ACOUSTIC EMISSION: NATURE'S ULTRASOUND

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ABSTRACT

Acoustic emission refers to the ultrasonic signals (elastic waves) emitted by materials undergoing microscopic changes of stress state. This naturally generated ultrasound is distinctly related to the source process (dislocation motion, fracture, and some phase changes). For example, the waveform of an acoustic emission from a crack propagation increment contains information about the location, growth distance, velocity, and orientation of the crack. Acoustic emission then is of interest as a naturally occurring phenomenon for the characterization of deformation and fracture mechanisms. It is also of interest as a possible passive monitoring technique for detecting, locating, and characterizing defects in structures. The current state-of-the-art of these applications is reviewed here in the context of an emerging science base, and future trends discussed.

INTRODUCTION

Acoustic emission can be thought of as the naturally generated elastic waves emitted as a consequence of sudden localized changes of stress (or equivalently strain) in a body.Imagine a body to which tractions have, at some time in the past, been applied. They induce an internal stress field $\sigma_{ij}^0(r)$. A static stress field is established when mechanical equilibrium exists between the tractions and the internal stress distribution.

Suppose a small crack instantaneously appears within the statically stressed body. The surfaces of the crack, being free to move, are able to reduce the strain energy of the body. Eventually, the crack faces settle to an equilibrium separation determined only by the crack geometry, the elastic constants, and the initial stress field. This "settling" process actually involves the communication of elastic information between the crack and the surfaces of the body through the propagation of elastic waves. They are the mechanism for the body to change its shape and thus relax the internal stress. After sufficient time a new state of static stress (mechanical equilibrium) will be established, $\sigma_{ij}^0(r)$. The difference in the two stress states $[\sigma_{ij}^0(r) - \sigma_{ij}^0(r)]$ can be thought of as the stress change tensor of the crack and is the source of acoustic emission.
The signal that is measured in an acoustic emission experiment is related to the transient displacement of the body's surface that is occupied by the receiver. This displacement is caused by the arrival of elastic waves that have propagated from the source region either directly or after reflection/mode conversion. This signal is thus related to properties of both the source and the impulse response of the body, the later being the function that describes the elastic information exchange process between the source and a point on the body surface. This impulse response is the dynamic Green's tensor for the equivalent linear elastic body filtered by the ultrasonic attenuation/scattering mechanisms present.

To fully appreciate the scope of potential NDE applications of the acoustic emission phenomenon, it is necessary to go beyond the intuitive reasoning described above and to formulate a theory that is capable of the quantitative prediction of acoustic emission signals from prescribed sources in realistic bodies. When coupled with an experimental data base such theory provides a basis to assess the reliability of particular applications and devise valid techniques for characterizing the source; the latter being the first step in evaluating the integrity of a monitored structure from acoustic emission data.

The objective of this review is to discuss the current elastodynamic theory used for predicting acoustic emission and to use such a science base to evaluate the reliability of its application for the detection of crack growth. An "ideal" measurement approach is then discussed, and recent NBS progress in transducer development and calibration highlighted. Finally, the issue of source characterization is addressed, and the difficult nature of the problem identified. To those who have been involved with the study of the ultrasonic characterization of cracks, it will become apparent that acoustic emission is no more than nature's own ultrasound, and similar approaches to the solution of both characterization problems are independently emerging.

THEORETICAL FORMULATION

The sequence of events giving rise to an acoustic emission signal are summarized in Figure 1. A causal sequence of processes occurs following the occurrence of the source event. This event can be thought of as causing a dynamic force field to be created at the source. This is propagated as a mechanical disturbance through the structure causing a surface displacement $U(t)$ that varies with source and receiver positions. A sensor located on the body detects the surface disturbance and produces an output voltage waveform. This waveform is electronically processed and then observed as an acoustic emission signal. The goal of a theoretic formulation is the precise prediction of acoustic emission signals for modeled sources in realistic bodies.

The Transfer Function Approach

If the system described in Figure 1 is a linear one, then, when viewed in the frequency domain, information is transmitted independently, frequency by frequency, from the source to the observed signal. Thus, the observed signal can be represented as a convolution between the source function, the impulse responses of the body, the transducer, and the electronic processing, this latter here assumed a perfect delta function of unit strength (i.e., noiseless coloration) for simplicity.
Elastic Waves Propagate

Defect Produces Stress Change at \( r', t \)

\[ \partial v \]

Fig. 1. Schematic illustration of the acoustic emission process.

For sources that can be modeled as combinations of dislocations (using a dynamic Saint-Venant's principle), the general formulation of Simmons and Clough can be simplified and, for the system depicted in Figure 1, the displacement in direction \( x_i \) at \( r \) as a function of time \( t \) is:

\[
U_i(r, t) = \int_0^t G_{ij, k}(r, r', t-t') \Delta \sigma_{jk}(r', t') dt' \]

where \( G_{ij, k}(r, r', t) \) is the dynamic elastic Green's tensor representing displacement in the \( x_i \)-direction at \( r \) as a function of time due to a unit strength force impulse at \( r' \) and \( t=0 \) applied in the \( x_j \)-direction. Thus the Green's tensor is the solution to the wave equation for a unit force source. The notation \( , k' \) is used to denote partial differentiation with respect to the \( x_k \) coordinate so \( G_{ij, k'} \) is the corresponding wave equation solution for a unit dipole. \( \Delta \sigma_{jk} \) and \( \Delta \tau_{jk} \) are the stress and surface traction changes associated with the source and \( S' \) a vector normal to the source surface \( \partial v \).

The convolution Eq. (1) provides the basis, in principle, for predicting surface displacement waveforms from stress change sources if the Green's tensor is known and the stress change field prescribed. In practice, the representation requires a Green's tensor to be evaluated between every source and every receiver point, a numerically exhausting task beyond normal computing capabilities further compounded by the possibility that each stress component might have a different temporal character. To simplify the formulation note that the stress change is greatest at the defect, and that defects are often small in dimension in comparison with \( |r-r'| \).

For infinitesimal sources, the usual approach is to expand the Green's tensor as a Taylor's series about the centroid source point \( r_0 \):

\[
G_{ij, k}(r, r', t) = G_{ij, k}(r, r_0, t) + G_{ij, k, l}(r, r_0, t) \Delta r_{l} + \cdots
\]

where \( \Delta r_{l} = r_{l}' - r_{0l} \). Substituting into equation (1), gives:
\[ U_i(r, t) = \int G_{i,j}k'(r, t', t-t')\Delta o_{jk}(t') dt' \]
\[ + \int G_{i,j}k',k''(r', t', t-t')\Delta \Gamma_{jk''} dt' + \cdots \] (2)

where the quantity:
\[ \Delta o_{jk}(t) = \int o_{jk}(r', t) dr' \]

is the dipole (or seismic moment) tensor and the quadrupole tensor is
\[ \Delta \Gamma_{jk''}(t) = \int \Delta\Gamma_{jk''}(r', t) dr' \]

Simmons and Clough\(^2\) show that at practical frequencies only small error is introduced (for infinitesimal sources) by truncating the series at the dipole (first) term provided the receiver is far from the source. The source quantity \( \Delta o_{jk}(t) \) is the volume integral of the stress change, i.e., it is the average stress drop considered distributed on the point \( r_o \). It is a dipole tensor\(^5\) and is equivalent to the quantity called a seismic moment in seismology\(^6\). Simple expressions exist relating elementary dislocations to equivalent dipole tensors\(^4\).

The final step of the formulation is to include the effect of the transduction process upon the signal. To date, only "nondisturbing" transducers of finite area \( S_T \) have been considered\(^7\). By "nondisturbing" it is assumed the change in waveform caused by the presence of the transducer can be neglected because it is small compared to the waveform itself. This approximation is excellent for interferometric detection schemes\(^7\) and for those based upon noncontact capacitance transducers\(^8\). Its validity for piezoelectric transducers is, however, yet to be determined for they undoubtedly load the surface. If the transducer is considered sensitive only to displacement (and not velocity or acceleration) its point impulse response can be denoted \( T_i(r, t) \), \( r \in S_T \) and is defined as the voltage at time \( t \) produced by a \( \delta \)-function displacement at point \( r \) in the \( i \)-direction at time zero. Under this definition, the voltage at time \( t \) due to an infinitesimal source is\(^2\):
\[ V(t) = \int_{S_T} T_i(r, t-t')G_{i,j}k(r, t', r-o, t-t')\Delta o_{jk}(t') dr d\Gamma t' \] (3)

This equation, for a point receiver, has the form of a convolution between a source function, the impulse response of the body, and that of a transducer. In the frequency domain the convolutions become products and so we can write that the complex (but scalar) voltage as a function of frequency \( \omega \) is:
\[ V(\omega) = T_{jk}(\omega)\Delta o_{jk}(\omega) \] (4)

where \( T_{jk}(\omega) \) is now the combined transfer function for the body and transducer, and \( \Delta o_{jk}(\omega) \) is the dipole tensor of the source.

Three important points are evident from the formulation:

- Information in the source is indeed transferred to the detected signal frequency by frequency. If a frequency component is zero in the source, the voltage signal will also be zero at that frequency. Of course, the same is true if the transfer function of the system has a zero even when the source component of that frequency is finite for a flat noise spectrum. Best signal-to-noise will therefore be obtained over the range of frequencies where the \( T \cdot \Delta o \) product is greatest. This varies from one source to another and effects detectability. There is no method for externally artificially enhancing a source strength, and hence signal-to-noise ratio as there is with say ultrasonics; a cause for concern in structural monitoring applications of AE. Two approaches to improve sig-
nal-to-noise ratio are emerging. If the defect location is known, there is some signal:noise improvement to be gained by the use of directional (focused) transducers whose sensitivity is greatest in the direction of the defect. In a different approach Linzer and Norton have developed a cross-correlation technique to improve signal:noise ratio by in effect averaging multiply detected signals from an array of receivers that have been time shifted to line up the dominant arrival.

The acoustic emission point source for an isotropic elastic body contains up to six independent components (the $A_{ij}$'s) (and many more for anisotropic bodies). However, a voltage is only a single parameter characterization of this source: Thus characterization schemes based upon analysis of this voltage only must be fatally flawed from the outset unless "a-priori" information is available to relate the stress components and thus constrain the number of independent components to only one. Thus the waveform characterization schemes common to many commercial systems must be used with great care.

A deterministic approach to source characterization would be to perform six (or preferably more) independent measurements of $V(t)$ (say at different locations on the body) and to perform a simultaneous deconvolution to determine the source components. The complexity of this approach combined with the inverse problems extreme sensitivity to noise probably rule out this direct approach for many practical applications. Nonetheless, the unique information potentially to be gained about defect sources themselves and phase (martensitic) transformations, together with the opportunity to critically evaluate the theoretical formulations, make it an important and worthwhile endeavor.

This formulation quite clearly shows that the problem of acoustic emission source characterization is a serious one, especially for practical monitoring applications where the Green's function is unknown and must be overcome if quantitative work is to be done in the structural integrity area.

Source-Signal Relationships

In early applications of acoustic emission to steel pressure vessel testing there was little or no understanding of the origin of acoustic emission signals. It was presumed that fracture always generated detectable signals. Later tests revealed the great weakness of this when it was found that many of the steel types used in pressure-vessels fail to generate detectable acoustic emission during crack growth. This discovery contributed to a loss of confidence in the technique, and was a key factor in the initiation of the science base thrust of the 1970s. A limited understanding of the relationships between source properties and signal detectability are however now beginning now to emerge, and are contributing to an improved reliability.

Using the elastodynamic techniques described above, an acoustic emission signal for a prescribed source can now be predicted as follows:

1. First, a representation of the source is deduced in terms of a local stress, strain, or dipole distribution. These three representations are equivalent and relate the plane and direction of source displacements to the source (dipole) representation through the Lamé constants $\lambda$ and $\mu$.

   Examples of dipole representations for defect and dilatation sources are shown in Figure 2.

2. The surface displacement waveform is next evaluated for each dipole component. This reduces to the calculation of the dynamic elastic Green's tensor for the body and its scaling by the dipole component strength. An
example of one such waveform for a dipole \( D_{33} \) buried in a half-space is shown in Figure 3. In the figure, the epicenter displacement is evaluated. Off-epicenter waveforms are different.

3. Finally, the signal from a transducer is evaluated by summing the waveforms of all the source components and convolving the net waveform with the impulse response of the transducer. Examples of net waveforms are shown in Figure 4 for the same sources as in Figure 2.

For buried sources we see that at the epicenter a \( \delta \)-function longitudinal wave dominates the signal. We also note that after the transverse wave has arrived, no further change to the displacement occurs, and the body is seen to have suffered a static displacement. In bounded media, multiple reflections/mode conversions delay the attainment of this static state, but it nevertheless is ultimately attained. The signals for other locations on a half-space or in other body types are different, but they all depend upon four controlling factors.

**Source Strength.** The strength of the dipole components (units of newton meters) linearly scale the signal. Thus, a 1 Nm strength vertical dipole causes a peak displacement in Figure 3 of 0.3 \( \mu \)m while a 2 Nm dipole of similar time dependence produces an identically shaped displacement waveform but of course twice the amplitude. It can be shown that the dipole strength

\[
\begin{align*}
D_{33} &= F_3 d x_3 (\text{Nm}) \\
D_{11} &= D_{22} = \lambda b_3 d A_3 \\
D_{33} &= (\lambda + 2 \mu) b_3 d A_3 \\
F_1 &= F_2 \\
F_3 &= F_3
\end{align*}
\]

Fig. 2. Examples of a force dipole (a) and dipole combinations used to represent various defect sources.
Fig. 3. The epicenter waveform due to a $D_{33}$ dipole in a half-space showing the origin of the waveforms structure.

Fig. 4. Epicenter waveforms for defect sources in a half-space\textsuperscript{12}.

... of crack sources are proportional to the product of the crack area and crack face displacement i.e. the crack volume\textsuperscript{13}. A typical crack of 30 $\mu$m radius and a 0.3 $\mu$m crack face displacement (~1000 $\mu$m$^3$ volume) gives rise to the waveform shown in Figure 5(b) with a peak displacement of 30 x 10$^{-12}$ m, easily measurable with either capacitance or (more sensitive) piezoelectric transducers\textsuperscript{5}.

Source Orientation. The amplitude of each wavefront in the displacement waveform varies with respect to the angle between the dipole force direction and the source-receiver direction. The vertical displacement component for a dipole has a $\cos^2 \theta$ variation where $\theta$ is the angle between the force direction and the vertical axis. Thus $D_{11}$ and $D_{22}$ (for which $\theta = 90^\circ$) make zero contribution to a vertical displacement epicenter signal. By summing all dipole contributions for defect sources it can be shown that the radiation pattern for a glissile dislocation varies as $\sin^2 \theta$ and for the microcrack as: $\cos \theta^2 + \frac{\lambda}{(\lambda+2\mu)} \sin \theta^2$. 

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The radiation pattern for a buried dilatation source is omnidirectional. The strong directionality of surface dilatations (e.g., thermoelastic laser sources) arises from reflection and mode conversion at the free surface.

**Source Time Scale.** The strength of the displacement singularity for each wave arrival is proportional to the dipole strength of the source. Thus, for the longitudinal wave with a \( \delta \)-function singularity, pulse area is conserved when the dipole strength is maintained constant but the risetime of the source varied. This has the effect of reducing, linearly, the displacement amplitude as the risetime increases, Figure 5. Thus, abrupt events are more likely to exceed the background noise and be detectable with acoustic emission. Note that the static displacement is unaffected. The response of a strain gauge during traditional mechanical property measurements is the average of many of these static components. Strain gauge data, which measures the d.c. frequency component of a source, can shed no light upon the dynamics of microscopic deformation/crack growth events; only acoustic emission may do this.

**Source-Receiver Distance.** In a linear elastic body the energy contained within each wavefront is maintained as the wave spreads through the body. Since the energy is proportional to \( u^2 \) and the area of the wavefront increases with distance \( r \) from the source, it follows that the displacement in the wavefront must decrease with \( r \). For the longitudinal wave, this decrease goes as \( 1/r \) in the far field, while the signal between wave arrivals goes as \( 1/r^2 \) (because the separation of wavefronts also goes as \( 1/r \)). Thus for epicenter signals from buried sources, the far field signal is dominated by a single arrival; the direct \( L \) wave. For other configurations where surface waves exist, far field waveforms are dominated by Rayleigh wave arrivals because their amplitude only falls a \( 1/r^{3/2} \). Near field waveforms have a complicated dependence upon \( r \) but fortunately such situations are infrequently encountered in practice.

**DETECTABILITY CRITERIA**

The four factors above determine the displacement amplitude of a temporal waveform and its spectrum. Provided there is adequate sensitivity in the transduction system over the bandpass of maximum source amplitude, these four factors determine the detectability of the source. They can be used to define a detectability criterion for a source. As an example of such an approach, consider the creation of a small horizontal microcrack of cross-sectional area \( A \), crack-face displacement (separation) \( 2\delta \), and volume \( V \) under mode I loading. Then, at a distance \( h \) vertically above the source, the epicenter longitudinal pulse has an area given by

\[
S_c = \frac{V}{2\pi c_1 h}
\]

where \( c_1 \) is the longitudinal wave speed. Assuming a parabolic increase in crack area with time, the peak amplitude of the pulse (by conservation of pulse area) is:

\[
x = \frac{V}{\pi c_1 \tau h}
\]

where \( \tau \) is the growth time of the crack (the time to reach its final size). For a mode I loaded crack, the volume of the crack is related to its length, \( a \):

\[
V = \frac{4\pi a^2 \delta}{3}
\]

and
Fig. 5. Shows the effects of varying the crack source risetime (duration) and the distance between source and receiver at the epicenter of a half-space.

\[ \delta = \frac{2(1-v^2)a_o}{3c_1\theta E} \]

where \( E \) is Young's modulus, \( v \) is Poisson's ratio, and \( o \) the applied stress. Substituting for \( V \) and \( \delta \) gives:

\[ x = \frac{8a^3(1-v^2)o}{3c_1\theta E} \]

If the crack grows at constant velocity \( (a = \nabla t) \) and there exists a smallest detectable displacement \( x_{\text{min}} \) (assumed independent of frequency here), then the smallest detectable crack is

\[ a_{\text{min}} = \left[ \frac{3c_1\theta x_{\text{min}}}{8(1-v^2)o} \right]^{1/2} \]  

(5)
Substituting typical values for steel leads to the detectability criterion:

\[ \alpha a^2 v > 5 \times 10^{14} h x_{\text{min}} \]

For \( h = 100 \text{ mm} \), \( x_{\text{min}} = 10^{-13} \text{ m} \), \( \sigma = 500 \text{ MNm}^{-2} \) and a crack growth velocity of \( 1000 \text{ ms}^{-1} \) (a brittle crack) the smallest detectable crack \( a_{\text{min}} \approx 1 \mu\text{m} \). We see that compared to ultrasonics, acoustic emission is an extraordinarily sensitive technique for detecting a change in crack length provided the cracks grow rapidly. Stationary cracks (benign defects) do not emit signals unlike ultrasonics where all discontinuities may be detected, even those that are benign and do not grow inservice.

The detectability of defect sources depends upon the distance and speed of crack advances. If these are known beforehand, then the reliability of crack detection may be inferred. Unfortunately the distance and velocity of microscopic crack advances are not at all well documented, in part because of the absence of suitable measurement techniques. However, based upon some informed guesswork, the likely ranges for these quantities are plotted on a crack length vs crackspeed map for various steel fracture micromechanisms, Fig. 6. Superimposed on this map is the detectability criterion. Processes to the left of this criterion are undetectable while those to the right are increasingly detectable. If the mode of crack growth is known, its detectability can be evaluated from such a diagram.

Turning to the problem of quiet crack growth, we realize that the ductile fracture of tough low alloy steels used for pressure vessels involve three fracture processes, schematically shown in Fig. 7. First, large inclusions located ahead of a defect crack or decohere. This is followed by microvoid nucleation at carbides located between the inclusion and the pre-crack. Finally microvoid coalescence occurs enabling the crack to advance to the inclusion. For tough low alloy steel only the decohesion/fracture of inclusions is detectable, and then only for the larger inclusions in the inclusion population. If the crack is growing through previously undeformed

Detection Threshold Assumes Transducer P Wave Sensitivity of \( 10^{-13} \text{m} \), Source-Transducer Distance 0.1m, Stress 500MNm\(^{-2}\)

![Diagram](image)

Fig. 6. An acoustic emission detectability map for steel fracture micromechanisms.
material, a sequence of emissions associated with the inclusions may be detected and will qualitatively indicate a potential problem. The signal waveforms themselves, in this scenario, cannot characterize either the length or orientation of the main crack. Thus, to assess the seriousness of the defect by a fracture mechanics analysis requires an additional ultrasonic or x-ray inspection to determine the crack length. However, the location for this inspection may be quite precisely indicated by the acoustic emission raising the overall reliability of the inspection methodology compared with an ultrasonic or x-ray inspection alone.

If the uncracked ligament has been deformed (i.e. inclusions already decohered) before the installation of acoustic emission instrumentation, or if no inclusions exist, (e.g. high purity steels) the crack will advance with no signals of detectable strength emitted. Such a quiet ductile crack is a disconcerting phenomenon. Prior deformation of the uncracked ligament during test vessel preparation (fatigue precracking) probably accounts for the failure of the Culceth tests in the early 1970s[15].

These tests have received considerable attention over the past ten years and raised many questions about the reliability of AE. However, it can be argued that they may have directed attention in the wrong direction. Today, with the enhanced reliability of traditional NDE techniques and the exhaus-
tive inspection code requirements for pressure vessel inspection, the proba-
bility of a ductile failure is very small. The entire basis of engineering
design focuses upon the elimination of this threat by ensuring adequate
fracture toughness and the absence flaws beyond a critical length before a
vessel goes into service. The greater threat today is from embrittlement
either due to corrosion, hydrogen, or segregation of impurities. For steels
in an embrittled state, cleavage and intergranular mechanisms of fracture
are dominant (raising greatly the probability of AE detection). Since tra-
ditional NDE searches only for critical flaws, and does not evaluate envi-
ronmental degradation of toughness, it fails to identify such a problem.
However, acoustic emission shows promise of covering this achilles heel of
the fracture mechanics approach to design because the growth of subcritical
flaws due to an environmentally induced reduction of toughnss has a high
detection probability.

THE INVERSE PROBLEM

It is often the case that numerous acoustic emission signals are emitted
over a prolonged period by incremental growth of a flaw before catastrophc
failure occurs. In these cases, detecting and locating the flaw alone is
not usually sufficient to determine if safe operation of the structure is
still possible. Questions arise such as: Is the source a crack-like flaw? How
large is the crack? What is its orientation? What mechanism of crack
growth is occurring? Especially where in-service inspection with alterna-
tive NDE techniques is inappropriate (e.g., due to inaccessibility) it is
natural to turn to the features of the acoustic emission signal itself for
answers irrespective of how inappropriate this may sometimes be.

In Section 2, the formal approach to the inverse problem was outlined.
If the source can be represented as an infinitesimal dipole combination,
then the strengths, orientations, and temporal form of these may in prin-
ciple be determined (by deconvolution) from a suitable set of recorded wave-
forms from a particular source. It is likely that the critical assumption a
point source is an invalid one, since in tough materials cracks of several
millimeters can be tolerated without catastrophic failure and thus this
approach also may be suspect from the outset. Nevertheless, the development
of the approach and its application to carefully designed laboratory tests
seems justified because it is the only valid one available today and it may
provide a basis for qualifying less direct techniques, such as those involv-
ing pattern recognition [6], in the future. The information obtained also
promises new insights into the micromechanisms of deformation and fracture
that would enhance our ability to further control fracture by tailoring
material microstructure.

Suppose $n$ voltage waveforms are measured from the same source by
arranging $n$ transducers over a structure. Then, the inverse problem of
deducing the source may be compactly stated in the form:

$$\Delta \sigma_i = [T_i Y]^{-1} V^Y \quad Y = 1, \cdots n$$

where the Voigt notation is used for the subscripts. $\Delta \sigma_i$ are the stress
components of the source and $T_i Y$ the combined impulse response of body and
transducer. Several problems arise when this is attempted in practice.

First $T_i$ must be evaluated with considerable accuracy because of large
noise magnification during subsequent deconvolution (ill conditioning of the
inverse problem). Thus, the Green's tensor for the body and the impulse
response for the transducer must both be known with good precision. Second,
simple deconvolution methods such as FFT division and time domain inversion may give inaccurate results due to ill conditioning even with accurate data, and more sophisticated techniques better able to exploit a-priori information (and noise statistics) are needed.

Green's Tensors

Dynamic elastic Green's tensors (body impulse responses) have so far been calculated for only a few bodies: the infinite body, the infinite half-space, and just recently the infinite plate. This is a considerable weakness of the direct approach to source characterization in an engineering structure. Fortunately for some situations, modeling the structure as a half-space or a plate may not involve too much error, at least for the transient edge of a signal. More serious may be anisotropic elastic effects which are not included in present codes.

The Green's tensor components for infinite plates are more complicated than those of the half-space because of the many multiply reflected/mode converted wave arrivals that pass through the receiver point. In Fig. 8, examples of Green's tensors for force steps and force dipoles are shown.

In one case the receiver is placed directly above the source, in the second it is positioned on the same surface as the source. The plate was 2.5 cm thick and the physical properties of A533B were used for calculations. For this steel, the longitudinal wavespeed $c_1 = 3.18825 \times 10^3$ ms$^{-1}$ and the shear wavespeed $c_2 = 5.85000 \times 10^3$ ms$^{-1}$. Each wave arrival causes a displacement discontinuity.

Comparison of Figures 8(a) and 8(b) shows that for the same source (i.e., a force in direction 3) and displacement direction, the transducer would be subjected to very different displacement waveforms. For case (1) the strongest arrival is the first longitudinal wave which causes a step displacement whose amplitude is proportional to the force. For case (2), the strongest arrival is the Rayleigh arrival with a $t^{-1/2}$ singularity for a simple force source. It is obvious that spectral analysis, amplitude distribution, ringdown count, or any other of the usual methods purported to characterize a source from a single waveform would give different results for these two cases, even though the source was the same in each. While these techniques may provide sometimes useful parameters of the signal, they clearly are not valid approaches to the characterization of the source.

Transducer Calibration

Transducers, based upon changes in capacitance, are available for the almost perfect measurement of the vertical component of surface displacement ($u_3(t)$) over bandwidths up to several tens of megahertz. At NBS and elsewhere, this has been verified by comparison of theoretical and experimental waveforms for both simple vertical forces on the surface of a half-space, Figure 9, and for pulsed-laser sources on a plate, Figure 10, which are modeled as a dilatation.

Unfortunately, these transducers are too delicate and lack sufficient sensitivity for practical work. For this, piezoelectric transducers are preferred. Traditionally, these devices are normally resonant in operation, have limited bandwidth and, because of their large face plate diameters, suffer phase coherence (aperture) effects. At NBS a calibration methodology is evolving for the full calibration of piezoelectric-transducers. This methodology has enabled the development of a new piezoelectric transducer with a much enhanced response for acoustic emission purposes.
The first step in calibrating the displacement response of a transducer involves determining the relative sensitivity to displacement in the three orthogonal directions. A technique for this based upon the properties of the half-space Green's tensor has been demonstrated in principle 23.

Using a regular cartesian coordinate system centered on a point, P, at the surface, and with axis 3 defined to be an outward pointing normal, it can be shown that four of the components of the Heaviside Green's tensor, $G^H$, are zero:

$$G^H = \begin{pmatrix} G_{11}^H & 0 & G_{13}^H \\ 0 & G_{22}^H & 0 \\ G_{31}^H & 0 & G_{33}^H \end{pmatrix}$$

Thus, if a horizontal force is applied at some angle $\theta$ measured from direction 1, and a transducer is positioned somewhere along the axis 1 direction, the output from the transducer

$$V = h[G_{11}^H \cos \theta + G_{22}^H \sin \theta] + v G_{31}^H \cos \theta$$
Fig. 9. Comparison of theoretical and capacitively measured acoustic emission waveforms.

Fig. 10. Epicenter displacement waveforms from a thermoelastic laser source.
Using these methods, Proctor has developed a piezoelectric transducer of high fidelity more suited to acoustic emission studies Figure 12. By design, this transducer has a contact diameter that is small relative to the Rayleigh wavelengths in the working bandpass (typically 0.1 to 1 MHz). This eliminates coherence artifacts (aperture effects) over the face of the transducer. A brass backing is attached to the piezoelectric cone. Its purpose is to delay and dissipate waves emerging from the back of the cone so that they do not re-enter the cone and cause reverberations. The response of this transducer is shown in Figure 13; it agrees remarkably with the theory predicted signal.

Model Problems

As a first step in the application of the direct approach to the inverse problem, Hsu et al. have attempted to determine the source function for a breaking glass capillary (a method of producing vertical force steps) on a thick plate. By using a capacitance transducer that responded only to vertical displacement the tensor nature of the inverse problem was reduced to a much simpler one-dimensional problem:

\[ U_3(t) = \int_0^t G_{33}(t-T) F_3(T) dT \]

where \( F_3(t) \) is the time function of the force applied in direction \( X_3 \); the quantity of interest in the inverse problem. Using matrix inversion techniques, the result shown in Figure 14 was obtained from a single signal measured at epicenter. Similar results have been obtained from signals measured on the same side of the plate as the source, but more complicated deconvolution procedures were necessary.

It is a feature of inverse problems in acoustic emission that variable accuracy of source reconstruction is obtained. This variation in deconvolution accuracy results from the differences in matrix condition number for different waveform shapes. The condition number is a useful measure of the where \( h \) is the horizontal sensitivity and \( v \) the vertical sensitivity. For \( \theta = 90^\circ \), \( V = hG_{32} \), and for \( \theta = 0^\circ \), \( V = hG_{11} + vG_{31} \). Furthermore, since only horizontal displacements occur at \( \theta = 90^\circ \), rotation of the transducer with

Fig. 12. The high fidelity piezoelectric transducer developed by Proctor.
fixed $\theta = 90^\circ$ provides a means of resolving the horizontal sensitivity into components along axes 1 and 2. A multichannel deconvolution extension of this approach potentially provides a means of ultimately determining the full vector impulse response.

Transducers such as those utilizing longitudinal poling of the PZT element are found to have almost no horizontal sensitivity. The calibration procedure for transducers responding to only vertical displacements then involves deconvolving the response of the unknown transducer against the response of a standard reference (capacitance) device to the same displacement waveform. The displacement waveforms used so far have been the surface-surface signal of a half-space (Figure 11(a)) or the epicenter signal of a plate due to force steps. Identical transducer transfer functions have been obtained by both methods.

![Waveform graphs](image1)

![Waveform graphs](image2)

![Waveform graphs](image3)

![Waveform graphs](image4)

Fig. 11. Amplitude and phase calibrations for vertical displacement sensitivity of a transducer.
Fig. 13. Comparison of theoretical and measured acoustic emission $U_3$ displacement waveforms using Proctor's transducer.

sensitivity of the inverse procedure to noise (errors) in the signal or the Green's tensor. It has been found that signals with very large amplitude first arrivals have relatively good conditioning while those for which the amplitude gradually increases are often poorly conditioned and prone to introduce very large errors during deconvolution. Simmons has examined in detail the limitations of traditional approaches to deconvolution for acoustic emission problems, and has devised new algorithms that allow source reconstructions from only those signal components (eigenvalues) with acceptable signal-to-noise.

This class of inverse problem has received much attention in other fields such as seismology. Stump for example has used a half-space Green's tensor to predict (forward model) synthetic signals at various locations due to a combination of dipoles representing earthquake sources. He then took groups of these signals, artificially added noise, and attempted to determine the magnitude of the dipole components. His results are summarized in Table 1 for various trial groupings. Stumps work demonstrated the importance of working with data sets which have low condition numbers, and with signals with high signal-to-noise.

Michaels and Pao using an infinite plate Green's tensor generated synthetic data from a shear crack and then obtained dipole tensor component with ~ 5% accuracy though they added no noise. The assumed tensor was:

$$
D = \begin{bmatrix}
0.0000 & 0.0000 & 1.0000 \\
0.0000 & 0.0000 & 0.0000 \\
1.0000 & 0.0000 & 0.0000
\end{bmatrix}
$$

Using iterative deconvolution methods the reconstructed tensor was:

$$
D = \begin{bmatrix}
0.0037 & 0.0002 & 0.9576 \\
0.0002 & 0.0010 & 0.0000 \\
0.9589 & 0.0000 & 0.0015
\end{bmatrix}
$$
Fig. 14. The source function of a point force deduced from an epicenter measurement.

Table 1

Estimates of the Dipole Tensor Components and Their Standard Deviations

<table>
<thead>
<tr>
<th>Source</th>
<th>D_{11}</th>
<th>D_{12}</th>
<th>D_{13}</th>
<th>D_{22}</th>
<th>D_{23}</th>
<th>D_{33}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>0.0</td>
<td>0.612</td>
<td>-0.584</td>
<td>0.676</td>
<td>0.389</td>
<td>0.198</td>
</tr>
<tr>
<td>Trial 1</td>
<td>0.002</td>
<td>±0.099</td>
<td>±0.088</td>
<td>±0.194</td>
<td>±0.336</td>
<td>±0.086</td>
</tr>
<tr>
<td></td>
<td>0.004</td>
<td>±0.030</td>
<td>±0.014</td>
<td>±0.042</td>
<td>±0.052</td>
<td>±0.080</td>
</tr>
<tr>
<td>Trial 2</td>
<td>-0.133</td>
<td>±0.198</td>
<td>±0.113</td>
<td>±0.348</td>
<td>±0.320</td>
<td>±0.836</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.002</td>
<td>±0.405</td>
<td>±0.237</td>
<td>±0.739</td>
<td>±0.679</td>
<td>±1.73</td>
</tr>
</tbody>
</table>

The time function used to generate the synthetic data were also recovered with a similar accuracy.
The extension of this approach to naturally occurring sources is a difficult problem. Using a model of a horizontal mode I loaded microcrack, Wadley and Scruby [14] were able to relate dipole components to one another and so to reduce the inverse problem to that of the determination of a single parameter, the crack volume (crack time dependence) from a single (epicenter) signal, Figure 15. These signals were capacitively measured over a frequency range of 80 kHz to 25 MHz. Deconvolution by a matrix inversion was relatively well conditioned because the signals had highest amplitudes at their leading edge. The deduced crack volume time dependences showed a rapid increase to a maximum value. This value should, in principle, have stayed constant indefinitely. The gradual decay arose because no account was made for the 80 kHz high pass filtering. Fortunately, because the cracks grew very rapidly, this had a negligible effect on the data, and when the crack lengths were deduced from the maximum crack volumes excellent agreement with independent metallographic evidence was obtained.

The independent deduction of all the components of the dipole tensor from multichannel data is being pursued at several laboratories including Harwell, Cornell, and NBS. While the fruits of this labor promise a unique insight into the micromechanisms of deformation and fracture, the application of the approach to NDE of crack growth in engineering structures is less certain.

Fig. 15. Epicenter acoustic emission signals from microfractures and their corresponding source volume time dependence.
One problem that has arisen is that a structure usually fails by the incremental growth of a large flaw and not by isolated microfracture. It was thought that if each increment of growth were acoustically detected and analyzed by the emerging techniques described above, a continuous record of the size and orientation of the flaw could be obtained by simply adding sources assuming each an isolated microcrack. However, Scruby and Wadley discovered that the deduced crack volumes from the formation of microcracks at the tip of a macrocrack were as much as ten times larger than those anticipated from metallographic analysis. This at first puzzling result was eventually suggested to be caused by the generation of additional emission from the pre-existing crack as its volume increased in response to microcrack extension of its tip.

Achenbach et al. using a 2-d model have since theoretically investigated this effect in detail and have confirmed the possibility of very large signal amplifications by the pre-crack. Furthermore, they show the effective amplification depends on the precrack length ($l$), the microcrack length ($l_m$), and the distance ahead of the precrack where initiation takes place ($e$), Table 2.

Table 2

<table>
<thead>
<tr>
<th>$\frac{l_m}{l}$</th>
<th>$e$</th>
<th>$\frac{v^m}{v_o^m}$</th>
<th>$\frac{(V-V_0)}{v_o^m}$</th>
<th>$\frac{V^1-(V+V^m)}{v_o^m}$</th>
<th>$\frac{V^1-(V+V^m)}{v_o^m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>1.000</td>
<td>1.035</td>
<td>0.03485</td>
<td>6.697</td>
<td>6.260</td>
</tr>
<tr>
<td></td>
<td>0.100</td>
<td>1.209</td>
<td>0.2095</td>
<td>1.647</td>
<td>1.161</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>1.414</td>
<td>0.4147</td>
<td>0.8572</td>
<td>0.4687</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>1.553</td>
<td>0.5550</td>
<td>0.5786</td>
<td>0.2745</td>
</tr>
<tr>
<td>0.10</td>
<td>1.000</td>
<td>1.055</td>
<td>0.05855</td>
<td>339.8</td>
<td>305.2</td>
</tr>
<tr>
<td></td>
<td>0.100</td>
<td>1.585</td>
<td>0.9194</td>
<td>41.48</td>
<td>16.56</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>2.578</td>
<td>3.815</td>
<td>16.80</td>
<td>2.628</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>3.355</td>
<td>6.814</td>
<td>11.03</td>
<td>1.085</td>
</tr>
<tr>
<td>0.01</td>
<td>1.000</td>
<td>1.059</td>
<td>0.06265</td>
<td>3.392x10^4</td>
<td>3.024x10^4</td>
</tr>
<tr>
<td></td>
<td>0.100</td>
<td>1.775</td>
<td>1.377</td>
<td>2.315x10^3</td>
<td>7.345x10^2</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>4.243</td>
<td>13.72</td>
<td>3.858x10^2</td>
<td>21.48</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>7.669</td>
<td>49.02</td>
<td>1.644x10^2</td>
<td>2.900</td>
</tr>
<tr>
<td>0.001</td>
<td>1.000</td>
<td>1.060</td>
<td>0.06309</td>
<td>3.001x10^6</td>
<td>2.672x10^6</td>
</tr>
<tr>
<td></td>
<td>0.100</td>
<td>1.804</td>
<td>1.452</td>
<td>2.120x10^5</td>
<td>6.511x10^4</td>
</tr>
<tr>
<td></td>
<td>0.010</td>
<td>4.952</td>
<td>19.60</td>
<td>2.207x10^4</td>
<td>8.989x10^2</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>13.16</td>
<td>159.7</td>
<td>3.836x10^3</td>
<td>22.19</td>
</tr>
</tbody>
</table>

Clearly $l$, $l_m$, and $e$ determine the amplification factor and since these quantities are unavailable, a considerable ambiguity arises in determining the actual distance of crack extension that occurred. Work by Scruby et al.
has indicated that the orientation of the crack may still be accessible
and the possibility also exists that very precise three-dimensional location
of each source location might overcome the problem of determining the crack
size. A more rigorous full 3-d model may also shed light upon other charac-
terization methods.

SUMMARY

Acoustic emission may be thought of as arising from the discontinuity in
 crack face displacement during dynamic crack extension in a static stress
field. Ultrasonic scattering from a crack occurs by essentially the same
mechanism although in this case the crack length is static and the imposed
stress dynamic. There is thus a great similarity between the formulations
for the scattering of ultrasound by a crack and those for its natural gen-
eration by crack growth. For those who have been concerned with ultra-
sonics, acoustic emission can be thought of as nature's ultrasound.

Over the last ten years a considerable improvement in the fundamental
understanding of this naturally occurring phenomenon has emerged. It's
reliability as a NDE technique is beginning to be quantified and science
based approaches to source characterization pursued. It appears that the
techniques for quantitative characterization of a flaws size and orientation
are still not perfected, and this continues to limit utilization of AE for
structural integrity evaluation because the quantities necessary for a frac-
ture mechanics analysis are difficult to evaluate from the recorded signals.

However, the situation would seem to bear further scrutiny. After all,
the very fact that an acoustic emission was emitted by a flaw is irrefutable
evidence that crack extension occurred, i.e., that the stress at the tip
exceeded the materials local fracture toughness. The remaining question is
not will the crack grow? Rather it is how long will it take for the struc-
ture to fail? This may be accessible through the rate at which emission
occurs and more detailed experimentally/theoretical study of flaw extension.

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