ACOUSTIC EMISSION FOR NDE IN THE NUCLEAR INDUSTRY

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ABSTRACT

Acoustic emission (AE) is emerging as a technique with a number of potentially important nuclear NDE applications. These include the monitoring of weld fabrication, shop, pre-service and in-service hydrotesting of the reactor pressure vessel, together with in-service continuous monitoring and leak detection.

Experience to date has shown some success with most of these applications, but has also highlighted four areas for development. The reliability of AE must be established by understanding the relationship between detected amplitudes and materials and testing parameters. Methods for reducing or discriminating against unacceptable ambient noise levels must be developed. More accurate location in 3-D must be determined also so that defect depth can be determined. Finally, research into source characterizing must be accelerated and the results incorporated into practical testing so that flaws indicated by AE can be immediately assessed.

1. INTRODUCTION

Although nuclear plant has a good safety record, efforts continue quite rightly to enhance safety assurance, either by the improvement of existing techniques for nondestructive evaluation (NDE) or by the introduction of new techniques. One such technique that has not yet received full acceptance for integrity monitoring is acoustic emission (AE).

Acoustic emission is the spontaneous release of transient elastic waves caused by sudden, localised changes in stress within a body. The elastic waves generated by crack growth or deformation are frequently of sufficient amplitude for defects to be detected and located by an array of transducers attached to the sample or structure. Analysis of measured elastic waveforms can in principle be used to characterise defect severity.

The potential of the acoustic emission technique for monitoring structures such as nuclear plant was recognised early on in its development, and AE soon became the object of extensive commercial exploitation before a deep understanding of fundamentals had been obtained. This period of over-sell was inevitably followed by one of disillusionment. However, AE has more recently commenced to show signs of increasing maturity as an NDE technique, through better instrumentation, a sounder physical basis, and greater care in the choice of applications.

It is important to grasp that AE differs from other NDE techniques in several key respects:

1. The elastic wave source is internal to the structure, originating in the defect itself, and receiving transducers alone are required. Thus a whole structure may be monitored continuously with a modest number of transducers. There is, however, no way of intensifying the sound field to improve sensitivity and avoid missing weak sources.

2. AE is a dynamic, “real-time” technique, in contrast to the static “post mortem” measurements of other techniques. AE thus selects automatically only defects that grow under operating stresses (i.e. potentially harmful defects). However AE is general irreversible and its measurements irrepresentable, and in the absence of source characterisation methods may be unable to discriminate against spurious noise sources.

3. AE signals are transient and random in time. Thus many standard noise reduction methods cannot be used to improve sensitivity.

4. AE amplitudes depend on the incremental area and rate of change of defect growth, in contrast to most ultrasonic inspections that size unstrressed flaws. AE can thus in principle be used to log the accumulation of damage in a structure, and possibly predict failure without recourse to fracture mechanical calculations. It can also be very sensitive.

These various strengths and weaknesses require a different inspection philosophy from, say, ultrasonic testing. Rather, AE should be viewed as an additional, complementary technique, giving new information about defect growth. Our inability to guarantee detection of every active flaw means however that it can never be a replacement for existing inspection procedures.

This paper will briefly introduce the major nuclear NDE application areas for AE, and then discuss aspects of the technique that require further development in order more fully to exploit its potential.

2. APPLICATION AREAS

There are four distinct areas where AE can be applied to help ensure pressure vessel integrity: during fabrication, pre-service proof testing, in-service proof testing, and continuous monitoring. Variants of the technique have also displayed considerable promise for leak detection, valve and loose parts monitoring.
2.1 Fabrication Monitoring

The early (i.e. before subsequent weld passes) detection, and location of weld fabrication defects enables a relatively cheap, on-the-spot repair to be immediately made. There is growing evidence (1-4) that AE will prove of great value in this area. It has been shown that some welding defects are detectable by AE during or immediately following the welding process (1). Weld cracks tend to be caused by a combination of high thermal stresses and impurity contamination. These potentially serious defects act as energetic AE sources during cooling. Slag may become entrapped in the weld, in which case it tends to crack and undergo decohesion from the metal during differential contraction generating energetic AE.

The welding process is accompanied by high electrical and acoustic noise levels. While cracks and slag inclusions are sufficiently energetic AE sources to be detected above the noise, other welding defects such as porosity and lack of fusion are weaker sources and less readily detected.

This application area shows considerable promise and has clear economic benefits. Although instrumentation development is still required (especially for meaningful characterisation), there do not appear to be any scientific barriers to its acceptance for fabrication monitoring of critical components.

A related area, the detection of stress relief cracking, has received less attention. Of particular importance to the nuclear industry are underclad cracks. These may form in the HAZ of the AISI 400 series steel during the heat treatment following cladding with austenitic steel. There is some evidence (5) that AE could make a valuable contribution in detecting and indicating the severity of these cracks at an early stage.

2.2 Pre-Service Testing

One major nuclear application area for AE has long been seen as the pre-service hydrotreat of the reactor pressure vessel. The objectives would be to detect the growth of defects that could lead to vessel failure during the proof test, and to locate less serious defects that may have grown sufficiently during the proof test to be candidates for fatigue growth in service.

Estimates (6,7) of the number of PWR and BWR pressure vessels monitored by AE during the pre-service proof test vary, but are generally in excess of twenty. Where data is available from these tests, little AE was detected. However, other inspection techniques showed the vessel to be of very high integrity, so that no definite conclusion about AE’s reliability for detecting potentially harmful defects can be drawn.

There have been a number of programmes examining and testing experimental vessels, probably the most important being the HSST programme (6-12) at Oak Ridge National Laboratory. The success (i.e. correlation between AE activity and serious defects) of all the vessel tests depended upon a number of factors. AE activity was a function of the type of defect, the composition and thermal history of the material, the testing temperature, and the mechanical history of the vessel.

A number of tests (13) have shown that plastic deformation processes such as inclusion decohesion/fracture, rather than ductile crack growth processes generate detectable AE in normalised low carbon steels. However other tests (12) have shown that realistic defect growth in for instance the HAZ of welded pressure vessel steel is an active AE source.

With the advent of better fabrication methods and more advanced ultrasonic inspection techniques, the probability of there being any detect growth for AE to detect during proof testing has been further reduced. The case for AE monitoring is therefore as another, additional safety check.

2.3 In-Service Inspection

The objective here is to use AE during the periodic in-service hydrotreat to pinpoint areas of the pressure vessel where there might be defects that have grown during service, and where ultrasonic inspection should be concentrated, and thereby reduce the time for inspection and radiation exposure to NDE personnel.

There are relatively few reported applications of AE here (6). Where data is available, the results show a similar measure of success to pre-service inspection. AE was able to detect some defects that had been identified by conventional NDE (14). However finding a “defect” by AE in an area of the vessel where access by other techniques is difficult or impossible poses problems, and points to the need for more quantitative methods to discriminate against spurious sources and “false alarms”.

2.4 Continuous Monitoring

The continuous monitoring of plant has also been seen as an important, indeed a unique, application area for AE, either in terms of monitoring the whole structure, or only higher risk regions of it. Published data here is however even more sparse than in the case of vessel proof testing, possibly due to regulatory pressures.

Most work (15-17) has been compelled to concentrate on the serious problems associated with high ambient noise levels (vibration, flow, boiling) during operation.

The results of a fatigue study of a 1/15 scale BWR vessel (18) however suggest that, provided the background noise problem can be solved, AE is likely to be a reliable detector of the fatigue growth of natural defects in critical areas of the structure.

Environmental factors such as corrosion and irradiation (15) are also likely to influence the detectability of defect growth, more probably by increasing AE amplitudes.

Continuous monitoring should include monitoring during fault conditions, when high thermal stresses may be generated. One study (19) reports higher AE amplitudes during thermal shock conditions than under hydrostatic loading.
2.5 Leak Detection

The leakage of fluid from a pressurised system, through a crack for instance, generates elastic waves in the vessel that can be detected (and located) as an apparent increase in the continuous noise level. Acoustic leak detection methods have been applied to nuclear plant (16) with some success. The sensitivity and thus the success of the technique depends on low ambient noise levels, and these are not always obtainable when a reactor is running at full power.

Valve status monitoring (20), derived from leak detection, is also being applied with success to nuclear plant.

3. AREAS REQUIRING TECHNICAL DEVELOPMENT

Experience with AE to date has shown at least some success in the application areas listed above. However four areas have also been highlighted for further development if AE is to become a reliable NDE technique. These will be taken up in more detail in later papers.

3.1 Reliability

The elastic wave amplitudes generated by defects are a function of material properties and microstructure, the nature of the defects that are growing, and external parameters such as stress history, temperature and environment. As an example of the variability of AE activity, crack growth in the same steel (21) can be either an energetic source (under conditions of high strength and/or embrittlement) or "quiet" (when fully tempered). In the first case crack advance may be by ductile shear or intergranular fracture, in the second by microvoid coalescence.

Systematic studies of microstructural, etc. effects have been carried out at a number of laboratories, although there is still a need for more work to characterise more fully the AE activity of structural steels. One such study is reviewed in a later paper (22), where it is concluded that non-metallic inclusions are the primary source of burst-type AE during the deformation of A533B steel.

Using a simple model for a fracture event, it is possible to estimate the detection threshold for various possible mechanisms. It can be shown (23) that the formation of a brittle crack of length a and width b at a velocity v, at a depth h below a transducer with detection threshold X (defined by noise) is detectable if

\[ a^2v > hX \times 5 \times 10^{14} \text{ watts}. \]

Taking h = 0.1 m and X = 10^{-11} m, Fig. 1 shows schematically the range of fracture events that should be detectable, including typical fracture processes in a structural steel.

Before the AE technique can be applied reliably to a given problem, it is necessary to know the possible modes of defect growth and the dependence of generated AE upon all relevant material and other parameters for that problem.

3.2 Noise Suppression

AE events are transient in nature and random in time, so that standard processing methods to improve signal/noise ratios cannot be applied. Thus the detectability of AE events is a function of background noise, so that every effort has to be made to reduce the noise. The problem is particularly serious during continuous monitoring because of high flow noise on-load (15-17). Where possible there is a need to develop methods for reducing, or discriminating against noise. Noise sources for AE are shown very schematically in Fig. 2.

Noise due to radio frequency interference can be reduced by good screening and grounding practice. Electronic noise can be reduced, by employing high quality, low noise amplifiers and by limiting the frequency band (or "window") for detecting. Employing a narrow band detection system, comprising resonant transducers and matched filters, is only effective if the signal-to-noise ratio is appreciably higher within the pass band than without (Fig. 2).

Acoustic and ultrasonic noise is generally more difficult to deal with. Low frequency mechanical vibration can be readily filtered out. Fluid flow and boiling however generate wideband noise that embraces the frequency bands common employed for AE monitoring (0.1 - 1.0 MHz), and band-pass filtering brings little benefit. At higher frequencies, where flow noise is reduced, ultrasonic attenuation becomes more significant. In instances where the approximate defect location is known, spatial filtering can give considerable benefit, using either a transducer array or guard transducers.

3.3 Location Accuracy

The location algorithms that are at present used are mostly limited to 1-D (linear) or 2-D (planar). They also use a single wave speed for the triangulation. While planar location is satisfactory for sources close to the surface of a plate, and a distant array of transducers so that Rayleigh surface waves dominate the detected signals, serious inaccuracies may arise in other situations. In the case of thin plates, propagation is by dispersive Lamb waves (24). In the case of a thick section plate with a buried source, the first arrival that exceeds each transducer threshold may be a compressional, shear, Rayleigh or head-wave. Fig. 3 shows the multiplicity of arrivals in a plate as a function of position (25). Reducing the 3-D problem to 2-D, i.e. ignoring source depth, gives planar location errors of about a plate thickness.

There is a clear need to improve source location accuracy especially for thick plate sections and more complex geometries such as nozzles. If triangulation methods are to be used, the different wave mode arrivals must be clearly identified. It will also be advantageous to develop 3-D algorithms, so that source depth (an important parameter) can be determined. Location techniques will be discussed in later papers (26,27).
3.4 Source Characterisation and Flaw Severity

Practical AE methods are unable to size or characterise AE source events reliably. This present weakness leads to difficulties, for it is not possible to discriminate against all spurious or insignificant sources or to assess flaw severity on the basis of AE alone. Where the apparent defect is accessible, other NDE techniques can be employed, perhaps expensive. However, if the AE source is an inaccessible region of the structure, the problem of how to evaluate and respond to it becomes more serious.

The information required for AE source characterisation (Fig. 4) is present in the radiated wave field, so that this needs to be measured. If n parameters are deemed sufficient to characterise a source, then m > n independent measurements (i.e. in different directions from the source) are required. The mathematical basis exists both for representing acoustic sources such as crack growth events and for elastic wave propagation in plate-like structures. The simplest representation for an acoustic emission source is as a point stress-drop tensor, which has 6 independent components (28). Elastic wave propagation theory can be used to compute the surface displacements at an array of points on the surface of the structure. Inversion techniques can be employed to deduce the source parameters from the measured acoustic waveforms. This is however a difficult area where considerable effort is still required.

The accurate measurements require improved detection and recording instrumentation. Most of the necessary instrumentation is now becoming available, although some developments are still needed in conjunction with extensive laboratory tests. Some of these are discussed together with the theoretical basis in papers in this Session (26,29).

SUMMARY

Acoustic emission is emerging as a technique with several important potential applications to nuclear inspection and monitoring. While there has been a measure of success in some areas, the technique has still to establish full credibility as a reliable monitoring tool. The key problems of source variability, background noise, inadequate location accuracy, and inability to quantify and characterise sources, are receiving attention. The papers that follow will bring out more fully the advancing understanding of AE and show in detail how the key problem areas are being tackled by research workers.

Already considerable advances have been made and these now need to be exploited practically. It is recommended also that tests are carried out with realistic defects, and under realistic conditions of loading and environment.

REFERENCES

22. K. Ono, These proceedings, 1982.
Fig 1  Detectability of fracture events in steels. Detection threshold assumes transducer P wave sensitivity of $10^{-13}$m, source-transducer distance 0.1m, stress 500MPa.

Fig 2  Schematic to show (a) typical noise sources encountered in AE monitoring; (b) typical AE spectrum (transducer response ignored); (c) detectability of AE source event, i.e. S/N as a function of frequency. The low amplitude event requires a band-pass window to improve detection. The high amplitude event can be recorded broadband.