positions D, E and H). Position D is the drive end of one of the motors and was solved by re-greasing. Position H is one of the critical 'MG' bearings supporting the 150 ton 'Yankee' dryer drum. This bearing was suffering from momentary oil starvation caused by bubbles flowing in its oil supply, leading to occasional metal to metal contact within the bearing (a fact unknown to the operators and undetectable with envelope FFT vibration). The problem was cured by doubling up the oil supply and the Distress® value reduced to 4 indicating no serious damage had occurred in this instance.

Experience has now been gained using similar AE measurements on literally tens of thousands of rotating machines including motors, pumps, gearboxes and shaft support bearings of all sizes. Not only has this shown that AE is readily applicable to most standard machinery (such as drive motors, fan support bearings, reduction gearboxes and centrifugal pumps) it has also highlighted its ability to monitor traditionally awkward machinery.

Such an example is a plain bearing, rotating at 45 rpm submerged in raw sewage. The bearing supports the lower end of a large Archimedes screw and has a greasing line fed to it operated by a greasing system. To take AE measurements on these bearings it was necessary to fit a permanently installed AE sensor directly onto the bearing housing. Experience has showed that they typically operate with a Distress® reading of around 6 or 7. However, one newly fitted bearing soon started to show an increase as can be seen from Figure 8. After two months it was realised that the grease line was not delivering grease to the bearings and modifications were made to rectify this which reduced the Distress® reading. Unfortunately the improvement was short lived and the value increased progressively over the next 18 months. Despite ample advanced warning this screw pump was eventually only stopped when the Distress® reading on the upper (wall-plate) bearing started to show a sudden increase. By this time the lower bearing was seriously damaged.



This AE record provides clear evidence that the premature failure of this bearing was not caused by a faulty bearing but by damage caused during the first 2 months of its operation as a result of a faulty greasing system. Finally it is worth noting that the AE measurements shown in Figure 8 are from an on-line AE system operating in an unsupervised way with access to the data being made via modem from a different part of the country. Such systems are ideal for monitoring remote and unmanned sites.

5 DISCUSSION

In this paper it has been shown that AE activity has understandable origins and that the amount of overall AE activity is not random but controlled by such factors as rotational speed, applied load and defect presence. It has also been shown that the envelope of narrow-band AE signals contain diagnostic information on the nature of the defect which is generating it. Finally some examples of its use in the industrial environment have also been presented and these are backed up by its application to tens of thousands of industrial machines in the UK over the last eight years.

Our experience is that bearing, gear and lubrication problems in most rotating machinery are readily detectable in the time domain AE signal. In most cases adjacent machinery and machine operations are not problematic and do not require special skills or signal enhancement techniques. In fact our experience has been gained with standardised instrumentation, sensitive at a fixed frequency and having no adjustments whatsoever.

We have overwhelmingly found that useful and timely information on machine condition can be directly gained without detailed knowledge of machine internal design, previous measurement history or application specific optimisation. This can be contrasted with Vibration monitoring where early detection requires the use of frequency domain analysis which requires great care over the setting up of the instrument (gains and filter settings, sampling rates, record lengths and precise information on the internal components operating within the machine as well as their rotational speeds). As a result AE measurements can provide a more objective measurement of machine condition.

This difference would be of little consequence if it was essential to know in advance of maintenance actions whether or not the fault with a bearing, say, was on the inner race, outer race, rolling element etc., since AE can only yield such information by a more detailed analysis of the signal (whether in the time or frequency domain). However, in most instances the maintenance function does not require such information. Hence AE has the practical benefit of enabling CM instruments to be quicker to use and simpler to interpret. As a result a single portable AE instrument can monitor large numbers of machines very quickly without the need for special skills in either taking the measurements or interpreting their meaning. With regards to on-line monitoring, experience is showing that the benefits of AE technology translate into easier to set up monitoring channels and fewer false alarms.

Nevertheless it must be recognised that certain specialists have amassed considerable knowledge and skill in conducting Vibration analysis and this can be called upon to diagnose the nature of faults where such information is required and appropriate specialists are on-hand. An emerging trend within industry is the use of AE instruments as the front-line tool to identify which of many machines have a problem so that appropriate attention, including Vibration based diagnostics, can be concentrated solely on those machines having problems. In this way the benefits of CM can be extended over a much greater percentage of machines with little increase in cost.

Machinery problems such as out of balance and misalignment these are known to be rich in low frequency signals at once per rev and its low harmonics and Vibration measurements must therefore be considered to be a more direct measure. AE measurements only detects these effects when they are of such a magnitude that they cause sufficiently high forces in the support bearings to break down the lubrication film and allow metal to metal contact.

6. CONCLUDING REMARKS

6.1 AE provides a sensitive yet simple means of detecting degradation in a wide range of rotating machinery.

6.2 Both lubrication and bearing/gear faults are readily detectable in the time domain AE signal.

6.3 Instruments with fixed settings and fixed interpretation are widely applicable in the industrial environment.

6.4 The technology can be readily applied as a front-line portable instrument for use by maintenance personnel or as an on-line machine surveillance system.

7. ACKNOWLEDGMENTS

The author would like to thank ISA Developments for permission to use AE data from their AIMS permanent monitoring systems. In addition the contribution of Clive Brashaw in devising and carrying out the laboratory bearing trials as well as the associated data analysis is gratefully acknowledged.

Note : 'Distress' is a Registered Trademark of Holroyd Instruments Ltd.