Quantitative acoustic emission and failure mechanics of composite materials

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This Paper considers quantitative acoustic emission (AE) techniques with real and simulated sources as powerful tools for investigating failure processes in composite materials. Using a simulated source acting as a point source and one or more point receivers whose characteristics are known, one has the necessary components of a materials and structure testing system. Examples are shown in which a composite material's attenuation and wavespeeds can be determined as a function of frequency and propagation direction. It is demonstrated that this testing procedure permits the ultrasonic characterization of ultra-attenuative and irregular shaped, high performance composite materials. The principles of quantitative AE source characterization procedures are also reviewed and applications are demonstrated in which the time characteristics of several simple sources are recovered.

Keywords: acoustic emission; ultrasonic testing; failure mechanics; composite materials

Acoustic emissions or AE signals are the transient elastic waves accompanying the sudden, localized change of stress or strain in a material. The focus of much past research dealing with AE has been towards the development of appropriate measurement systems and signal processing methods. The aim of this work has been the development of procedures for recovering from the detected AE signals, quantitative information about the source of the emission, that is, its location, its type and its time history. Unfortunately, the characteristics of the source of emission are often obscured by the geometric wave dispersion effects accompanying the propagation of a broad-band transient signal through a structure acting as a wave-guide and by the transduction characteristics of the sensor used to detect the AE signals. Recognizing this, the recent research dealing with quantitative AE methods has focussed on the development of broad-band displacement or velocity sensors and appropriate signal processing procedures by which the detected signals can be processed to remove the wave dispersion effects from the signals so that the characteristics of the source can be unambiguously recovered.

Applications of quantitative AE to investigate details of the fracture processes in various brittle and ductile materials have been reported[1–4] but studies of the failure mechanisms in composite materials have up to now used only conventional AE measurement methods (cf. Reference 5). With these, some success has been reported for delineating between fibre- and matrix dominated failure mechanisms[6]. However, these results are empirical and thus are dependent on the geometry of the specimen and the operating characteristics of the transducer used to detect the signals.

The allure of AE measurements for monitoring the integrity of the structure is that active potential failure sites emit. As pointed out by Henneke[7], in contrast to metals, the early damage in composites is distributed over an extended region of the material and thus techniques for globally monitoring or inspecting a material are required. Implementation of quantitative AE source characterization techniques using current technology is impractical and it may not be necessary. Since the development of damage in a composite is complicated and no failure criterion has as yet been established, all damage detected in a composite with AE techniques may, in fact, not be detrimental to the serviceability of the composite structure. What is needed is a measure of the total damage state in a composite specimen and monitoring of its growth. For this, it is proposed to consider the use of an active ultrasonic testing system which is based on a measurement system similar to that used for quantitative AE measurements. But in this system, an input simulated source, whose characteristics are known, is used as the excitation source. As before, the signals are detected with a well-characterized sensor. The characteristics of the propagating medium can, in principle, be recovered from analysis of the detected signal, provided that a theoretical basis exists by which the measured signals can be identified, processed and interpreted. This forms the basis of a powerful, new ultrasonic materials testing technique, and is referred to as the point-source/point-receiver testing method[8].

The essential features pertaining to the propagation of transient signals from a source to a receiver which are relevant to both the point-source/point-receiver (PS/PR) testing method and the quantitative AE source characterization procedure are outlined in the following section. The PS/PR testing system and its applications to characterize several composite materials are discussed in the section after that. In the fourth section is a brief summary of the quantitative AE source characterization technique and its first application to characterize a simple source in

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a composite material. This section also considers some of the problems which still await solution in order to characterize the failure mechanisms in composite materials. In the last section, some concluding remarks are made.

Wave propagation, system characteristics and signal analysis

Key to both the PS/PR testing method and the quantitative AE source characterization procedure is a theoretical basis by which the measured signals can be identified, processed and interpreted, and a receiver whose temporal and spatial transfer characteristics are known or can be determined in an experiment. In the PS/PR testing method, the input source is known and the characteristics of the propagating medium are recovered. This is reversed in the quantitative source characterization procedure. In both cases the analysis is restricted to point sources and point receivers. The term 'point' refers ideally to an excitation and a detection region whose lateral dimension is much smaller than the effective wavelength of the highest frequency component of interest in the measured signal. This wavelength will also be much shorter than any dominant dimension of the specimen.

Wave propagation

The analysis of transient elastic waves between a point source and a point receiver in a bounded structure is discussed in several papers (cf. Reference 9). The following is a summary of the results essential for the analysis to follow.

The displacement signals, u_k, detected at a receiver location, $\underset{\sim}{x}$, in a structure from an arbitrary point source, $f(\underset{\sim}{x}',t)$, located at $\underset{\sim}{x}'$ having source volume, V, can be written as [10]

$$u_k(\underset{\sim}{x}, t) = \int_V f_j(\underset{\sim}{x}', t) * G_{jk}(\underset{\sim}{x}/\underset{\sim}{x}', t)\,dV' \qquad (1)$$

where the term G_{jk} represents the dynamic Green's function of the structure and the asterisk denotes a time-domain convolution. Insight into this formulation can be obtained if one makes a Taylor series expansion of the Green's function about any reference point, say the point $\underset{\sim}{x}^{0'}$, to give [10,11]

$$u_k(\underset{\sim}{x}, t) = \int_V f_j(\underset{\sim}{x}', t) * G_{jk}(\underset{\sim}{x}/\underset{\sim}{x}^{0'}, t)\,dV' + \int_V (x_i' - x_i^{0'}) f_j(\underset{\sim}{x}', t) * G_{jk,i}(\underset{\sim}{x}/\underset{\sim}{x}^{0'}, t)\,dV' + \ldots \qquad (2)$$

The first term in this expansion represents the monopole source contribution to the signal, which can be rewritten compactly as

$$u_k^{(m)}(\underset{\sim}{x}, t) = F_j(t) * G_{jk}(\underset{\sim}{x}/\underset{\sim}{x}^{0'}, t) \qquad (3)$$

where $F_j(t) = \int_V f_j(\underset{\sim}{x}', t)\,dV'$ is the total force acting throughout the source volume. This is F_z for a force normal to the surface of the specimen. For a point source, the force is only a function of time. For such excitations, the output signal is directly related to the time function of the source with just one kernel appearing in the convolution integral. For the displacements normal to the specimen surface, the explicit form of this integral is

$$u_z(\underset{\sim}{x}, t) = \int_0^t F_z(t-\tau)\, G_{zz}(\underset{\sim}{x}/\underset{\sim}{x}^{0'}, \tau)\,d\tau \qquad (4)$$

The second term in Equation (2) represents the dipole contribution to the signal which can be rewritten compactly as

$$u_k^{(d)}(\underset{\sim}{x}, t) = M_{ij}(t) * G_{jk,i}(\underset{\sim}{x}/\underset{\sim}{x}^{0'}, t) \qquad (5)$$

where $M_{ij}(t) = \int_V (x_i' - x_i^{0'}) f_j(\underset{\sim}{x}', t)\,dV'$ represents the moment tensor of the source and $G_{jk,i}(\underset{\sim}{x}/\underset{\sim}{x}^{0'}, t)$ is the spatial derivative of the Green's function. This contribution can be the result of any combination of double forces which model the source. Under certain operating conditions, thermoelastically generated sources can be made to resemble such dipolar sources in which only one component of the moment tensor is required to give an adequate description of the source, e.g. $M_{xx}(t)$ (Reference 12). The formation of a crack in a brittle solid such as glass can be modelled similarly[13]. The magnitude of the component of the moment tensor is called the dipole source strength. The convolution integral for this case relating the output signal to the excitation time function is equivalent to that given by Equation (4). For a normal displacement signal, the appropriate Green's function is $G_{xz,x}$.

A solution to the forward problem can readily be computed for a specimen of flat plate-like geometry. That is, given the thickness of the specimen, the material's longitudinal to shear wavespeed ratio and the source/receiver separation, the dynamic Green's functions appearing in Equations (3) and (5) can be computed using one of the available algorithms[9,14]. If the measurement system includes a point receiving transducer whose output voltage signal is related to the input displacement signal by the sensor's transfer function, $R_k(t)$, then the results given by Equations (3) and (5) must be further convolved with this transfer function to obtain the output voltage signals of the system corresponding to each of the excitations.

An important example is shown in *Figure 1a*. This is the normal velocity signal computed for a vertical force source acting on a plate specimen and detected at the epicentre point of the back surface of the plate directly under the source point. This example was obtained for a 7090 Al/SiC composite specimen, 1.884 cm thick, whose longitudinal and shear wavespeeds were 0.708 cm μs^{-1} and 0.368 cm μs^{-1}, respectively, with zero wave attenuation. Thus, this result represents the behaviour expected for an ideal, isotropic material. An analogous case of a horizontal dipolar, crack-like source is shown in *Figure 1b*. The signals corresponding to other source and receiver configurations can be computed similarly. It is seen in the time records that the arrivals of both the P- and S-waves can be easily identified. Hence, in the first example, even though the force was applied normal to the specimen surface, both longitudinal and shear wave modes are excited. The identification of the wave arrivals is possible, provided that the source/receiver separation is not greater than $\approx 10h$–$15h$, where h is the thickness of the plate. It is also clear from the waveforms shown in the figures that while the wave arrivals are readily identifiable, the signals characteristically possess a 'tail', i.e. each wave is geometrically dispersed as it propagates through the specimen. This dispersion is unrelated to the

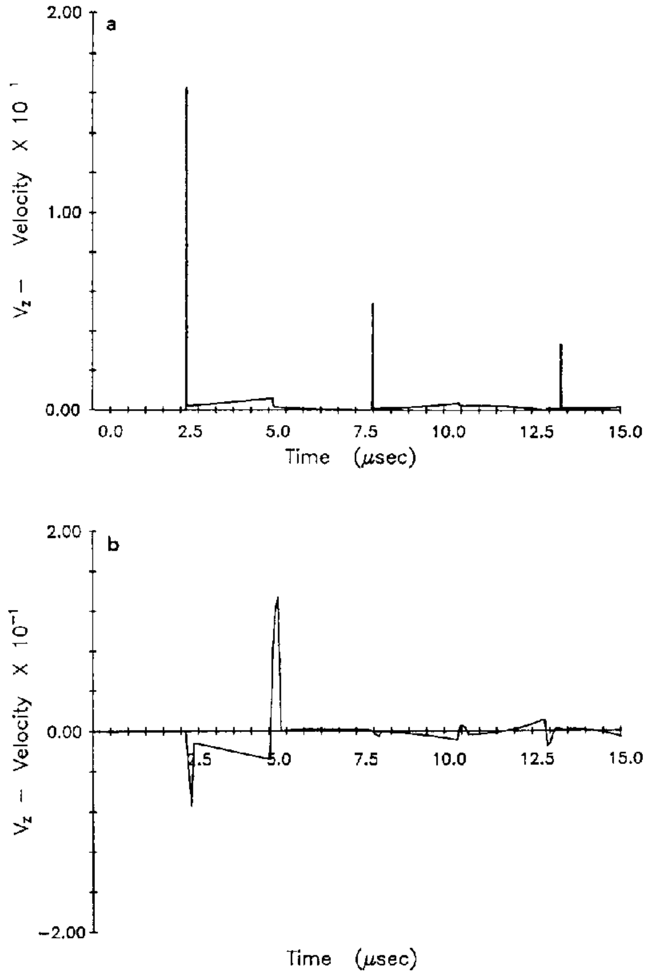

Figure 1 Ideal epicentral velocity signal from a step excitation source. $c_p = 0.708$ cm μs^{-1}; $c_s = 0.368$ cm μs^{-1}; no attenuation. (a) Normal force; (b) horizontal dipole source

properties of the medium and its presence in a signal must be removed if the correct material-related frequency characteristics of a measured signal are to be determined.

Additional insight is gained by considering the evaluation of the displacement signals in the frequency domain. An explicit formulation of the epicentral situation was given by Knopoff[15] and it has recently been extended for the case of a viscoelastic medium by Weaver[16]. It is found that the Fourier phase function of the P-wave arrival of the velocity signal is given by

$$\phi(\omega) = kL + \frac{A}{kL} \quad (6)$$

where $k(\omega)$ corresponds to the dispersion relation, L is the source/receiver separation and A is a correction factor specified by

$$A = 2 - 8\left(\frac{c_s}{c_p}\right)^2 + 16\left(\frac{c_s}{c_p}\right)^3 \quad (7)$$

For materials whose Poisson ratio is $\approx 1/3$, the value of A is ≈ 2. The first term of Equation (6) is identical to that derived for plane waves by Sachse and Pao[17]. The phase functions of other source types are expected to exhibit a similar form and the analysis of the first shear wave displacement arrival can be made similarly[18].

Point-source/point-receiver testing method

Conventional measurements in the ultrasonic testing of materials, when used as the basis of a materials characterization procedure, typically rely on one or two piezoelectric transducers operating as source and receiver, attached to a specimen to launch and detect ultrasonic waves in the object to be characterized. In the procedure, measurements of the signal arrival time (or velocity) and amplitude (or attenuation), possibly as a function of frequency, are then correlated with the composition and the macro- and microstructure of the material, which may include voids, flaws and inclusions distributed through a region of the material. It is known that the propagation of acoustic signals from a source to a receiver point is influenced not only by the geometry of the specimen, but also by the material's macrostructure, specified in terms of its size, shape and for composite materials, the ply configuration. In addition, the wave propagation is strongly affected by the specimen material's microstructure, including its anisotropy, heterogeneity, elastic, inelastic and viscous properties, and its wave attenuation characteristics. Absolute ultrasonic measurements with plane waves present serious measuremement challenges, many of which are overcome with the PS/PR method. Although the geometric characteristics of the wave propagation may be more complex than those for the case in which plane waves are used, the existence of a theory for PS/PR signals permits these effects can be accounted for in the detected signals to recover the material-related wavespeeds and attenuation properties of the propagating medium. A limitation of the existing method is that the results will be applicable to materials whose heterogeneity is on a scale much smaller than the wavelengths of the probing ultrasonic pulse.

Measurement system

A PS/PR testing system, consisting of a well-characterized point source and point receiver, is analogous to that used in exploration geophysics. An actual PS/PR measurement system is shown schematically in *Figure 2*. It resembles a typical system used to make quantitative AE studies. The new feature is the presence of the input source element which may or may not have a sensor attached to it to generate a synchronization pulse with the excitation signal. In the PS/PR method, the excitation and detection regions are small, hence the extent of the required specimen surface preparation is minimal and, furthermore, specimens of arbitrary geometry can be easily tested, in particular those which are neither planar nor flat.

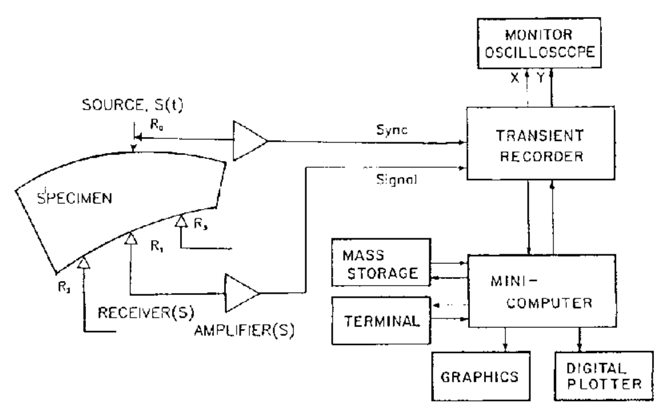

Figure 2 Schematic of the system for point-source/point-receiver ultrasonic measurements

The ideal point source and point receiver with perfect impulse response can only be approximated with real sources and receivers. However, to achieve acceptable signal-to-noise ratios, it is possible to use transducers with a small but finite aperture, provided that the generated and detected acoustic fields in the specimen are uniform and resemble those expected from a point source and point receiver. Equally important is that the transduction characteristics of the source and receiver are known. This includes both the primary and secondary quantities being generated and detected. The temporal transfer characteristics of both source and receiver must be known a priori or determined in a calibration experiment, and they must possess an appropriate frequency response relative to the material property being investigated. There are, however, many measurement situations in materials in which the viscous dispersion and wave attenuation are sufficiently low so that only a measurement of the first arrival of a signal is required and a complete characterization of the sensor is not needed. Obviously, in all cases the source and the receiver must possess an adequate signal-to-noise ratio to permit signal identification and subsequent processing operations to be performed reliably. A discussion of various point sources and receivers and their operating characteristics is found in Reference 8.

Signal identification and waveform analysis

According to the convolution equations, Equations (3) and (4), for a source of known type and time function and for a specified source–receiver separation, only the time-dependent input source function and output displacement signals are required to be able to invert these equations to recover the dynamic Green's function corresponding to the particular testing geometry and specimen material. For a source corresponding to a force normal to the specimen surface, one obtains

$$G_{zz}(t) = u_z * [F_z(t)]^{-1} \tag{8}$$

where the z-direction is normal to the surface of the specimen. If the source function is a perfect step, the deconvolution can be made with the successive substitution algorithm[19]. For cases in which a conventional piezoelectric transducer is used to detect the signals whose transfer function is given by $R_z(t)$, Equation (8) becomes

$$G_{zz}(t) = V(t) * [F_z(t) * R_z(t)]^{-1} \tag{9}$$

where $V(t)$ is the transducer output signal. Solutions for this case and that of a finite step excitation have been obtained by a least-squares deconvolution algorithm[20]. Equations (8) and (9) can also be written in the frequency-domain; however, it is often advantageous to perform the deconvolution in the time-domain since no windowing is needed and the processing can be halted after any particular ray arrival.

If the measurement system consists of a source whose excitation is an impulse or a Heaviside step and the receiver is a high fidelity displacement or velocity sensor, then, according to Equations (3) and (4), the detected signals will correspond directly to the dynamic Green's function of the specimen, thus requiring no further signal processing. This observation emphasizes the significant advantage realized when a source and a receiver possessing ideal characteristics are used. An example is shown in *Figure 3*. This corresponds to the normal velocity signal in

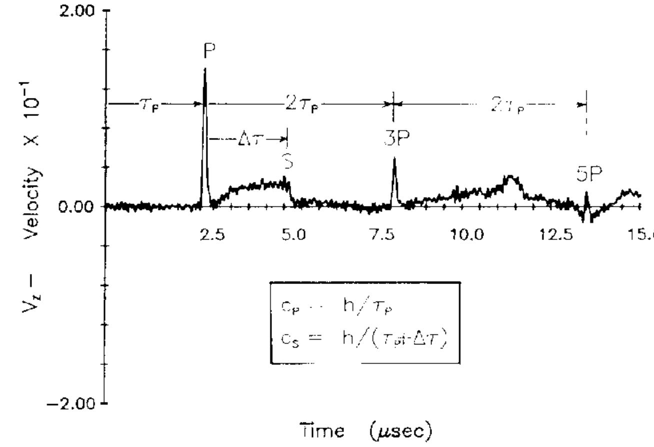

Figure 3 Measured epicentral normal velocity signal from a normal force step source with 7090 Al/20% SiC whiskers. The wave arrivals are indicated

a 7090 Al/SiC metal matrix composite resulting from the fracture of a capillary which is a step function in time.

Once the Green's function has been determined, the ultrasonic wavespeeds can be recovered by identifying the arrival times of the P- and S-wave signals. If the instant of excitation is known, only the first arrivals of these signals need to be determined. When this is not known, the arrival times of additional signals propagating through the specimen are needed. The 3P and 5P signals corresponding to the longitudinal wave propagating three and five times, respectively, through the specimen are also identified in the actual waveform shown in *Figure 3*. The longitudinal and shear wavespeeds of the material can be recovered from the measured arrival times according to the formulae shown in the figure. Many measurements in which only the determination of the arrivals of the P-wave and S-wave signals is required are possible with conventional piezoelectric point sensors, which are principally sensitive to the wave motions normal to the surface of the specimen. In these cases, a direct evaluation of the material's longitudinal and shear wavespeeds can be evaluated in a simple test.

The frequency-dependence of a particular wave arrival is determined by properly windowing that portion of the waveform containing the signal amplitude and transforming this amplitude to obtain the Fourier phase function of the signal. Once this function is found, it is substituted into Equation (6) which, in turn, is solved numerically to obtain a solution for the dispersion relation of the wave in the material. It is noted that a valid solution is only obtained for frequencies $f > c/[\pi L(2)^{1/2}]$ but this suffices for most applications. Once the dispersion relation has been found, the phase and group velocities, c and v, for the material can be evaluated as a function of frequency from the following: $c(\omega) = \omega/k$ and $v(\omega) = \partial\omega/\partial k$.

Since the computed, ideal waveform corresponds to the propagation in a non-attenuative material, the attenuation of either the P- or the S-wave amplitude in a real material can be determined by making a comparison of the measured and computed waveform amplitudes of the corresponding wave arrivals. It follows that the frequency dependence of the attenuation can be determined by processing the windowed signal amplitude in the frequency domain to form its magnitude spectrum, $V(f)$, and evaluating

$$\alpha = \frac{20}{L} \log_{10}\left[\frac{V(f)}{V_{\mathrm{ref}}(f)}\right] \; [\mathrm{db/length}] \tag{10}$$

where $V_{ref}(f)$ refers to the magnitude spectrum of the wave velocity amplitude of the non-attenuated, ideal signal.

Applications

The normal velocity signal at epicentre corresponding to a step excitation on a specimen of a 7090 Al/SiC metal-matrix composite was shown previously in *Figure 3*. Measurement of the arrivals of the P- and S-wave amplitudes leads at once to the recovery of the longitudinal and shear wavespeed values, $c_p = 0.700$ cm μs^{-1}; $c_s = 0.380$ cmμs^{-1}. These are within 3% of the values determined by a conventional ultrasonic measurement.

Since these measurements are made in a low attenuative material and only the time of arrival of a particular wave is sought, a characterization of the receiving sensor is not required. It suffices that the successive wave arrivals are clearly identifiable in the waveform to obtain results similar to those obtained with the capacitive displacement sensor. However, with the piezoelectric sensor, the measurement is straightforward since no special surface preparation of the specimen or critical transducer alignment with the specimen surface are required. It is also possible to test highly attenuative materials. The result obtained in a chopped-fibre/epoxy, wedge-shaped specimen having a non-uniform layer of another material on one side is shown in *Figure 4*. The detection region of the specimen was left unprepared and hence the piezoelectric transducer with its excess couplant exhibited considerable ringing. However, even for this unfavourable testing situation, the first P-wave arrival is easily detected and can be used to determine an effective longitudinal wavespeed value for this material.

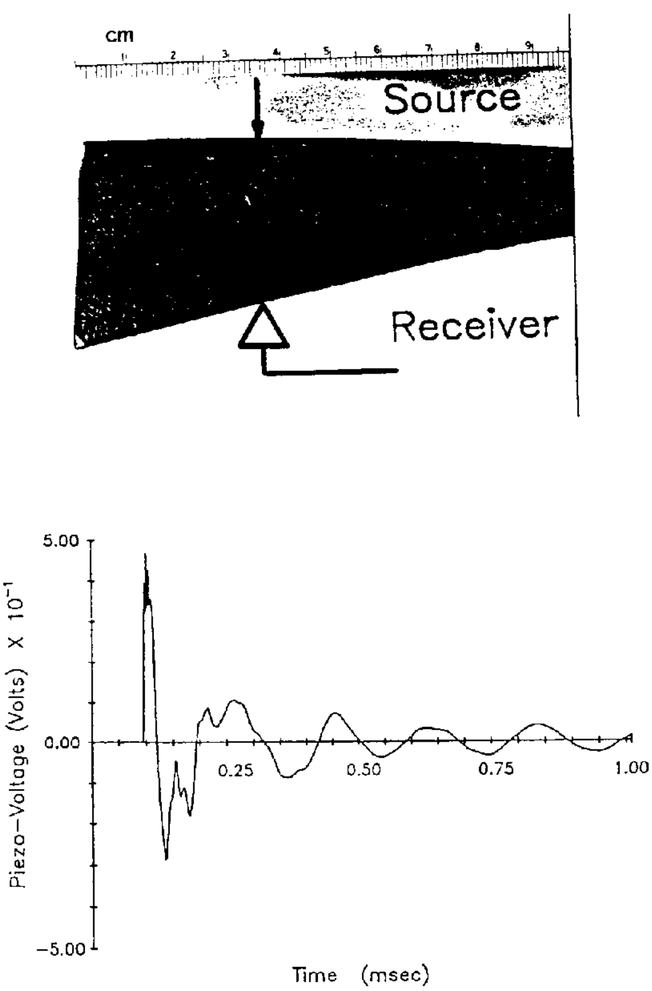

Figure 4 Epicentral waveform from a normal force step source detected with a piezoelectric transducer in a chopped-fibre/epoxy composite wedge

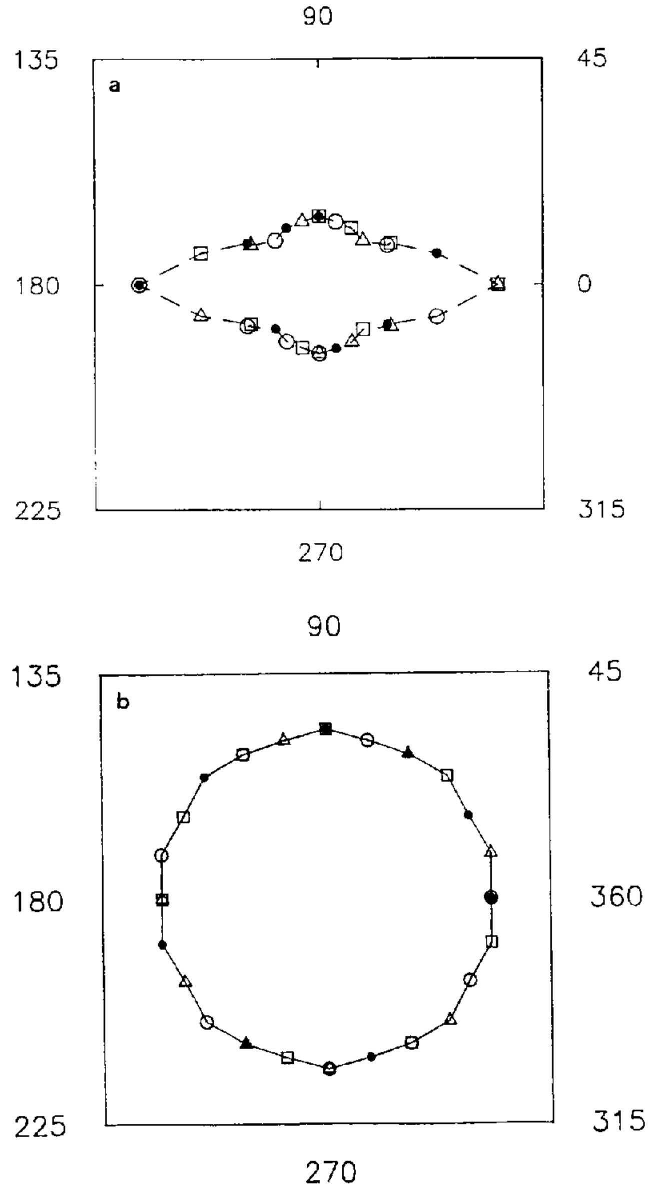

Figure 5 Wave velocity surfaces: (a) unidirectional 32-ply graphite/epoxy; (b) metal-matrix composite

To determine the orientation dependence of wavespeeds in a sample, an array of transducers is required. In the simplest configuration, the receiving elements are located equidistant about the source point. The sensors may be on either side of the sample and the first P- or S-wave arrivals are identified in the detected signals. An example of the results of waveform measurements made in an elastically anisotropic specimen of graphite-epoxy composed of 32 plies whose lay-up was unidirectional is given in *Figure 5a*. The wavespeeds of the P-wave in various directions of the material are shown. To obtain this result, the fracture of a capillary was used as a monopolar source with eight point piezoelectric sensors placed at various angles around it. The time of the first arrival was measured in each of the detected waveforms and the wavespeed was computed by dividing the arrival time by the source-receiver separation.

The graphite-epoxy specimen possesses a four-fold symmetry, which can be determined from inspection of the detected signals or from knowledge of the material's fabrication. Recognizing this symmetry, it is possible to generate additional pseudo-points by projecting each of the measured data values in directions oriented at 180, 90 and -90° to those measured. As the results demonstrate, the 24 additional points all lie on the same wavespeed surface. This finding verifies the consistency of the measurement results. The case of a specimen of 6061 Al/SiC metal-matrix composite, which is nearly isotropic, is shown in *Figure 5b*. As expected, the longitudinal wavespeed surface closely approximates a circle. The wavespeed is 0.693 cm μs^{-1}, which is in good agreement with the results obtained by conventional ultrasonic testing methods.

Application of the Fourier phase analysis method for determining the dispersion relation and the frequency-dependent phase velocity of the longitudinal wave in the 6061 Al/SiC metal-matrix composite specimen is shown next. The signal resulting from a capillary fracture source which was detected at epicentre with a piezoelectric point transducer whose response approximated a velocity sensor, is shown in *Figure 6a*. Also indicated is the windowed, first arrival of the P-wave signal. From the magnitude spectrum it is found that the signal contains little energy above 8 MHz, reflecting the frequency response of the transducer and amplifier used to detect the

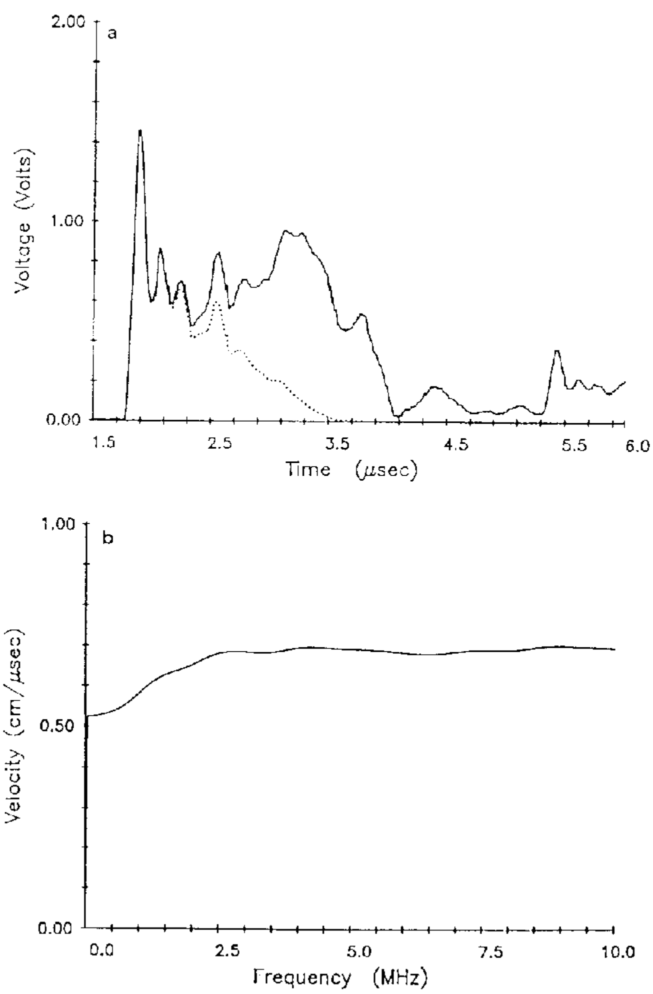

Figure 6 Wave dispersion measurement in 6061 Al/SiC metal-matrix composite. (a) Piezoelectric transducer signal (velocity): ——, original signal; . . . . , windowed signal. (b) Derived phase velocity

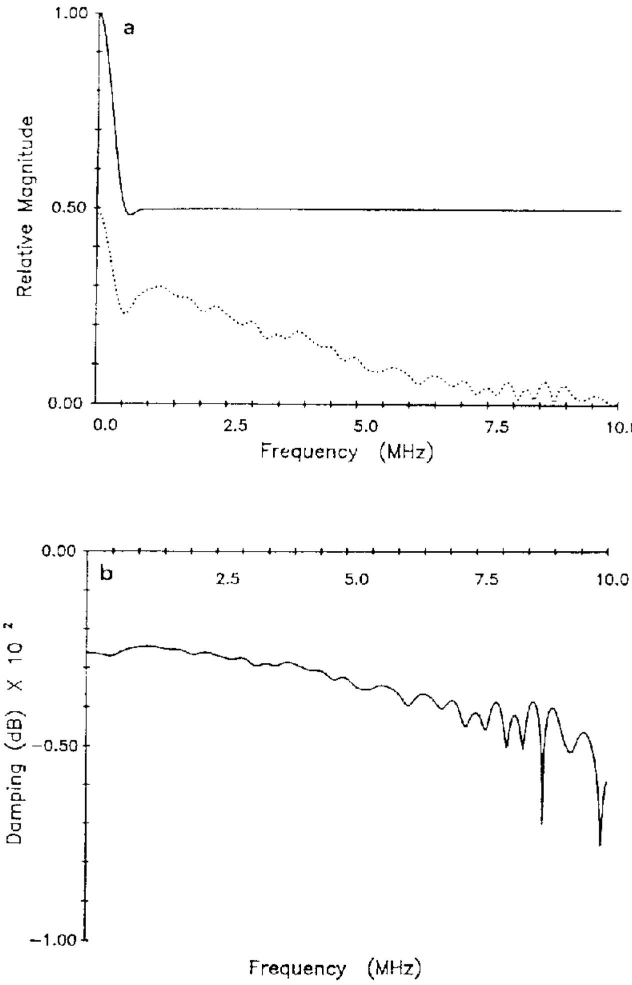

Figure 7 Wave attenuation measurement in 7090 Al/SiC metal-matrix composite. (a) Magnitude spectra (scaled): ——, ideal material; . . . ., real material. (b) Derived attenuation

signals. Because the low frequency correction is only significant at frequencies of < 0.5 MHz, it is omitted from the dispersion relation of the derived phase velocity shown in *Figure 6b*. It is seen from the latter, that the phase velocity between 3 and 10 MHz is nearly constant at 0.690 cm μs^{-1}. At lower frequencies there is a decrease to lower wavespeed values which is due principally to the response of the piezoelectric transducer used to make the measurements and the omission of the low frequency correction.

To demonstrate an attenuation measurement, the velocity signal resulting from a step force applied to a specimen of 7090 Al/SiC metal-matrix composite, shown previously in *Figure 3*, is analysed. The first P-wave is windowed and compared to the computed response for the ideal case of a non-attenuating material shown in *Figure 1a*. The Fourier magnitude spectra of the measured and ideal P-wave amplitudes are shown in *Figure 7a*, while the result obtained from applying Equation (10) is shown in *Figure 7b*. In this example, only a relative measure of the attenuation of the longitudinal wave is determined, since the vertical scale in *Figure 7a* was not calibrated absolutely and the magnitude of the force drop of the source used to generate the signal in this experiment was not measured. In waveforms detected in extremely absorptive materials, only the lowest frequencies can propagate and, hence, an unambiguous identification of the particular wave arrivals may be difficult. For such materials, other techniques may need to be developed.

The few examples shown here were used to illustrate the various signal analysis procedures described in the previous section. Numerous additional examples obtained in a variety of different materials are contained in another paper[21].

Quantitative acoustic emission source characterization

The characteristics of an AE source refer to its location in a structure and its source type and time characteristics. According to Equations (3) and (5), the latter can be specified in terms of time-dependent forces or moment tensor components. The procedures by which a source of AE can be located in a structure have been discussed elsewhere[22] and are omitted in this Paper. The development of reliable source location procedures applicable to highly anisotropic materials are still under development.

An investigation of failure processes in materials via quantitative AE source characterization relies on several elements including: 1, a mechanical or thermal loading system to reproducibly activate various failure processes; 2, a load, deformation measurement system; and 3, a broad-band AE system consisting of elements similar to that used to make point-source/point-receiver measurements. While a solution to the general source characterization problem requires an inversion of Equation (1), in most cases one has sufficient information about the loading method or source mechanics or from an inspection of the generated AE signals to be able to select whether the source can be represented by a monopolar or dipolar model so that the appropriate Green's functions can be used in the inversion procedure. When the source is represented by several force or double-force components, Equation (3) or (4) can be written in simplified form according to

$$U(t) = S(t) * [c_1 G_1(t) + c_2 G_2(t) + c_3 G_3(t) + \ldots] \qquad (11)$$

where the *c*s correspond to the magnitudes of the various components used to model the source.

The solution to the inverse source problem then involves determination of the source-time function, $S(t)$, and the source strength magnitudes given by the *c*s from the measured displacement signals. A number of processing algorithms have been developed for this. These include several algebraic schemes, least-squares methods, double-iterative and frequency-division algorithms. A detailed description and a comparison of these processing procedures is summarized in another paper[23]. An alternative approach by which the ratios of the moment tensor components can be recovered involves measurement of the radiated field of the AE signals from the source. This procedure is very useful for analysing real AE signals. The amplitude of the emitted signal measured by a set of transducers at a distance R and at various angles from a dipolar source, such as the formation of a Mode I crack, can be written in terms of the normal displacement amplitude, u_z, which is expected to be of the form

$$u_z(\theta, t) = a(t)\,[b + \cos^2(\theta - \theta_c)] \qquad (12)$$

where θ is the orientation of the receiving transducers in the polar-cylindrical co-ordinate system and θ_c is the orientation of the normal to the crack plane. For a single horizontal dipole source, aligned parallel to the normal of a Mode I crack, the term b is expected to be zero. For another crack model[10], given in terms of three orthogonal dipoles of strength $\lambda+2\mu, \lambda$ and λ (λ and μ are the Lamè constants), the term b is expected to be ≈ 0.28.

Recently, Netravali *et al.*[24] fabricated composite model specimens consisting of glass fibres imbedded in an epoxy matrix. Using indentation techniques to selectively cause failure in the fibre, matrix or interface, they observed in preliminary experiments particular AE waveforms corresponding to various failure modes. Analogous experiments with real composite specimens are still underway. In this Paper several source characterization examples are presented in which the source can be adequately represented by just one component. In that case, Equation (9) can be easily inverted, such that the source function is given by

$$S(t) = U(t) * [G(t)]^{-1} \qquad (13)$$

where $[G(t)]^{-1}$ is the inverse function of that Green's function of the source component appropriate to the particular test configuration[1,4].

Applications

The measurements were made in the 7090 Al/SiC metal-matrix composite whose wave surface was similar to that shown in *Figure 5b*, indicating that this material is essentially elastically isotropic for waves at low megahertz frequencies. The computed dynamic Green's function for this material, corresponding to a force normal to the surface of the specimen, was shown previously in *Figure 1a*. Application of Equation (13) has been made to characterize the normal force sources obtained by breaking a glass capillary and a pencil lead and impacting with a 1/16in diameter sphere on the surface of the specimen. Shown in *Figures 8a* and *b* are the results for the impact source. For the capillary break, a step source function was recovered whose rise-time was ≈ 0.25 μs, while, as shown in *Figure 8b*, the impact source is 11 μs in duration. All the source characterization results are in agreement with those obtained previously in conventional materials[1,20,25].

While these first source characterization results are encouraging, there remain several unresolved problems. These are related to procedures for reproducibly activating various failure modes in real composite materials and methods for analysing AE signals which have propagated through a composite specimen which is highly anisotropic and attenuative. However, even when quantitative information about a source is recovered from the AE signals, the interpretation of these results in terms of a failure model relevant to composite materials needs to be developed. In metals, the magnitudes of the recovered moment tensor components have been used to delineate between various failure modes[26]. Whether an analogous procedure will be applicable to composite materials remains to be seen. Furthermore, in brittle, isotropic elastic materials the characteristics of a source may be interpreted in terms of a displacement-discontinuity model to recover the crack jump of the source[10]. With the Dugdale-Barenblatt thin-zone model, and assumptions regarding the microstructural linkage distance and failure stress, the time-dependent size of a crack can be obtained from the time function of the source recovered from the AE signals[13]. What the appropriate failure model is for a particular failure process in a composite material is still unknown at present.

Conclusions

This Paper has described the elements of quantitative AE systems for measurements in composite materials. When used with a simulated AE point source, one obtains a powerful materials testing system in which the ultrasonic

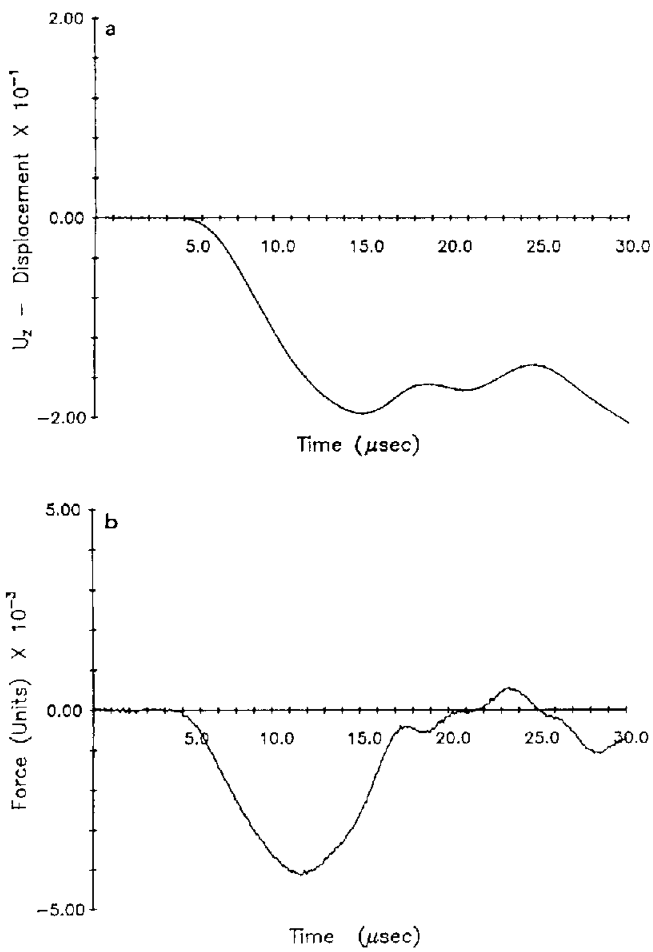

Figure 8 AE source characterization measurement in 7090 Al/SiC metal–matrix composite with 1/16in ball impact. (a) Detected displacement signal; (b) recovered impact source function

wavespeeds and attenuation can be determined as a function of frequency and propagation direction in composite materials. When the material's properties are known, quantitative information about a source of emission can be recovered from the emitted signals. Key to both systems is a theoretical basis for analysing the propagation of transient elastic waves through a bounded structure, a broad-band sensor whose transduction characteristics are known a priori or which can be determined in a calibration experiment and signal processing algorithms for recovering the characteristics of the source or the medium from the detected signals.

PS/PR measurements require a minimal amount of surface preparation and they can be made on composite specimens which are neither planar or parallel. Information regarding the propagation characteristics of both longitudinal and shear wave components is possible from a single waveform. It is also possible to select an excitation source whose time characteristics result in signals possessing high energies at low frequencies facilitating measurements in ultra-attenuative composite materials.

A signal processing procedure was demonstrated for recovering from the emitted AE signals, the characteristics of several simple sources active in metal–matrix composite specimens. Results similar to those found in conventional materials are obtained. Additional work with real sources needs to be undertaken. With the continued development of non-contact point sources and receivers and signal processing procedures, the measurement techniques described in this Paper show great promise as powerful tools for characterizing micro- as well as macro-structural features, and investigating the dynamics of failure processes in composite materials.

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