ANALYSIS OF ACOUSTIC EMISSION: A VIEW

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ABSTRACT

Acoustic Emission (AE) a long-known phenomenon and a recent technique, has rapidly become an important discipline in the field of Non-destructive Evaluation. The technique has tremendous potential; its range of possible applications is very wide. However, it has suffered from a premature entry into industrial applications before sufficiently thorough examination and understanding of the various fundamental aspects. Retrieval of causative and source information from signals is a difficult task due to the diversity of AE sources and variability in experimental conditions and due to the distortions suffered by the stress waves as they propagate in the medium.

In such a situation, it is reasonable to postulate that some of the source characteristics would be relatively insensitive to the distortions in the signal path and would persist in the signal in some form. So, one could attempt to retrieve a few source characteristics from the signal and this is best done by utilising pattern recognition methods. Investigations carried out by the authors indicate the feasibility of this approach. Further, it is encouraging that serious efforts are being put in by researchers in the AE community to mathematically estimate the distorsioins in the signal path as also to eliminate them through deconvolution using cepstral analysis techniques. Success of such investigations would further improve the efficiency and effectiveness of pattern classification of AE signals. Thus, in our view, a good beginning has been made to better understand the scientific principles underlying the technique and this should lead to a more reliable usage and wider acceptance of the Acoustic Emission Technique as a tool for non-destructive evaluation.

KEY WORDS

Acoustic Emission, Signal Analysis, Pattern Recognition , Cepstral Analysis, Deconvolution, Source Model, Spectral Window, Frequency Spectrum, NDT.

INTRODUCTION

In the study and application of fracture mechanics there is need for detection of the existence, initiation and growth of defects by "Non-destructive methods". In this context, we define a non-destructive method as one that does not during or due its application, add any significant incremental damage to the system being examined. Obviously no single technique can meet all the needs. However, the Acoustic Emission Technique (AET) has been recognised to occupy a preeminent position in the armoury of NDE(Non-destructive Evaluation) techniques that can be brought to bear upon fracture mechanics. There are good reasons for this. Its detection capability in relation to inaccessible areas is unique and it has extra special sensitivity to minute incremental growth of defects. The method does not just determine the geometry of a flaw, but directly indicates the severity of the flaw, under its operational conditions. Further, the evaluation is carried out under operating conditions and does not require shut down or unloading of the system. It is in this context of NDE for fracture mechanics, research and application that we had a close look at AET over a decade ago. Looking at it from the vantage point of distance from the active centres of work, we saw certain patterns in the field. Our own subsequent approach was significantly influenced by this perception. Over the years we have been gratified to see that our view point has been reinforced by the direction in which AET research has been moving elsewhere. In this presentation we will try to share our view with you.

RELATING AE TO ITS SOURCE : THE TASK

When a material, component or structure is subjected to a change or fluctuation in its mechanical, thermal or chemical environment, a variety of internal and interfacial processes occur. These give rise to small spurts or bursts of energy release which are called acoustic emissions (AE). The bursts of energy travel through the material as stress or pressure waves and can be picked up at convenient locations in or on the material with suitable transducers. A signal so obtained is a product of the original emission, structural resonances, distorsions and noise acquired in the medium and the transducer interface, reflections from the boundaries and the response function of the transducer. But it may be postulated that the signal contains features which are related to the characteristics of the source of emission. In brief : A signal is a coded message. If we know the code we would directly and comfortably evaluate the state of the material. Unfortunately we do not know the code. So, concerted efforts should be directed towards breaking the code. This is the challenging task we continue to face.

HISTORICAL PERSPECTIVE

Literature

That materials under strain emit a cry of distress has been known for ages and has long attracted the attention of scientists, e.g. Bose (1927), Obert and Duvall (1942). Such sounds have also been recognised as early warnings of impending danger, as in the case of mine bursts. However, the initiation of systematic studies of emissions and their correlations with defects and processes is fairly recent. Kaiser's (1950) studies of

emissions from metals during deformation may be considered as a land mark in scientific studies of the acoustic emission phenomenon and its use in the hydrotesting of rocket motors of the Polaris Missile (Green, 1964) as the initiation of AET as an NDE technique. Developments in instrumentation and electroinic data processing on the one hand and the demands of NDE on the other have been strong motive forces for developing AET into a major discipline.

Drouillard's bibliographies (1974, 79, 82/83) refer to earlier appreciation of acoustic emission from pre-historic times and trace modern development of the technique starting with Kaiser's work. The rapid growth of interest can be judged from the increasing number of publications on the subject from 1950 to 1976 (Fig. 1). The decade from 1963 to 1975 has seen an annual growth rate of 25%. To-day there are a few thousand papers covering various

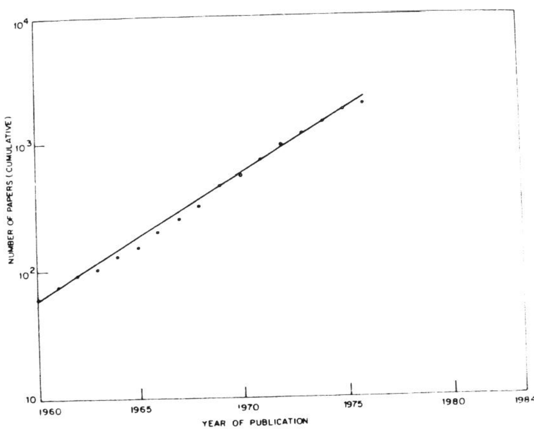

Fig. 1. Growth of AE literature.

aspects. Lord Jr. (1981) published a first comprehensive review in 1975 and updated it in 1981. Useful reviews have also been written by Ying (1973), Wadley et al. (1980), Spanner (1978), and Lord and Koerner (1980). The most valuable sources of information are the Special Technical Publications of the American Society for Testing and Materials (STPs 505, 591, 696, 697, 750) and books and monographs by Spanner (1974), Pollock (1973), Ono (1980), Dunegan and Hartman (1979) and Nichols (1980). Other good sources are Proceedings of AE symposia in USA, Europe and Japan, NTIAC Newsletters and some contemporary journals (Materials Evaluation, NDT International, British Journal of NDT, Journal of Acoustic Society of America, Ultrasonics, Journal of Testing and Evaluation, Engineering Fracture Mechanics, and Journal of Acoustic Emission et al. Realising the necessity of a forum for exchange of technical information and standardisation of terminology vis-a-vis for promotion of active research in the area, the pioneer workers in USA formed an Acoustic Emission Working Group in 1967. Since then such working groups have been formed in Europe, Japan and India. The Indian group was formed in March this year.

Applications

The first major application of AET to a practical problem was in the hydrotest of filament would rocket motor casings for the Polaris Missile, in 1963-64. This successful application gave a boost to the method and led to intensive studies and innovations in instrumentation. These have made it possible to extend the applications to many critical areas in nuclear, chemical, petroleum, aerospace and other industries and also in materials science and fracture mechanics research.

Considerable success has been recorded in the qualification of pressure vessels. Crack detection has been established in a variety of structures. Correlations have been achieved for stress intensity factors. Identification of deformations, micro cracking, phase transformations etc. in a variety of materials and structures has been found possible. On-line monitoring for a variety of purposes, e.g. characterisation, evaluation and quality control of welding, has been achieved. Extensions to other areas like fluid leak detection and materials evaluatioin has been achieved. Applications have been made to metallic and non-metallic materials and fibre reinforced composites. A combinatorial system, Acousto-Ultrasonics, which is particularly valuable for evaluating strategic materials like composites has been developed. New facets of the technique such as Magneto Mechanical Acoustic Emission have been discovered.

In spite of these many successes in the first decade of developoment, one finds a feeling of disappointment with and resistance to acceptance in many circles. This is partly because high hopes were raised in very early stages.

From the early stages, a significant objective of AET research has been on-line continuous monitoring or intermittent surveillance of critical structural systems in aerospace and nuclear engineering for initiation and growth of defects and damage, and early warning of impending failures. Till now only limited successes have been achieved in these directions. Success at the level desired is a long way off.

Techniques of Measurement and Analysis

The land marks in instrument development and underlying concepts are worth recapitulating.

Ambient noise has been a major problem. In most cases this is avoided by working in a high frequency range (generally 100 KHz and upwards) and using narrow band instrumentation. Interference from emissions generated outside the critical region is handled by a spacial discrimination process. Location of individual events is carried out by a triangulation process. Both are based on the times of arrival of the signal at the different transducers of an array. Historically, first microphones were used as sensors. These are sensitive only in the audio range. But they pick up ambient and structural noises as well as their sensitivity is limited. So, in the next stage accelerometers were tried. These respond through contact, so that they do not pick up environmental noise and also, their sensitivity is higher. But a satisfactory situation was reached only with the use of piezo-electric transducers which are rugged, highly sensitive and can be constructed for desired natural frequencies or for wide band response. By filtering out frequencies below and beyond the necessary range, external noises can be suppressed. Resonant types are used with narrow band instrumentation and non-resonant types with wideband instrumentation. Currently, for wideband studies capacitance transducers and optical detectors are also being utilised. These are highly advantageous for laboratory studies and research, but are difficult to adapt for field conditions.

Acoustic emission instrumentation has been going through a process of evolution. In the early years, researchers put together bits and pieces of general pourpose instruments to carry out experiments. Initially, when experiments were carried out in the audio range, michrophones and other general purpose instruments and sound proof laboratories were utilised.

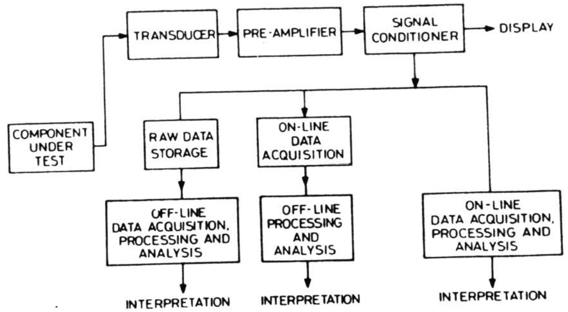

Fig. 2. Basic blocks of AE instrumentation.

Later, equipment was specifically designed to suit AE studies in the high frequency range. Although, over the years, sophistication in AE instrumentation has increased enormously, the basic blocks have remained the same (Fig. 2). These are signal detection, data acquisition, data processing and data analysis units. Most of the sophistication has been to handle a variety of structures and situations in the field and to provide maximum flexibility to choose parameters best suited to each study. The type and bulk of acquisition and processing units are essentially dependent on the size and detail of the structure to be monitored and the noise environment. The purpose for which AE is being employed, the level of sophistication contemplated for signal analysis and cost factors govern the choice of the analysing units. The options in organising AE signal analysis can also be seen from Fig. 2. At its simplest, signal analysis would consist of correlations with one or more of the time-domain parameters (like ringdown counts, event counts, rms values, event duration). Early success with and ease of handling time domain parameters have led to extensive development of instrumentation based on them. This has inhibited the evolution of alternative or complementary procedures, such as, use of spectral parameters and pattern recognition approaches that would be essential for developing AET as a suitable tool for handling a wider range of more complex situations. This feeling provided the principal motivation for undertaking the line of investigations we have pursued in regard to signal analysis. This view point seems to be gaining ground as can be seen from the recent assessment of Wadley et al. (1979) that 'commercial pressures to obtain results in the field on full-scale structures must be held partly responsible for the lack of fundamental studies'.

This in turn has also led to a slowing down of the extension of applications and an increasing resistance to the acceptance of AET as a standard NDE tool, particularly in Europe. Thus, the need now, to establish and extend the scope of AET, is to move towards more sophisticated, but feasible and economical signal analysis techniques like pattern recognition. Elsley and Graham (1976) are perhaps the earliest to start exploring pattern recognition possibilities. More recently, efforts are also being directed at homomorphic deconvolution techniques (or cepstral signal processing) to eliminate the effects of reverberations. If these efforts prove successful, the pattern recognition problem itself gets simplified.

MORPHOLOGY OF THE AE SIGNAL

The sources of acoustic emission are divers. However, for the present purpose we will discuss the subject primarily in relation to defects such as cracks without losing generality in understanding. We can model the morphology of an AE signal as in Fig. 3. Evaluation of the source mechanism and its characteristics is best done by measurements of the energy release at the source itself. Unfortunately this is a formidable task. Such a method not being readily available the best approach would be to systematically link up the sequence of transfomations and losses from the source to the point where the signal is acquired so that some kind of deconvolution could be performed to identify the essentials of the source characteristics. Although the physical concepts involved in the sequence of transformations from the source to the signal are known, a mathematical representation to obtain an exact and rigorous solution to the above problem is difficult owing to the complexity of the situation. Thus, a principal aspect of an AE study would be to establish some satisfactory and useful correlations between the source and the signal.

To further understand the difficulties involved, let us consider the system in its component parts step by step. Given a material and a situation, no information is available 'a priori' regarding the location and nature of the source. The activation of the source itself is dependent on the local characteristics of the material and the stimulus which are not sufficiently defined. The next uncertainty is the time description of the stress wave resulting from the energy release and its propagatioon through the medium. It is generally thought that the stress wave propagates as a spherical wave

front at constant speed in all directions. But in reality the nature of the wave generated is dependent on the characteristics of the source itself and hence is subject to variations. After leaving the vicinity of the defect,

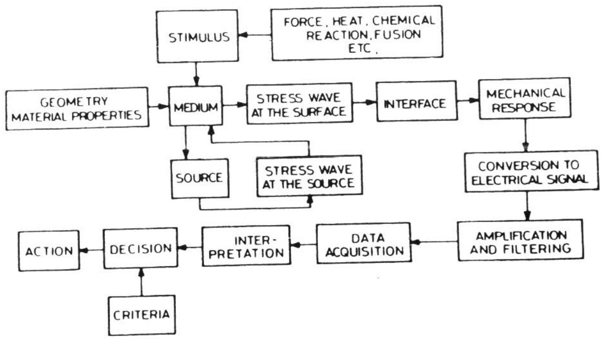

Fig. 3. Morphology of AE signals

the profile of the wavefront can change due to directional variations in the wave speeds associated with wave propagation in anisotropic, inhomogeneous media. The wave is damped and distorted in a complex manner because of thermoelastic effects, grain boundary scattering, acoustic diffraction, dislocation damping, interaction with ferro-magnetic domain walls and scattering by point defects in addition to the attenuation due to the expanding wave front. In practice, the emissions are picked up by transducers mounted on the surface, thus adding some more parameters arising from interface characteristics, and the properties of the medium (mode convertions and multiple reflections). Knowledge of the exact transfer function of the transducer is essential to eliminate additional uncertainties. Thus, the most commonly used piezo-electric transducers, which respond differently to different modes, require absolute calibration which is a difficult task. The next block in the chain is signal amplification and data acquisition which if carefully undertaken can be achieved without introducing any further distortion to the data. Finally, the analysis and interpretation is a subjective process though governed by strict scientific principles and hence needs careful attention.

A survey of laboratory research and field applications indicates the following situation:

1. AE technique is qualitatively dependable in many situations.

2. Coupon testing yields consistant results but application to complex structures poses problems of analysis/interpretation.

3. Repeatability is difficult to achieve. This is due to subjectivity in the choice of certain experimental parameters such as threshold value, location of the transducers, variations in instrumentation characteristics and the randomness inherent in the process itself.

4. Variation in results and interpretation arising from the choice of the analytical technique.

5. In adequacy of the modelling of the source, their behaviour, and the signal path of the phenomenon.

Taking an overview of the situation one realises the reason for the skepticism in some places towards an early achievement of viable methods for quantification of AE data and standardisation of techniques. And also this over view should give us a sense of direction for research and development that can break through this impasse.

MODELLING THE SOURCE AND ESTIMATING THE SIGNAL

Acoustic Emission sources, we noticed, are diverse in nature. Whatever be the nature of the source, activation of the source results in release of energy which causes sudden localised change in the stress state and consequent radiation of stress waves. Recording stress waves as released by the source being a formidable task, several attempts have been made to exctract the source characteristics from experimental observations made elsewhere on the surface of the structure. These too have not been very successful on account of the complexity of the problem as described in the last section on Morphology.

On the basis of his investigations, Schofield (1961) proposed that AE sources are of transient nature. Both Kaiser and Schofield observed that the spectra of AE signals contained predominant frequencies which were functions of the applied load. It has since been realised that these frequencies are related to the natural frequencies of the test specimens. Later Eagle and Tatro suggested that the source wave form is oscillatory with gradually decaying amplitude and has well defined peaks in the frequency spectrum. Stephens and Pollock (1971) disagreed with this postulation and suggested a pulse model and showed that the frequency spectrum of an AE source waveform is essentially broad band. This was a land mark in the AE research for source characterisation. Later, James and Carpenter (1971), Pascal and Sedgewick (1968), Fisher and Lally (1967), Kiesewetter and Schiller (1976) and Mason (1976) proposed qualitative and quantitative correlations between micro-mechanisms of deformation in materials and experimentally measured acoustic emission parameters. In some cases, subsequent experiments have negated earlier findings of correlation. In most of these attempts, the models are oversimplified, while in many

others either the analytical back up or the experimental base was not sound. Thus, most of them have been unsuccessful in assuring qualitative correlation or ingiving quantitative detail to the source characterisation problem. This problem of satisfactory modelling, without making the solution intractable, has to be dexterously handled. A first step would be to consider two alternative models, in one avoiding distortions in the medium and reverberations at the surface, in the other finding a means of filtering out these distorsions and reverberations. The first model helps to simplify the characterisation of the source. The two models together would help to make pattern recognition simpler and satisfactory interpretation of real-life data more tractable. A seminal paper in the direction of the first model, using experimental concepts and techniques with proper analytical back up, was given by Breckenridge et al. (1975). A possibility for achieving the second is provided by the cepstral technique which has been successfully used in speech and seismic signal analysis. The next advance appears to be by Hsu et al. (1977) who numerically computed the surface displacement as a function of time at an arbitrary point on an infinite plate due to an arbitrary source force function. Excellent agreement was reported using reproducible step-function of stress by breaking a pencil lead and picking up the signal by a capacitance transducer. Scruby et al. (1978) at Harwell have also contributed significantly to source characterisation. They have developed a special 'Yobell Specimen' which avoids reflections. Green (1978) and his co-workers have developed a method of optically sensing acoustic emission signals. They used a modified Michelson interferometer; the advantages of this method is large bandwidth, high sensitivity and the sensor not loading the material system.

It would be useful at this stage to emphasise that the successes of the foregoing and similar investigations has been specifically due to (a) development of an excellent experimental set up that overcomes the usual problems associated with wave propagation (b)utilisation of a capacitance transducer or optical detector which does not load the system and (c) adequate theoretical back up.

The overcoming of difficulties in characterisation of the medium, in terms of wavepropagation and multiple reflections, in practical engineering structures is a long way off. So, parallel to these efforts, we should investigate the possibilities of seeking features in the signal that individually or in combination, are relatively insensitive to the foregoing effects and so can be directly linked to the source characteristics. Such an approach would imply exploring paths of pattern recognition. While capacitance transducers and optical detectors have been sucessfully utilised in the laboratory for this type of studies, these are not generally suitable for engineering applications. So, we feel that even in laboratory studies it is worthwhile introducing piezo-electric transducers into the instrumentation. So, source-signal correlatioon eliminating medium and boundary effects and using piezo-electric transducers will be considered later in this section.

A Model

Following our foregoing discussions, let us consider a situation in which the medium and boundary effects can be ignored and postulate that an incremental motion of a defect gives rise to burst type of emission. Such a motion can be represented as a sequence of three phases as in Fig. 4: (i) initial short period of acceleration (ii) intermediate period of growth and (iii) final short period of deceleration. The amplitude 'A' of the stress pulse generated thereby is given by

$$A = k_m \frac{d\xi}{dt} \qquad (1)$$

where ξ is the displacement of the defect. The model is generally simplified by presuming a constant acceleration within each phase. From this we generate a sequence of four simple situations (out of a possible ten) as shown in Fig. 4.

(a) The defect velocity rises and falls instantaneously and is steady in between. This results in a rectangular pulse (Fig. 4a).

$$a_1 = a_3 \rightarrow \infty \text{ and } a_2 = 0$$

This simple model was considered by Hill and Stephens.
(b) Model (a) is improved by admitting varying velocity in the intermediate growth phase as in Fig. 4b.

$$a_1 = a_3 \rightarrow \infty, a_2 = k_2$$

(c) Alternatively, model (a) can be extended by incorporating equal and finite acceleration and deceleration as in Fig. 4c.

$$a_1 = -a_3 = k_1 \;,\; a_2 = 0$$

(d) Combination of features of (b) and (c) yields a more general form of the rectilinear (quadrilateral) model as in Fig. 4d.

$$a_1 = -a_3 = k_1 \;,\; a_2 = k_2$$

The next step is to estimate the signal. From this information, hopefully we may identify sufficient signal parameters to correlate with the source wave characteristics (say, the slopes a_1, a_2, the maximum amplitudes A_1, A_2 and the duration T). With such a correlation established, one should be able to identify from the signals if the source has emitted any of the four waveforms considered.

Response Estimation

The response (signal) to be expected from the transducer can be estimated by treating the transducer and instrumentation as two bandpass filters in cascade and using Fourier transforms. This response can obviously yield only that part of the source spectrum that is within the bandwidth of the "Frequency Window". The significant question is : Is it possible to 'guess' the important parameters of the original pulse from this measured part of

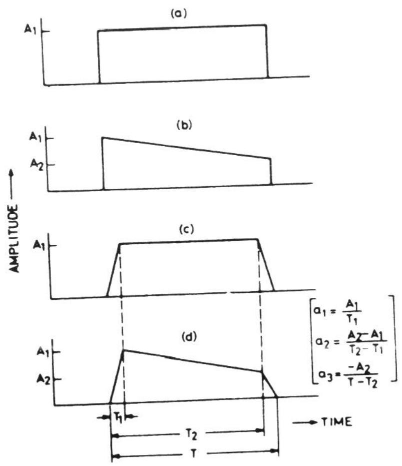

Fig. 4. AE Source stress waveforms.

the spectrum? Our investigations suggest that the answer can be positive. We illustrate this fact briefly.

The instrumentation in general is designed for wide bandwidth, while the transducer may be designed for wide or narrow bandwidth. The total response of the system is governed by the narrower of the two. For convenience of analysis, let us assume an ideal bandpass filter characteristics for the total system.

The transmissibility and phase response of an ideal bandpass filter ($f \pm \Delta f/2$) are given in Fig. 5. The filter phase response is

$$\phi = 2\pi(f - f_o)\, t_L \qquad (2)$$

where t_L is the transmissioin time of the filter. The response o(t) of the filter to an input function g(t) is given by

$$o(t) = \int_{-\infty}^{\infty} G(f)\, H(f)\, e^{j2\pi ft}\, df \qquad (3)$$

where G(f) is the Fourier transform of the input function g(t) and

$$H(f) = e^{-j2\pi(f-f_o)t_L}, \text{ in } f_o - \Delta f/2 < f < f_o + \Delta f/2 \qquad (4)$$
$$= 0 \text{ , elsewhere}$$

is the frequency response function of the ideal filter.

The response of the system to the source models presented in Fig. 4, has been analytically estimated for both narrow and broad band filters depicting the resonant and non-resonant transducers respectively. These are shown in Fig.6.

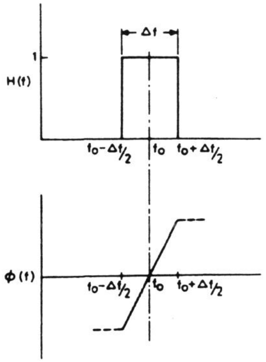

Fig. 5. Filter response.

Signals from a number of experiments were examined and some of them were found to exhibit the features predicted for the source models considered. An example is shown in Fig. 7. This may be compared with the predicted signal for Model (d) (Fig. 4).

Location of the Spectral Window

The location of the spectral window has a major effect on the characterisation of the AE signal. When a resonant piezo-electric transducer, which is conventional for AE applications, is used, three qualitatively distinct locations are possibale as shown in Fig. 8. At the first location, though the transducer has a flat characteristic, distorsions are introduced due to specimen resonances. Hence, the event parameters in time and frequency domains would be correlated to the dynamic characteristics of the structure. So, if the presence of an AE source (such as a gross defect) can affect these dynamic characteristics, it would be possible to derive information regarding the source severity from the signals obtained.

The third location is in the zone which includes the transducer resonant frequency. The transducer sensitivity is highest in this case, as such this location is most commonly used.

At the second location, which is intermediate between the first few resonant modes of the structure and the transducer resonant frequency, the transducer is likely to pass the source spectral components without undue distorsion. However, one has to be careful in evaluating the source characteristics since what is obtained is still only a part of the source spectrum. If one can construct the entire spectrum, with suitable assumptions, with the

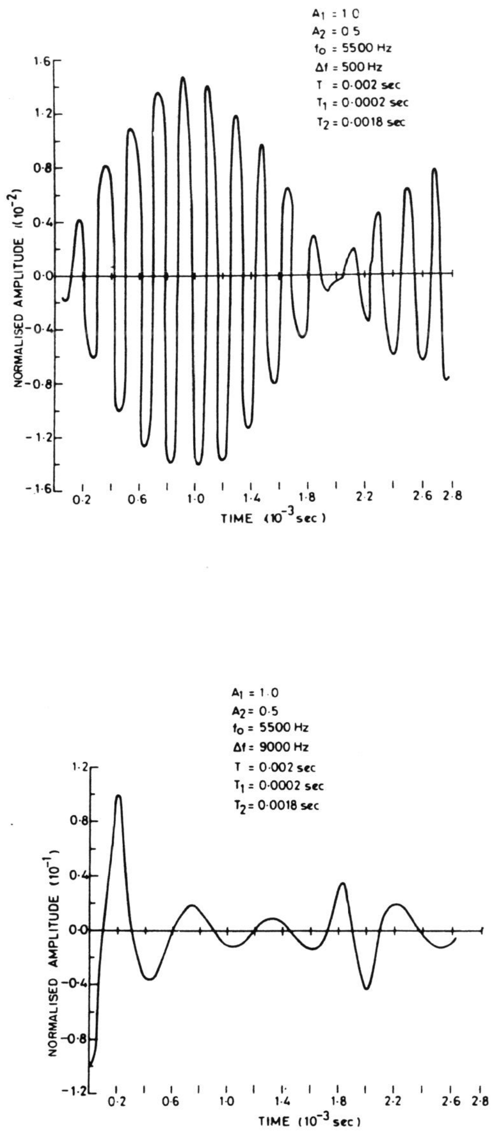

Fig. 6. Analytically estimated signals.

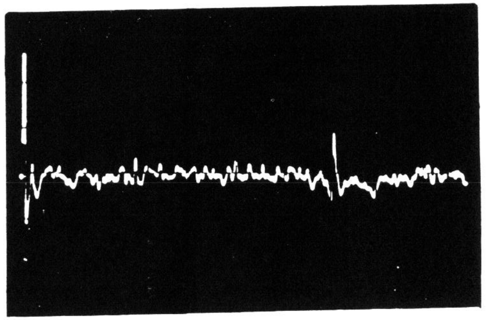

Fig. 7. Typical event observed in experimental data

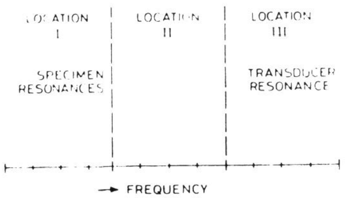

Fig. 8. Window locations

available frequency domain information, the original source waveform could be obtained by an inversion process.

MEASUREMENT AND ANALYSIS

With the developments of the past three decades, which we indicated briefly in the foregoing pages, we are to-day, at a stage where AET is being sucessfully utilised for industrial applications such as proof testing of pressure vessels and occupies a unique place in the field of non-destructive evaluation; it has tremendous potential for further developments. But, the question, 'How do we record or extract the source stress wave form as released by the source?', still remains unanswered. So, we need a pragmatic approach. One can address the problem by trying to identify features in the signal which are practically insensitive to the various distorsions suffered by the source stress wave and exctracting the significant informatioin from such features, using suitable signal processing techniques. To examine the feasibility of the above approach and

identify proper methods of signal analysis, let us at this stage consider the underlying fundamental factors. A source in a given material may be unique. But due to the statistical variability associated with natural phenomena, the activation of the source within a small interval of time would be random. In addition a small incremental change of state in a material can activate more than one source in a small volume of material and in a small interval of time. Further, there is some amount of variability associated with notionally identical sources. Variability in the metallurgical structure and experimental conditions further complicates the situation. So one must apply random data processing and analysis procedures, which are more elaborate than deterministic procedures. Reviewing the work directed towards quantification of AE data by various contemporary researchers, Lord Jr. (1981) reflects "It appears however, that a unique characterisation of a general AE source is not yet possible from the detected displacement, due to the variability of the displacement, with source type, orientation, time dependence etc..." and he comments regarding the work carried out by Wadley et al. (1978) that "It is now concluded that the histogram approach to source characterisation is the most reliable due to variability of individual source parameters".

Let us at this stage attempt to briefly review some developments in the area of AE signal analysis. Stephens and Pollock (1971) proposed a pulse model and tried to use broad band instrumentation and spectral analysis approach. They also expressed the opinion that various parameters of the acoustic emission signals can be used to provide information regarding the source and listed the following possible correlations:

Wave form	- fine structure of source event
Frequency spectrum	- nature of source event; integrity of the specimen
Amplitude	- energy of source event
Amplitude distribution	- type of damage occurring; rate of damage occurring
Distribution in time	- type of damage occurring; integrity of the specimen
Arrival times at several transducers	- source location

This proposition, that AE source stress wave is transient aperiodic in nature and has a broad spectral content, should have alerted the investigators in the AE community to the need for wideband instrumentation and spectral analysis. However, it took some time for such an awareness of this to surface. This probably, was due partly to the difficulties encountered in sophisticating the instrumentation and partly because of pressures for utilising the commercially available equipment for industrial applications. Subsequently, significant studies in the frequency domain were reported by Graham and Alers (1976). They developed a method for quickly and easily analysing in the frequency domain AE events as short as 20 micro seconds. Subsequently several other investigators in the field also attempted spectral analysis. However, very few investigators attempted to use statistical and random data analysis procedures, be it in the time domain or be it in the frequency domain. A significant point to note is that, in most of the cases, attempts have been made to examine select

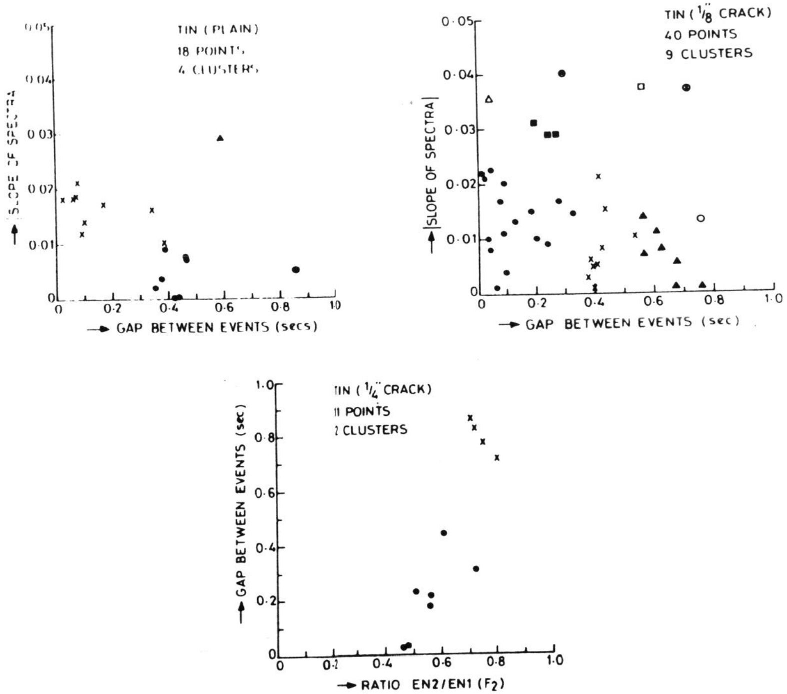

Fig. 9. Typical cluster diagrams.

aspects of an AE signal in their isolation, rather than examine the signal in its totality. Keeping the randomness of AE data in view, it is often useful to carry out a multi-parameter analysis. Statisticians call it exploratory data analysis. The common procedures that can be adopted are histogram plots, scatter plots, cluster analysis procedures, linear discriminant analysis, analysis of variance and regression analysis. One can adopt parametric methods and use statistical estimatioin theory to validate the results. This type of analysis is often useful in indicating similarities and dissimilarities in the data, thus forming a tool for differential diagnostics.

Thus, a close look at the phenomenon of acoustic emission reveals that, as in the case of speech, seismic, electro cardiac and electro encephelographic signals (to name a few), with acoustic emission signals also, pattern recognition can be a very fruitful diagnostic method. As already mentioned, while the general variability associated with the source and experimental conditions, and simultaneous activation of multiple sources, give a random character to AE signals, occurance of multiple reflections within the specimen and within the detecting transducer influence the waveform of the

observed signal and obscure the nature of the source wave form. Despite

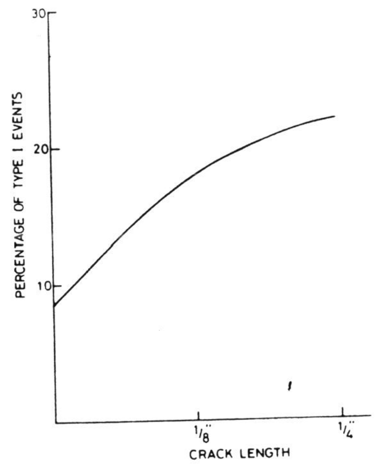

Fig. 10. Variation of percentage of a group of events with defect severity

these distortions introduced into the signals it appears reasonable to believe that some basic features which are unique to a given source should still be present in some form in the corresponding signal. If such be the case, it should be possible to extract these features from the signal and characterise the source. Consider the relationship between acoustic emission and deformation in a material with cracks as an example. Each material deforms in its own characteristic manner. A number of micro and macro processes contribute to the gross deformation and deterioration of the material under strain and cause series of emission events. Thus, the events emitted by the deformation process contain information regarding the general deformation processes as well as what happens at the cracks. It can therefore be postulated that by extraction and selection of suitable features from the event parameters it should be possible to group AE events into clusters, each cluster being related to a different source. It may also be possible that the severity of the individual cracks can be estimated. Some of the results obtained by Murthy (1982) to verify the feasibility of this approach are presented hereunder.

Experiments and Results

Experiments were conducted on sets of 3 specimens, each set consisting of a plain specimen and two specimens with different initial crack lengths. Two materials, tin and zircaloy, which have some similarity in their deformation mechanisms, were considered. The emission data was recorded on magnetic tapes and was further digitised and stored as digital data with the help of a computer. From this data a total of eighteen parameters were estimated for each event. For pattern classification, each event forms a sample point in the measurement space of n dimensions (n = 18). The next step is to extract suitable features. While each of the n parameters could be utilised as features, it is preferable to reduce the dimensionality to make classification efficient. So, features were extracted by combining some parameters both from time and frequency domains. From these, a few features were chosen for classification purposes; the choice was based on the properties of the material relevant to its fracture mechanics. 'A priori' no information was available regarding the structure of the data. So, a heuristic clustering procedure was utilised to identify the natural groups in the data. Clusters formed and grew, each possibly related to a source type operating in the material. Some typical cluster diagrams are shown in Fig. 9. A result of interest is that in each case the relative density of

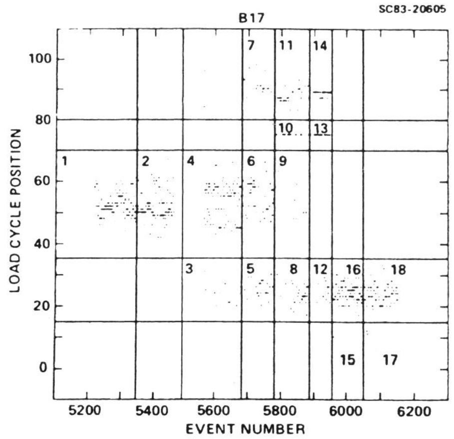

Fig. 11. Experiment B17 test history in terms of sequential AE event number and the load cycle position at which each event occurred. The events were divided into the 18 clusters shown for analysis purposes.

the principal cluster is correlated to the defect severity (Fig.10).

There appear to be two other groups actively involved in exploring these concepts. Graham (1983) indicated the approach first in 1976. Recently he has successfully classified data pertaining to different sources such as fatigue cracking, crack face rubbing and fretting (Fig. 11) Hutton et al. (1983) in a co-ordinating study, used pattern classification to discriminate acoustic emission from various other noise sources. Thus, in our view a good beginning has been made for establishing the feasibility of applying pattern recognition concepts for AE signal analysis.

CONCLUDING REMARKS

Acoustic emissioin techniques have tremendous potential for various non-

destructive applications. They are uniquely suited for certain types of application such as monitoring of flaws during proof testing. However, after three decades of research and development work in the field it has not received the extent of interest and level of acceptance it deserves. Premature entry of the technique into industry can be partly held responsible for this. The results are still mostly qualitative. There are still certain fundamental and important aspects which need systematic and scientific investigation.

Basically acoustic emission sources are divers in nature. There are macro-sources such as crack growth and micro-sources such as dislocation movements. These two broad classes of sources probably need independent experimental and analytical treatment. Recording the source stress wave form as released by the source is a formidable task and is unlikely to be achieved in respect of defects in inaccessible locations typical of practical structures. Mathematical deconvolution also presents many difficulties. However, new techniques in experiment and analysis are being continuously evolved and computers are aiding both. In this situation parallel efforts are suggested in the following directions to advance the understanding and applicatioon of the acoustic emission phenomenon.

1. Mathematically estimate the distorsions introduced by the medium, so that they may be separated out from the signal.
2. Develop deconvolution techniques that can eliminate medium and boundary distorsions from the signal; an example is the cepstral analysis that helps eliminate boundary reverberations.
3. Develop methods to identify features in the signal which are relatively insensitive to the distorsions effected by the signal path and use them with pattern recognition procedures to establish source-signal correlations.
4. Develop laboratory techniques for recording stress wave forms at the source.

It is easy to see that each of these developments will aid the others and help to simplify the signal processing problem of acoustic emission.

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