Presented at : BINDT organised CM2005 Conference, Cambridge, July 2005

THE APPLICATION OF AE IN CONDITION MONITORING

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ABSTRACT
The application of Acoustic Emission (AE) in a condition monitoring role is far from new. This paper provides an overview of the AE technique and gives an introduction to the background and issues involved in its application in the condition monitoring of both machinery and structures. Recent development in training and certification are also discussed. Finally an attempt is made to look into the future direction of AE technology.

KEYWORDS
Acoustic Emission (AE), Condition Monitoring, Machinery, Structures, Training, Certification.

BACKGROUND TO AE TECHNIQUES
Historical
Acoustic Emission (AE) as an instrumented technique is more than 50 years old (Ref. 1). In this early work the sounds associated with the failure of materials were detected. It was observed that when plastic deformation occurred in stressed material it generated detectable activity and that this activity was irreversible in the sense that it did not recur if the same stress was reapplied. Since that time this branch of AE application has been the subject of much research and development and today it offers a valuable testing technique for materials, components and structures with a deep body of knowledge and practical experience existing worldwide (see for example Ref. 2).

The acceptance of AE for the testing of materials was long and tortuous and it is a commonly expressed view that this resulted from it being oversold during the 1970's. A more generous and possibly more accurate interpretation is that its early exploitation was hindered by :

a) the inherent difference in the implementation philosophy of AE compared with all other NDT technologies (this still remains an obstacle to its use but has been overcome by a combination of specialist AE service companies and the inclusion of AE in the portfolio of some NDT service providers).

b) The complexities and cost of digital signal processing at that time (this has been greatly simplified and made more affordable with the advent of microprocessors, DSP's and the ubiquitous PC).

A major factor in the eventual acceptance of AE by the NDT community was its demonstrable success in monitoring composites (e.g. in the aerospace and chemical industries) at a time when other NDT techniques could not be so readily applied to them (e.g. Refs, 3 & 4).

When used for material or structural testing purposes AE monitoring provides a way of passively listening to naturally occurring high frequency elastic waves (often called stress waves) resulting from various defect growth mechanisms (e.g. plastic deformation and crack extension in metals and fibre breakage and delamination in composites). However it was soon discovered that AE sensors were responsive to many other microscopic energy loss processes and this has enabled AE monitoring to be also applied to a wide range of machinery and process applications. Application examples are too numerous to mention but include weld monitoring/control, powder flow monitoring, machine tool monitoring and leak monitoring. Also falling into this category is the use of AE for machinery condition monitoring and this area of application is fast approaching 40 years old (Ref 5).

Acceptance of the AE technique for machinery condition monitoring has also been long and tortuous, not only for reason (b) above but also because it was necessary to educate and convince a sceptical market in which vibration monitoring was already well established.

About AE signals

AE applications are concerned with the detection of naturally occurring elastic waves that are emitted by a wide range of processes. A common feature of the many processes that give rise to AE is that they involve transient changes (either in isolation or multiples) in the localised elastic energy stored in the immediate vicinity of the source. Broadband elastic waves are launched into the surrounding elastic material to communicate the altered stress conditions.

In general source amplitudes reduce as the detection frequency increases which would suggest that AE detection ought to be carried out at low frequencies. However from the early days of AE application it was soon realised that by restricting monitoring to the higher frequencies (i.e. at ultrasonic rather than audio frequencies) the signal to noise ratio could be markedly improved enabling lower levels of activity to be detected. This is because although the amplitude of AE signals reduces as the detection frequency increases, the detectable background noise levels usually reduce at a much faster rate.

Commonly used AE sensors counteract the reduction in AE signal amplitudes that high frequency detection entails by the use of resonant transducer designs. Peak sensor responses are usually designed to fall somewhere within the range of 50 kHz to 1 MHz and they are specifically designed not to be sensitive at low (audio) frequencies. The sensitivities that can be achieved (at the expense of bandwidth) enable surface displacements as low as 10^{-13} metres to be readily detectable. Although high fidelity broadband AE sensors are available (e.g. both point contact piezoceramic and laser interferometer designs), these are primarily used in research studies and seldom in industrial applications.

After amplification and filtering the resulting AE signals are oscillatory, high frequency and have a wide dynamic range. Furthermore, the activity they detect has a randomness that requires either averaging or statistical characterisation over a time period to be meaningful. To accommodate these characteristics AE signals are typically treated with specialised AE instrumentation.

CONDITION MONITORING

What do we mean by 'condition' ?

The term condition monitoring (CM) is in very widespread use and many CM instruments are commercially available. We all know what 'condition' as a word means, just like we know what we mean by, say, 'temperature'. The difference is that as a scientific measurement 'temperature' and its unit(s) of measurement have been very rigorously defined. But this is not, and possibly cannot be, the case for 'condition'.

For example, we know that a perfect machine could be considered to be in 100% condition and that a failed machine could be considered to be in 0% condition. The problem is in defining unambiguously any intermediate state. Even more difficult would be to do this in a way that was universally applicable to all machine types. The result is that no CM instruments are calibrated in terms of 'condition'. Instead they measure related characteristics of a machines operation which can be interpreted in terms of the inferred condition. An analogous situation would be to infer the temperature of something by measuring how long it takes a droplet of water to evaporate from its surface; its related to temperature but depends on many other factors also.

In many cases it can be considered that degradation in machine condition is related to wear processes. The occurrence of wear in a machine gives increased energy loss and results in the evolution of sound, heat and debris These various attributes form the basis of most CM techniques. Since a particular CM technique usually concerns itself with only one (or one aspect) of one of these attributes it is self evident that the use of several CM techniques provides a more complete picture from which a better inference of machine condition can be made. However such an ideal approach will usually be tempered by economic realities. In particular the savings of Condition Based Maintenance must outweigh the costs associated with its implementation and these are strongly dependent on the costs of CM; purchase cost, training costs and running costs (incl. manpower costs).

In contrast degradation in the condition of static structures is more usually associated with processes like crack growth, plastic deformation and corrosion but may also include rubbing and scoring of surfaces as joints loosen or subsidence occurs. Structural condition monitoring (which is often referred to as Structural Health Monitoring or Structural Integrity Monitoring) is an emerging field and is currently less established than machinery condition monitoring. However it is an area of continuing R&D activity and one in which there is a strong interest by the end user community. In a similar way to machinery condition monitoring this interest is driven by the desire to assure continued safe operation in the most cost effective manner.

Application of AE to machinery condition

All operating machinery has associated energy losses and this results in stress waves being generated that can be readily detected by surface mounted AE sensors. Although there are exceptions it is usual for the signal to noise ratio to be high with the activity being primarily generated by friction and impacts at contacting surfaces. Other commonly encountered source processes include crushing of debris, turbulence and cavitation.

Since faster surface speeds within machinery result in greater energy release rates they produce higher continuous signals levels (such continuous signals result from the overlapping of many small transient signals). To illustrate this the average signal magnitude detected from a greased roller bearing in good condition at various rotational speeds is presented in Figure 1.This form of relationship is typically found for AE measurements on most rotating machines. However for any particular measurement system the actual signal levels detected at any particular speed will also depend upon the bearing type and size, the applied load, the effectiveness of the lubrication and the presence of damage.

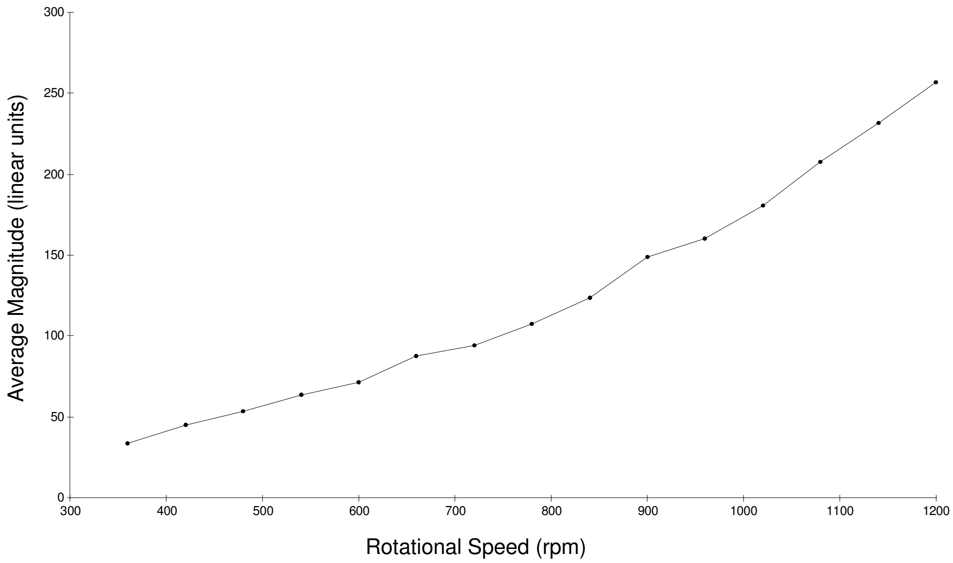

Figure 1 – Effect of rotational speed on the continuous signal level

In addition to the continuous component, the detected signal may exhibit discrete signal excursions each of which corresponds to the occurrence of more significant source transients which may be indicative of damage. As an example Figures 2(a) & 2(b) shows equivalent dynamically enveloped signal waveforms from a roller bearing with and without an introduced defect (defect caused by spark eroding a line on the inner race). The clearly visible transients in Figure 2(b) result from

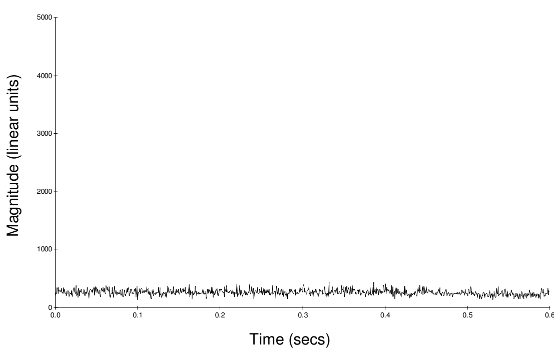

Figure 2(a) – Dynamic envelope signal from a roller bearing in good condition.

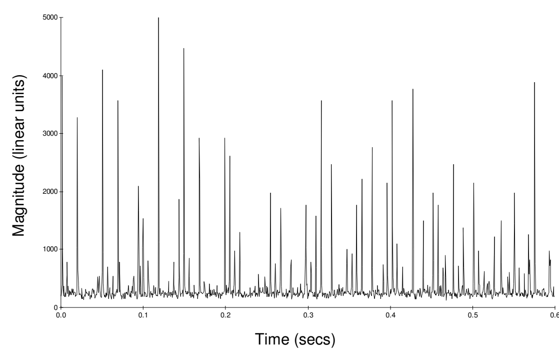

Figure 2(b) – Dynamic envelope signal from a roller bearing with a defect on the inner race.

impacts as individual rolling elements pass over the spark eroded line on the race. The high sensitivity of AE sensors to such transients provides the basis for the direct detection of damage related signals at a very early stage by analysing the signals in the time domain.

Notice also how the signal in Figure 2(b) has underlying time intervals at which transients repeat but that there is significant variation in amplitude with some of the expected transients missing altogether. This most likely corresponds to the relative position of the defect with respect to the loaded zone at the precise time a roller impacts with it. Such time and amplitude variations could in their own right be used to reveal more about the nature of the defect. However, on those occasions when such diagnostic information about the fault is required it is more usual to transform the time signal into the frequency domain in order to observe defect repetition frequencies in a similar way to which vibration based envelope analysis is often conducted (Ref. 6). For such an analysis it is clearly necessary to have detailed knowledge of the machine or bearing geometry as well as precise speed information. In many industries this is seen as a stumbling block

The high signal to noise ratio of AE signals from machinery also has its benefits for monitoring linear and reciprocating machinery. In such cases the opportunity exists to directly interpret the detail within the dynamic AE signal by relating signal features to known machine occurrences at specific timings or phase angles within the machine operation. Applications of this type include actuator mechanisms, diesel engines and reciprocating compressors. To illustrate this an example of analysed waveforms from a 6 cylinder diesel engine are presented in Figure 3. Figure 3(a) presents plots of the maximum, mean and minimum values for the AE envelope signal from 12 successive engine cycles for cylinder #2. This is not untypical of most of the other cylinders with a reasonably consistent waveform from cycle to cycle. In contrast Figure 3(b) shows that for cylinders #1 and #6 there is an occasional reduction in signal amplitude at one particular peak. This is understood to be a result of the engine only just being started and significant thermal gradients existing across the two end cylinders affecting the smooth running (e.g. causing occasional valve sticking).

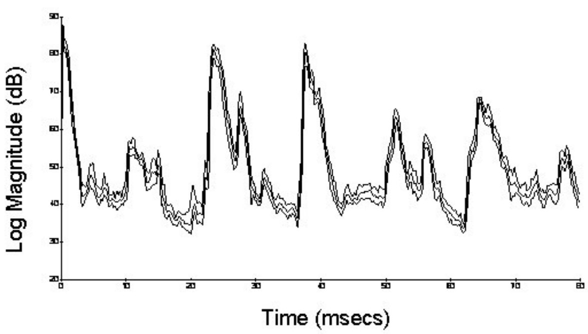

Figure 3(a) – Analysis of dynamic envelope signal from a central cylinder of a diesel engine. (max, min & mean plotted of 12 cycles)

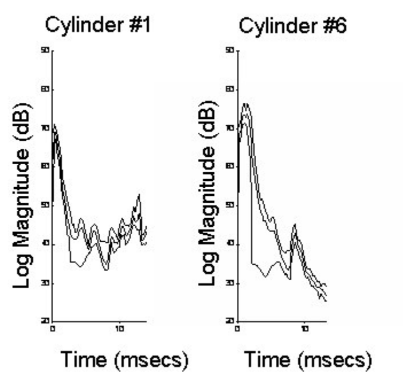

Figure 3(b) – Features in dynamic envelope signals from the end cylinders (max, min & mean plotted of 12 cycles

Another consequence of the speed dependence of detected signal level (as illustrated by Figure 1) is that as the surface speed continues to reduce the detected continuous signal level will eventually drop below the limit of detection of the measurement system. This is sometimes the case when monitoring very slowly surface speeds. Although this may appear to be a limitation to the application of AE methods to slowly rotating machinery, experience suggests that even when there is no discernible continuous signal level the presence of damage is still detectable by the occurrence of detectable transient signals (subject to their being an adequate sound path between the source and the sensor). The success of AE in such applications is especially important since the human senses become ineffective at very slow speeds and vibration monitoring becomes especially difficult if not impossible to apply.

Application of AE to structural condition

As has already been discussed AE has been successfully developed for the testing of material, components and structures. Signal processing capabilities as well as knowledge of AE sources and wave propagation have greatly improved since the publication of Josef Kaisers pioneering work in 1950 (e.g. Refs. 7, 8 & 9). In addition, experimental procedures have been much refined, extended and standardised (e.g. Refs. 10 & 11). Such testing procedures usually involve the application of controlled overstressing of the material beyond its normal working load (Ref. 12). This can easily be arranged for simply loaded structures (such as a pressure vessel) but may not be possible to achieve in practice on a complicated structure (such as a bridge).

For this reason there is increasing interest in the use of AE for long term or continuous monitoring of structures whilst in service. In this role AE is being used as a structural condition monitoring technique. In general terms the method of interpretation is familiar to those involved in machinery condition monitoring; trends are observed, comparisons are made between equivalent items and significant signal excursions are analysed.

As an example of this Figure 4 shows trend plots of 'Hit rate' from two sensors attached to re-bars and embedded in a newly constructed concrete bridge at equivalent positions on either side of the bridge. Signals are processed using the first hit method so that even if an individual transient is detected by more than one AE sensor it is only the sensor that sees it first (i.e. physically the closest) that registers the activity as a Hit. Comparison of the two trends in Figure 4 clearly identifies that something is starting to happen in the vicinity of sensor B around the 1st of May. Visual inspection, initiated as a result of the AE indication, found delamination cracking at a cast joint line in the concrete close to sensor B. At that time no such cracking was observable in the vicinity of sensor A. Later on the 20th May there is a marked increase in first hit activity detected by sensor A and visual inspection confirmed that delamination cracking was starting in the vicinity of this sensor also.

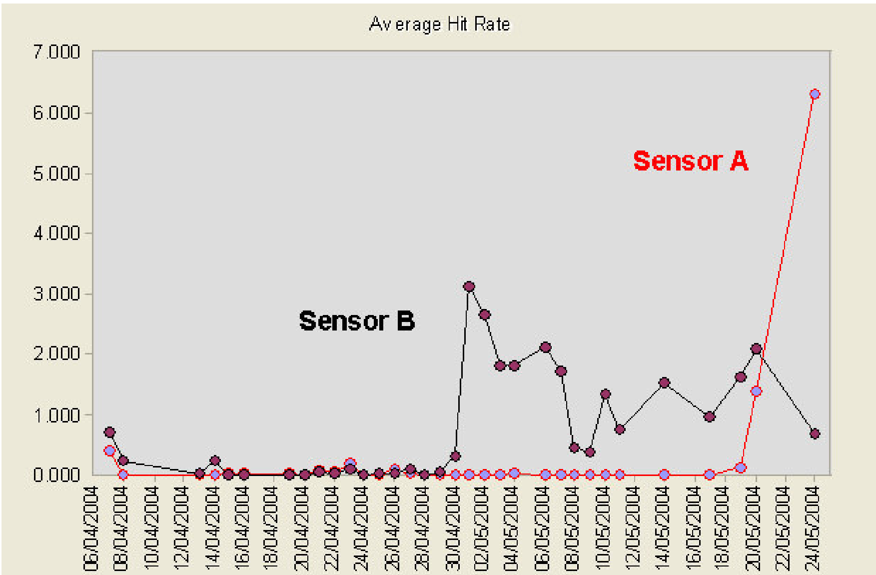

Figure 4 – Trends of Hit rate from AE sensors embedded in a concrete bridge

In fact the use of AE for structural monitoring typically requires the use of multiple AE sensors and a broad range of signal processing techniques to :

- provide adequate detection coverage
- localise the source(s) of activity
- prevent the misinterpretation of non–deleterious signals
- help ascertain the criticality of non repeating signals.

These requirements are additional to those usually required for machinery condition monitoring applications and as a result AE based instruments designed for machinery and structural monitoring are quite different in their design. One of the fundamental differences is that when conducting machinery monitoring it is usually acceptable to make short duration measurements at long intervals. This typically involves periodic monitoring with a portable instrument but in those cases where a permanently installed system is required, it is usual for multiple sensors to be scanned sequentially into a single signal-processing channel. In contrast, for structural monitoring it is most important to be listening simultaneously to all sensor channels so that irreversible activity is not missed and source localisation techniques can be applied.

Training and Certification

It is a fact that different manufacturers of AE instrumentation have different approaches to signal detection and processing in addition to the form of the user interface. In view of this, there is a need for specific training on the correct use of each AE instrument that is to be used. However in addition to this there exists a need for AE practitioners to understand the underlying principles behind AE, its strengths and weaknesses as well as the approaches that should be adopted to maximise the effectiveness of AE measurements in practice.

In this respect we are currently at an important point in the development of AE for condition monitoring. The COMADIT group of BINDT has been working for some years on examination syllabi and question banks. As part of the PCN scheme and with reference to ISO 18436 examinations are being set at three skill levels. During 2005 approval of independent training schemes at third party organisations will begin in order to satisfy the training needs prior to the taking of these examinations.

Considerable effort has been put into this task by many of the leading AE practitioners in the UK who have given their time freely for this purpose. The long lasting legacy of this will not only be the foundation stone from which the scheme can grow further as technology continues to develop but also a sustained improvement in the quality of AE based CM measurements. This broadening and deepening of the understanding of AE within industry will also break down the last barrier to the universal acceptance of AE for machinery and structural CM.

THE FUTURE FOR AE

By way of a disclaimer it is worth bearing in mind that probably the most common feature of predictions is that they are generally wrong because they cannot take into account tomorrows discoveries and new capabilities. Undeterred by this I would suggest that the future for AE looks very promising. The rationale behind this statement is as follows :.

AE sensors provide a useful additional measure that has high sensitivity to energy loss processes in a very wide range of situations. This extra piece of indirect information is complementary to that from the more familiar direct sensing means. The problem has always been unfamiliarity with AE technology and interpretation of its signals. This is diminishing as understanding of AE signals improves and increased processing power is allowing the information from multiple sensory inputs to be more easily interpreted and acted upon.

Another consequence of the increased processing power of general purpose instrumentation will be a reduction in the need for specific AE instruments. For example rather than produce an AE instrument to monitor a diesel engine it will become the norm to simply input the signal from an AE sensor into the engines controller.

This trend has already started, standardised industrial AE sensors are available with pre-processed AE signals to provide dynamic high level voltage and 4-20 mA outputs. Field experience suggests that appropriately designed AE sensors are very robust and can be expected to give many years of service in the industrial environment. Currently an installed base of many thousands of AE sensors is being used in the fields of process and machinery monitoring. In the future we can expect an increase in the numbers of specific application within these broad fields.

One day structural monitoring will follow this route but for the moment the need to interpret transient high frequency signals being detected simultaneously on multiple sensors hinders this development. New developments in wireless interconnectivity and low power electronics will hopefully change this.

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