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Plate theory is more easily applied to the analysis of composite laminates than exact three-dimensional elasticity theory. Under conditions such that plate theory is applicable, it is suggested that plate waves are useful for understanding acoustic emission (AE) phenomena. To test this idea, pencil leads were broken on aluminum plates and composite plates, and the resulting waves were detected with a broadband ultrasonic transducer. Both the fundamental extensional and flexural modes were observed. Their characteristics are described and the implications for AE source location are discussed as well. Several transducers, commonly used for acoustic emission measurements, are compared with regard to their ability to reproduce the characteristic shapes of plate waves. Their different responses show why similar test specimens and test conditions can yield disparate results.

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INTRODUCTION

For many acoustic emission studies, the test specimen is geometrically platelike. That is, the thickness is much smaller than the other two dimensions. Considering only linearly elastic displacements, away from the source the propagating waves will be governed by Lamb's homogeneous equation, the solutions to which are called Lamb waves. In the limit when the wavelength is much larger than the plate thickness, a simpler set of governing equations derived from classical plate theory can be used to understand the motion. In this "thin plate" case, the waves are called plate waves and there are two modes of propagation. One is called the extensional and the other the flexural mode. Both have in-plane and out-of-plane components due to the Poisson effect, and in acoustic emission (AE) measurements it is usually the out-of-plane component that is measured, since the measurement is made on the surface of the plate rather than the edge. For the extensional mode, the larger of its two displacement components is in the plane of the plate, while the larger displacement component in the flexural mode is perpendicular to the plane of the plate.

Waves in thin plates have been studied theoretically by Lamb, Mindlin, and many others (Ref. 1, and references therein) while experimental studies are not nearly as numerous.[2,3] The velocities of the lowest symmetric (extensional) and antisymmetric (flexural) Lamb waves or so-called "exact solutions" reduce to the plate wave solutions asymptotically as the plate thickness goes to zero.

The relevance of plate theory to acoustic emission measurements has not been explored heretofore. Typically, practical AE measurements have concentrated on the rms voltage produced by all sounds striking a transducer. Or, certain parameters, like amplitude and counts, have been used to describe AE "events." More fundamental efforts have been directed toward very general wave propagation studies in thick plates ($\lambda \gtrsim h$), based on three-dimensional elasticity theory, where many higher Lamb modes enter into the measurement.[4,5] The mathematical complexity involved in extending this approach to anisotropic materials is formidable. Absolute measurements of epicenter motion in an isotropic plate have been carried out for calibration purposes,[6] but for practical acoustic emission measurements, the sensor position is often determined by test fixturing or other constraints, and it is usually not the case that the source position is known in advance. The computations involved for off epicenter measurements are very time consuming even for isotropic materials. Thus, it may be some time before this approach can be fully exploited by the nondestructive evaluation (NDE) practitioner working with composites.

In cases where the wave motion can be described by plate theory, which include a fair number of practical situations, it will be shown that the acoustic emission is amenable to a straightforward interpretation in terms of the fundamental wave modes and that there are practical uses of this interpretation. In a follow-on paper, it is shown that acoustic emission produced by matrix cracking in a composite plate does indeed result in plate waves. In this paper, waveforms produced by breaking pencil lead on aluminum and graphite/epoxy plates will be exhibited and the fundamental extensional and flexural wave modes identified. It should be noted here that breaking pencil lead is, at present, the most commonly used technique for calibrating AE equipment. Measurements that used four different types of common AE transducers will be described and some interesting differences noted.

I. THEORY

Both plate wave theory and the exact elasticity or Lamb wave theory for isotropic materials are discussed in many papers (cf. Ref. 1, and references therein). Recent plate wave work on certain laminated plate symmetries is also available.[7] Only the aspects of plate wave theory relevant to the discussion of the experimental data are given here.

For an isotropic plate the extensional mode is analogous to the extensional wave in a rod and just as in the case of the rod, it is dispersionless. The (velocity) dispersion equation is given by

$$c_e = [E/(1-\nu^2)\rho]^{1/2},$$

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where E is Young's modulus, ν is Poisson's ratio, and ρ is the density.

The flexural wave dispersion equation for the plate is analogous to flexural waves in an Euler beam and the velocity shows a similar dependence on the frequency

$$c_f = [D/\rho h]^{1/4}\omega^{1/2},$$

where $D = Eh^3/12(1-\nu^2)$, ω is the circular frequency (rad/s), and h is the plate thickness.

Velocities for the aluminum plate used in these experiments were computed and are given in Table I.

For the case of propagation in the main symmetry direction in an orthotropic laminated plate (the zero degree direction in a $[0,90]_s$ laminate) the structure of the dispersion equations changes very little from the isotropic case. The extensional mode remains dispersionless and the velocity is given by

$$c_e = [A_{11}/\rho h]^{1/2},$$

where A_{11} is the in-plane laminate stiffness in the 1 or x direction (see Ref. 8). This equation differs from that in Ref. 7 by the thickness h appearing in the denominator.

For the flexural wave mode the dispersion still varies as the square root of the frequency. When referring to waves, the term flexural means perpendicular to the plane of the plate. The flexural wave is sometimes called the transverse wave, but this will not be used here because of the possible confusion with the (in-plane) transverse direction terminology commonly used for composite materials.

For a laminated orthotropic plate the flexural velocity is given by

$$c_f = [D_{11}/\rho h]^{1/4}\omega^{1/2},$$

where $D_{11} = \int_{-h/2}^{h/2} [Q_{11}(z)]\, z^2\, dz$ is the usual definition of the bending stiffness, Q_{11} is the reduced lamina stiffness, and z is the coordinate in the thickness direction of the plate. In Ref. 8, the on-axis orthotropic stiffnesses are denoted Q_{xx}, Q_{yy}, Q_{xy}, and Q_{ss} rather than Q_{11}, Q_{22}, Q_{12}, and Q_{66}. Both are common notations. Values for the IM6/epoxy material taken from the tables in Ref. 8 are given in Table I along with the calculated velocities.

An important fact to be pointed out is that the wave speeds are different for the different modes. The extensional mode wave speed in the aluminum plate was about twice as fast as the flexural mode, at the highest flexural frequency measured, and, in the composite laminate, it was about five times as fast as the flexural mode. Combined with the nondispersive nature of the extensional mode, this enabled the modes to be identified quite easily.

TABLE I. Calculated plate wave velocities.

Material properties	Aluminum plate (2024-T4) Plate velocities	Bulk velocities
E = 73 GPa	$c_e = 5380$ m/s	$c_1 = 5950$ m/s
$\nu = 0.30$	(0.212 in./μs)	(0.235 in./μs)
$\rho = 2770$ kg/m^3	$c_f = 4.45(\sqrt{f})$ m/s	$c_2 = 3180$ m/s
$h = 0.0020$ m	[175($\sqrt{f}$) in./s]	(0.125 in./μs)
(0.080-in. thickness)		

c_1—dilatational, c_2—shear

Reduced stiffness	Graphite/epoxy plate (IM6/3501-6) Plate properties	Plate velocities
$Q_{xx} = 204.15$	$A_{11} = 5.75\times10^7$ N/m	$c_e = 8200$ m/s
$Q_{yy} = 11.26$		(.323 in./μs)
$Q_{xy} = 3.60$	$D_{11} = 3.29$ N-m	$c_f = 3.2(\sqrt{f})$ m/s
$Q_{ss} = 8.40$		[126($\sqrt{f}$) in./s]
$\rho = 1600$ kg/m^3		
$v_f = 0.66$ (fiber volume fraction)		
$h = 0.006\,24$ m (0.025-in. thickness)		

Plate is a $[0,90]_s$ laminate.
Velocities are for waves traveling in the 0° direction.

II. EXPERIMENT

In this study a 0.238-cm-thick × 23-cm-wide × 46-cm-long aluminum plate was used to compare the current measurements with those found in the literature. Only measurements of flexural mode waveforms could be found in the literature. Waveforms for the fundamental extensional mode in a rod have been documented but this does not seem to be the case for plates. The composite plate layup was $[0,90]_s$. The material was IM6/3501-6A. Plate dimensions were identical to the aluminum, except for the thickness, which was 0.0635 cm.

An ultrasonic transducer (Harisonic, 2.25 MHz) was used to provide a trigger signal to a digital oscilloscope (LeCroy 9400A) and another transducer was used to measure the propagating waves. The digital oscilloscope (DSO) had a 100-MHz maximum transient sampling rate and built-in fast Fourier transform (FFT) firmware. The sampling rate was adjustable and typically set to 100 MHz (10 ns per point). Four different transducers were used to measure the waves so that an assessment could be made concerning their usefulness to plate wave AE measurements. Three were resonant types: PAC R15, PAC P50, AET 175L. The fourth was a broadband ultrasonic (Harisonic, 5 MHz) transducer with a frequency response function typical of that type. Measurements were made in the relatively flat tail (the 0- to 1-MHz range) of the ultrasonic (UT) transducer. The transducers were coupled to the specimens with vacuum grease. The transducers were connected to preamplifiers set at 40-dB gain with a choice of 20-kHz high-pass filters or no filtering (wideband). The signals from the preamplifiers were connected directly to the DSO.

Lead breaks (Pentel, 2H) were performed either on the surface of the plate and just behind the trigger transducer or on the edge of the plate, again just behind the trigger transducer. The pulse was measured at various distances from the source depending on the separation desired between the modes. Care had to be taken to monitor reflections when the receiver began to near an edge.

III. RESULTS AND DISCUSSION

A. Aluminum plate

Pictures of flexural waves in thin aluminum plates can be found in Press and Oliver[2] and Medick.[3] Examples of flexural waves in a thin aluminum plate from the work of Press and Oliver are shown in Fig. 1. The two works used completely different sources. Medick used a 220 Swift rifle bullet impacting perpendicular to the plate, while Press and Oliver used a spark gap excitation. In both works, the receiver was a capacitative type of transducer, which meant high fidelity over the frequency range of interest. Note that the measurements are for large distances from the source and the dispersion is quite evident; the lower frequencies are traveling more slowly as predicted by plate theory. The same general type of displacement was measured in the present work where the source was a lead break on the surface, Fig. 2, however, the time scale is much shorter and the extensional component can be seen in front of the flexural wave. The receiver was a broadband ultrasonic transducer (Harisonic, 5 MHz), which was used because of its relatively flat frequency response in the 0- to 1-MHz range.

In order to compare the velocities predicted by theory with the experimental measurements, Fig. 2 can be used. The time at the zero crossing at the first appearance of the extensional mode was 24 μs. The trigger time was at 6 μs so the propagation time was $\sim 20\ \mu$s. Using

$$c = (d_r - d_s)/t,$$

where $d_r - d_s$, the receiver to source distance, is 10 cm, the velocity is 5000 m/s. More accurate measurements over longer propagation distances yielded 5400 m/s, which is in close agreement with the theoretical velocity of 5380 m/s listed in Table I. For the flexural wave in Fig. 2, the period of the next to last peak is roughly 26 μs, which corresponds to a frequency of 38 kHz. Using the formula in Table I, the theoretical velocity is 868 m/s. The experimental number is

$$c = 10\text{ cm}/58\ \mu\text{s} = 1700\text{ ms},$$

which is about twice as large. This discrepancy was noted for

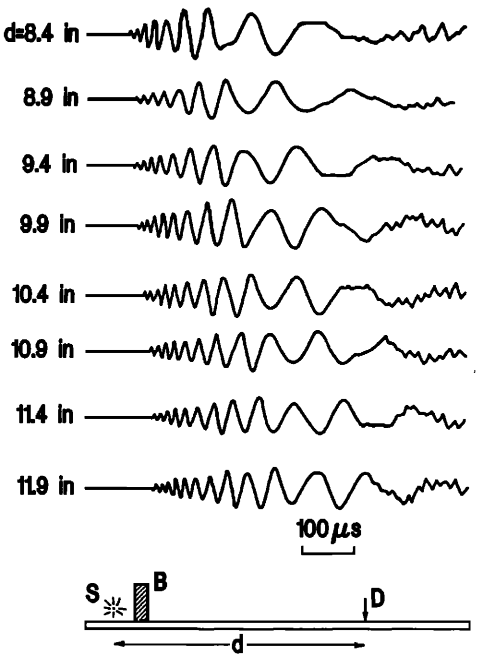

FIG. 1. Flexural wave excited in an aluminum plate by a spark gap source and detected with a capacitative transducer (after Press and Oliver).

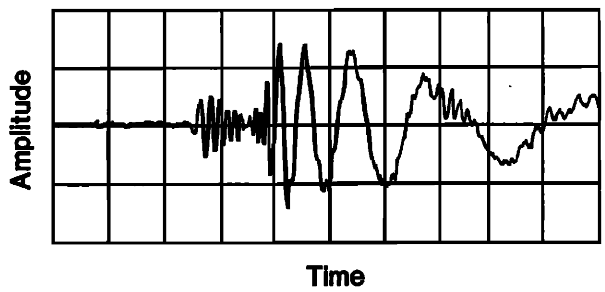

FIG. 2. Lead break on an aluminum plate measured with a broadband ultrasonic transducer (Harisonic, 5 MHz). Source and receiver separation was 10 cm. Ordinate is 5 V/div (zero at center) and abscissa is 10 μs/div.

all flexural wave measurements even down to very low frequencies where the theory should get better. It is understandable and well-known that the theory is incorrect at higher frequencies since inertia effects and shear are not taken into account. This discrepancy has been investigated for the aluminum plate and can be explained by considering the group velocity and the highly dispersive nature of the plate geometry.[9] Obviously, this can affect source location analyses. However, it does not affect the results in this paper. In addition to the velocities, other aspects of the waves were used to identify the wave modes. The shape of the flexural wave is also a distinguishing feature.

Further, there was another way of identifying this mode. The out-of-plane nature of the displacement was verified by exerting thumb pressure between source and receiver. The flexural wave was damped out almost completely, while the extensional wave was hardly affected. As will be seen later, since source location in all currently available AE analyzers uses threshold triggering, it is argued that the flexural wave can and should be filtered out of the signal and only the extensional wave be used for accurate source location.

Figure 3 shows the same measurement except that a pointlike transducer (Physical Acoustics, P50) was interchanged with the broadband transducer. The peaks in the extensional wave are not as sharp indicating that the high-frequency response is not as good. Also the low-frequency response is not as good as evidenced by the lower amplitudes of the lower frequency part of the flexural wave.

The waveform produced by a lead break on the edge of the aluminum plate was markedly different from that on the

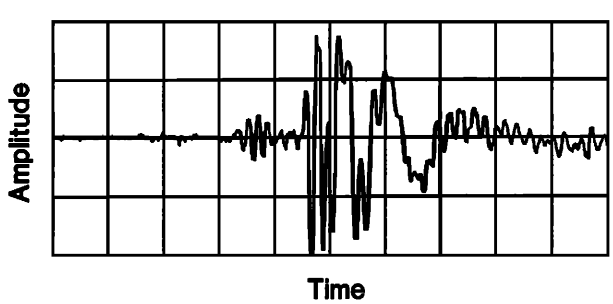

FIG. 3. Lead break on an aluminum plate measured with a pointlike transducer (Physical Acoustics, P50). Source and receiver separation was 10 cm. Ordinate is 5 V/div (zero at center) and abscissa is 10 μs/div.

surface. It could be expected that the flexural wave would have a much smaller amplitude than the extensional wave due to the in-plane source motion. As anticipated, the waveform shown in Fig. 4 now has a much larger extensional component compared with a surface lead break. Recall that the measurement is still being made on the surface. That is, the out-of-plane component of the extensional wave is larger. Of course, the in-plane component of the extensional wave should be much larger still.

The size of the flexural component could be made to vary depending on how precisely the lead could be made to break at an angle measured from the perpendicular to the plane of the plate. This has good implications for acoustic emission measurements. It should be possible to discern the directional properties of an event by measuring the ratio of the extensional and flexural amplitudes. In a composite material for instance, in-plane cracking would yield a higher extensional to flexural amplitude than a failure mode whose displacement is mostly perpendicular to the plane of the plate. Examples of the latter are delamination and spalling (from impact). Amplitude along may not suffice as a distinguishing characteristic, which requires further study, but, whatever characteristics are finally decided upon, the point is that each source will have different plate waveforms corresponding to the directionality of the source.

B. Graphite/epoxy plate

Similar results were obtained for graphite/epoxy plates. Both unidirectional and cross-ply laminates of different thicknesses were studied but only results for a $[0,90]_s$ plate will be given here. The power spectrum of each type of wave is shown, uncorrected for transducer response, so that the various transducers can be compared relative to the flat tail of the broadband ultrasonic transducer.

1. Broadband transducer (5 MHz, Harisonics, surface contact)

The first thing that will be noticed about the waveforms in Fig. 5(a) is the unmistakable plate wave shape similar to the measurements on aluminum. The main differences observed in this work between the two materials were, basically, the greater attenuation and higher extensional velocity in the composite. The attenuation was observed to affect the high

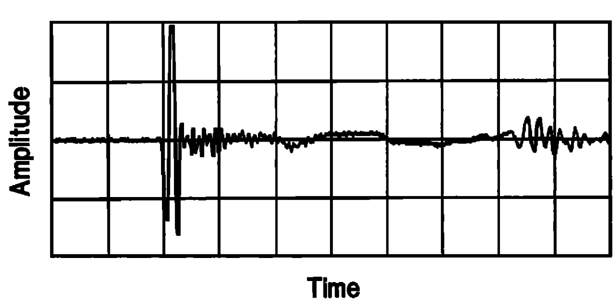

FIG. 4. Waveform produced by lead break on edge of aluminum plate. Measured with broadband ultrasonic receiver. Source and receiver separation was 5 cm. Ordinate is 5 V/div (zero at center) and abscissa is 10 μs/div.

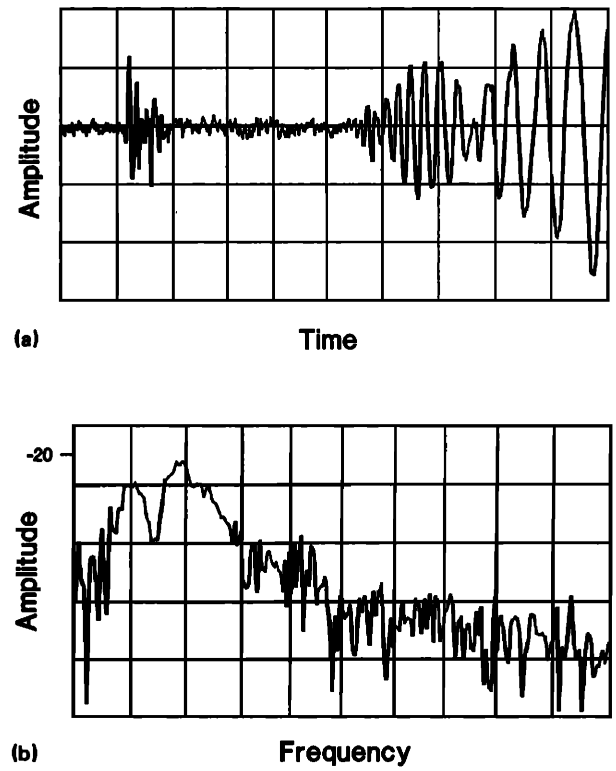

FIG. 5. (a) Lead break on surface of graphite/epoxy plate measured with broadband ultrasonic transducer. Extensional mode and flexural mode are well separated. Source and receiver distance was 17 cm. Ordinate is 0.2 V/div (zero at second division down from top) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

frequencies more than the low frequencies, by gradually increasing the source to receiver distance and repeating the lead breaks. The extensional mode and flexural mode velocities were 8100 m/s and 1500 m/s, respectively, at the first zero crossing. This is about a 5 to 1 ratio as opposed to about a 2 to 1 ratio in the isotropic case. The power spectrum corresponding to the time domain in Fig. 5(a) is shown in Fig. 5(b).

The extensional wave had higher frequency components than the flexural wave. This was determined by computing the power spectrum of each mode independently and noting that the flexural wave frequencies are predominantly below 200 kHz, while the extensional wave spectrum spread to nearly 1 MHz. This means that in AE tests on composites, the flexural wave will travel much further than the extensional wave because the damping increases with increasing frequency. This can greatly affect location results and is part of the reason that location calibrations can vary greatly from one lead break to the next. Variations in the lead fracture produce pulses with smaller extensional modes that do not cross threshold and the clock is subsequently triggered on the flexural wave which is much slower.

In addition to breaking leads on the surface of the plate, lead breaks were done on the edge while attempting to keep the flexural motion to a minimum. This produced, primarily, an extensional mode propagating in the plate. Practically no flexural mode wave can be seen in Fig. 6. Notice the sharp response. The source and receiver separation is 17 cm, just as

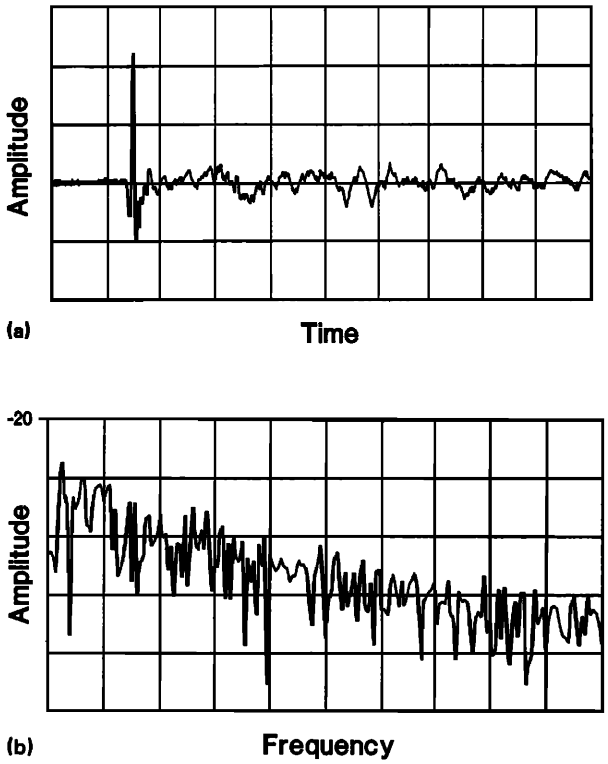

FIG. 6. (a) Lead break on edge of graphite/epoxy plate measured with broadband ultrasonic transducer. Between source and receiver, 17 cm. Ordinate is 0.5 V/div (zero at center) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

for Fig. 5 where a distinct flexural component can be noticed. Thus the geometry of the source has a great effect on the waves produced. The power spectrum in Fig. 6(b) shows the decrease in amplitude with frequency. Since the pencil lead break is a step function at these frequencies, the roll-off can be attributed to attenuation.

2. Pointlike transducer (0–1 MHz, Physical Acoustics, P50)

The same measurements using a P50 transducer are presented in Figs. 7 and 8. Here again, the change in frequency response is evident. The low-frequency components in the flexural wave are highly damped. However, this can be an advantage when these components are not desired, such as in source location with threshold triggering of the timing circuits. An edge break waveform is shown in Fig. 8 for the same source to receiver distance. Just as in the case of the aluminum plate, some ringing can be seen. This is in contrast to Fig. 6. Again, no flexural component is seen. The power spectrum is shown in Fig. 8(b) and this should be compared with Fig. 6(b).

3. Resonant transducer (150 kHz, PAC, R15)

Lead breaks were also measured with a Physical Acoustics Corporation R15 sensor, which is a narrow-band type with its main resonance near 150 kHz. This is probably the sensor most commonly used for acoustic emission measure-

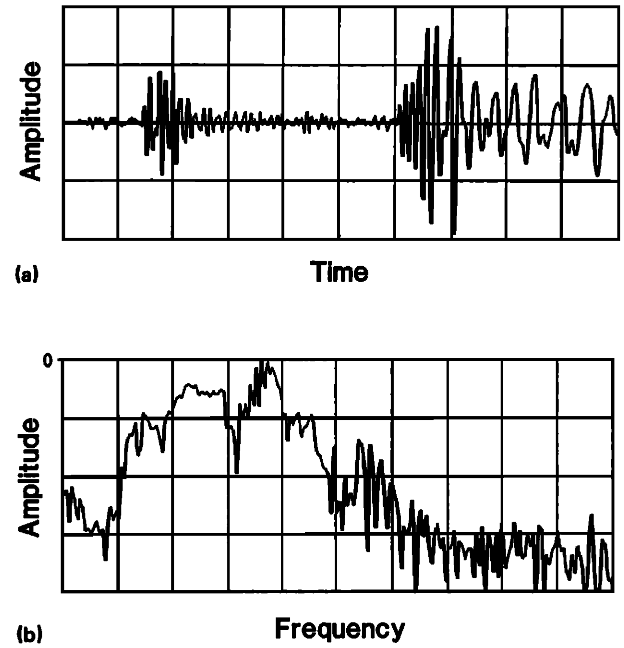

FIG. 7. (a) Lead break on surface of graphite/epoxy plate measured with pointlike transducer (Physical Acoustics, P50). Source and receiver distance was 17 cm. Ordinate is 2 V/div (zero at center) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

ments at the present time. The waveform shown in Fig. 9 is for a break on the surface and a source and receiver separation of 17 cm. The preamplifier (PAC, 1220A) was wideband and set to 40-dB gain. The extensional and flexural modes are not

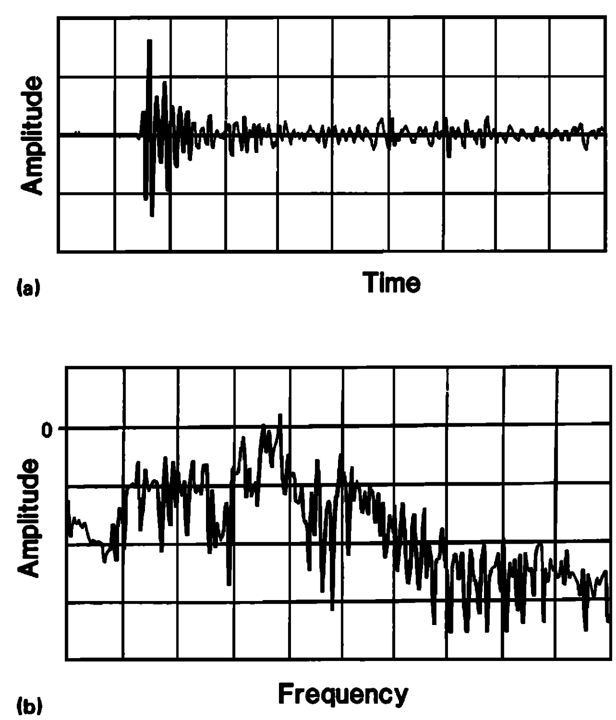

FIG. 8. (a) Lead break on edge of graphite/epoxy plate measured with P50 transducer 17 cm from source. Ordinate is 5 V/div (zero at center) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

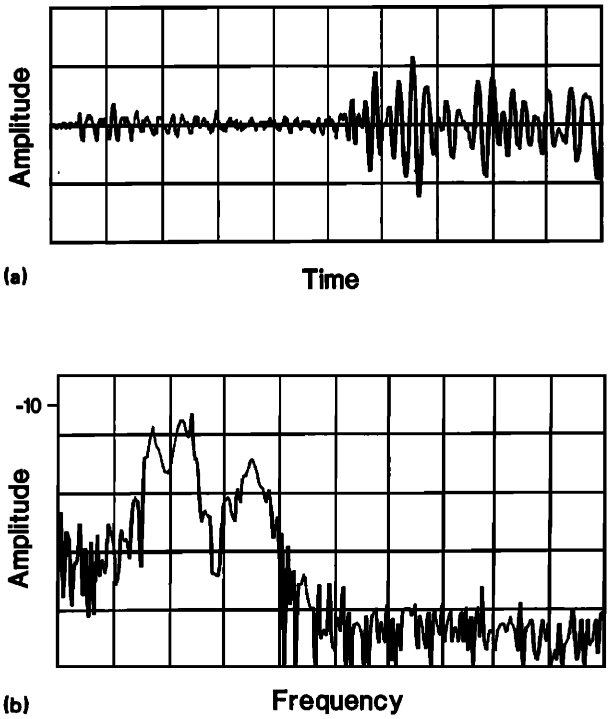

FIG. 9. (a) Plate wave measured with a 150-kHz resonance, narrow-band acoustic emission transducer (Physical Acoustics, R15). Lead break on surface. Distance between source and receiver was 17 cm. Ordinate is 5 V/div (zero at second division down from top) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

well separated and long time scale measurements showed that the sensor continued to ring well after the pulse had passed. Nevertheless, both components are discernable (albeit to the trained eye). The early part of the extensional wave, at least, could be used to locate the source provided the amplitude was large enough. This need for large amplitude has been noted by Hamstad[10] during a study of location inaccuracies when using this type of sensor with commercial AE analyzers. If the amplitude of the extensional component is not large enough, the same phase points are not correctly matched, i.e., the timing circuits are triggered by different parts of the same wave that has arrived at the separate transducers. The location error can be quite large (> 50%).

The result of a lead break on the edge of the plate is shown in the next figure, Fig. 10. The expected increase in the size of the extensional pulse is verified. However, the differences with the P50 measurement, Fig. 8, and the broadband transducer in Fig. 6 should be noted. The two main peaks in the frequency spectrum are at 154 and 244 kHz. Again, all of the spectra shown in this paper are uncorrected for the response of the transducer. However, the 5 MHz UT transducer has an almost flat response in the 0- to 1-MHz tail of its spectrum. Also, the response of the preamplifiers used was measured using a swept sine and the response was flat from 0–1.5 MHz.

4. Resonant transducer (175 kHz, HSBIT, AET 175L)

Waveforms for a Hartford Steam Boiler Inspection Technologies AET 175L sensor are shown in Figs. 11 and 12

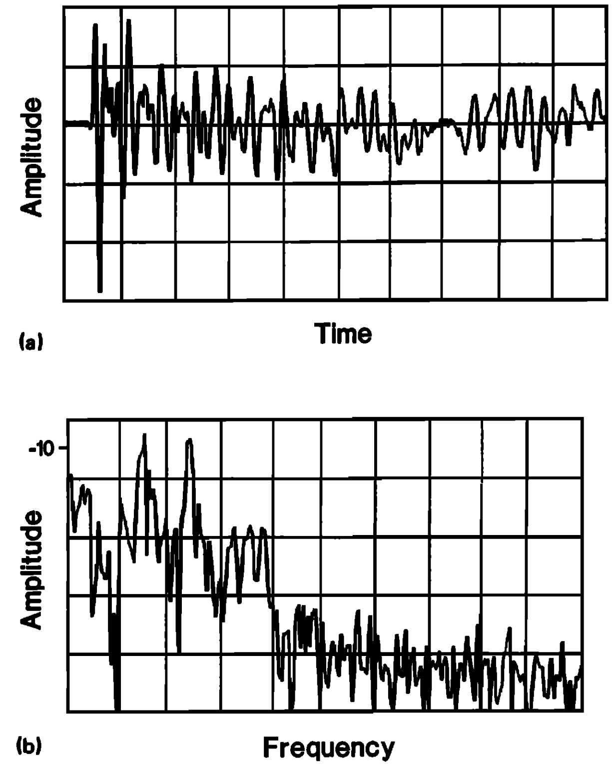

FIG. 10. (a) Plate wave measured with a 150-kHz acoustic emission transducer (Physical Acoustics, R15). Lead break on edge. Distance between source and receiver was 17 cm. Ordinate is 5 V/div (zero at second division down from top) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

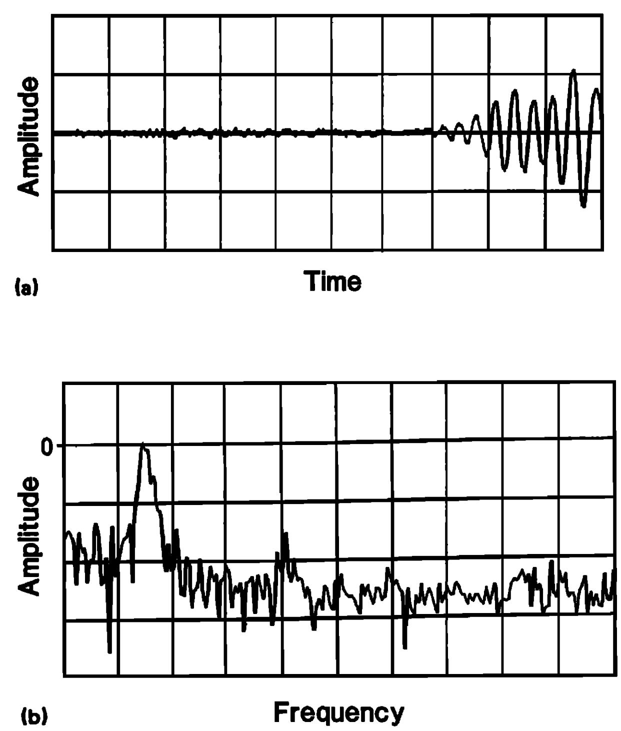

FIG. 11. (a) Measurement made with a 175-kHz resonance, AE transducer (Hartford Steam Boiler Inspection Technologies, AET 175L). Lead break on surface. Source receiver separation was 17 cm. Ordinate is 5 V/div (zero at center) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

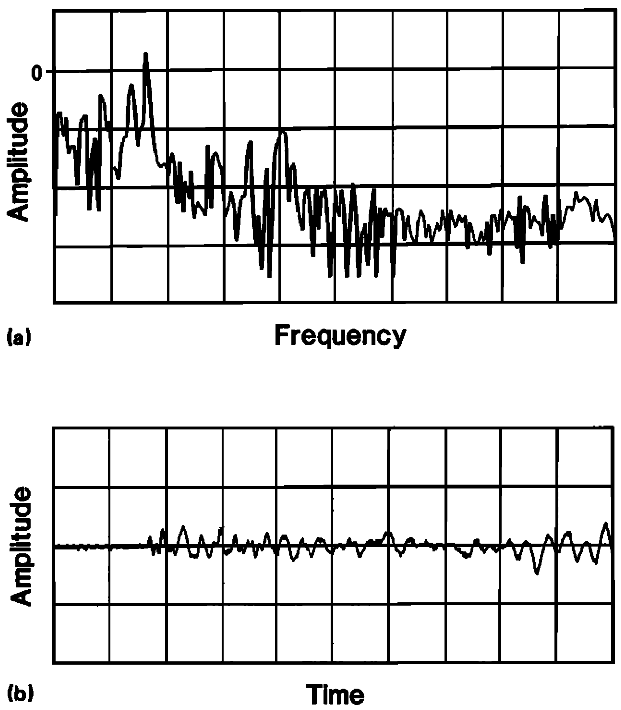

FIG. 12. (a) Measurement made with a 175-kHz resonance, AE transducer (Hartford Steam Boiler Inspection Technologies, AET 175L). Lead Break on edge. Source receiver separation was 17 cm. Ordinate is 5 V/div (zero at center) and abscissa is 20 μs/div. (b) Power spectrum. Ordinate is 10 dB/div (0 dB is 1 mW into 50 Ω) and abscissa is 0.1 MHz/div.

for a surface break and an edge break, respectively. This is also a commonly used narrow-band transducer. The principal resonance is at 175 kHz. This particular sensor is relatively insensitive to the extensional wave. This means that measurements made with it are based on the flexural wave and, consequently, location timing, peak amplitude distributions, etc., will be quite a bit different from those made with, say, the R15 sensor. However, it should be noted that the event data need not necessarily be different because other factors such as attenuation, combined with analyzer threshold settings, may make the results similar. Both systems (sensor/preamplifier/analyzer combination) would be measuring the flexural wave and not the weaker extensional wave. Thus a comparison of systems without a knowledge of the wave propagation and transduction aspects could result in confusion.

IV. CONCLUSIONS

Under the condition that the thickness of a platelike specimen is much less than the smallest wavelength in the pulse to be measured, then one or both of the two lowest plate modes are generated depending on the type of source. The velocities of the extensional mode agree with theory, but there is some discrepancy between the flexural wave velocities predicted by classical plate theory and the measured velocities, especially for the graphite/epoxy composite plate. The relative amplitude of the displacement components in each mode is related to the directionality of the source.

The extensional wave, since it is not dispersive, should generally be used for accurate source location when using threshold based triggering of location clocks. AE analyzers need to be adjustable to higher digitization rates to take this into account. Using the peak of a signal for location can lead to great error since the first sensor could be triggered by the extensional wave while the second transducer might be triggered by the flexural wave after the signal has propagated some distance.

The frequencies in the waves are different, the flexural wave exhibiting predominantly lower frequency components than the extensional wave, and the extensional wave attenuates more rapidly than the flexural wave, especially in graphite/epoxy composites. Thus threshold triggered timing circuits are highly susceptible to error if both wave modes are allowed to affect trigger circuitry. Proper filtering can be used to eliminate one of the waves.

A flat frequency response transducer would be a suitable transducer to choose for this type of measurement. In the relatively flat, 0- to 1-MHz range, a broadband, 5-MHz ultrasonic transducer had ample sensitivity to detect both the extensional and flexural waves produced by a lead break source.

ACKNOWLEDGMENTS

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