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AE Source Orientation by Plate Wave Analysis*

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Abstract

Lead breaks (Hsu-Neilsen source) were used to generate simulated acoustic emission signals in an aluminum plate at angles of 0, 30, 60, and 90 degrees with respect to the plane of the plate. This was accomplished by breaking the lead on slots cut into the plate at the respective angles. The out-of-plane and in-plane displacement components of the resulting signals were detected by broad band transducers and digitized. Analysis of the waveforms showed them to consist of the extensional and flexural plate modes. The amplitude of both components of the two modes was dependent on the source orientation angle. This suggests that plate wave analysis may be used to determine the source orientation of acoustic emission sources.

Keywords: acoustic emission, plate waves, source orientation

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Introduction

In conventional acoustic emission (AE) testing, the elastic wave produced by an AE source is converted to a voltage signal by a resonant transducer. Certain parameters such as the peak amplitude, energy, duration, and rise-time are recorded by an AE analyzer. These AE parameters are usually plotted against test parameters such as load, strain and temperature. After repeated tests on identical specimens, empirical inferences are made about the sources of the emissions. The sources are the (micro) failure mechanisms assumed to be operating at a particular point in the test. Sometimes, other nondestructive and destructive techniques are used to verify the failure mechanisms. This approach has been successful, particularly in applications in which the presence of emission is used as an early warning signal. There are limitations to this approach, however. Different sources yield values of the AE parameters that overlap substantially. In composite materials, for example, the ability of the AE technique to distinguish between matrix cracking and fiber breakage has been the subject of considerable discussion in the literature for years. It has also been shown that the amount of emission and the values of the AE parameters are heavily dependent on the previous load history of a specimen. It is becoming clearer that the set of parameters in current use is insufficient to distinguish between sources. One obvious way around these difficulties is to determine if more information about AE sources can be extracted from the waveforms. The so-called quantitative AE techniques attempt to do this. The effects of source motion, wave propagation and transduction are treated theoretically and are compared with experiment.

The time response and directionality of certain individual AE sources have been determined by several researchers (Ohtsu and Ono, 1986; Kim and Sachse, 1986; Scruby, Baldwin, and Stacey, 1985; Eitzen et al., 1981 and references therein) in laboratory experiments. In order to accomplish this it was first necessary

to remove the coloration of the waveforms of the transducer and detection electronics. It was also necessary to remove the effects of multiple reflections and mode conversions caused by the geometry of the specimen. First of all transducer effects were minimized by detecting with broad band transducers. Then, the remaining effects were removed from the AE signals by deconvolution which uses previously measured absolute calibrations of the sensor. Likewise, the effects of the detection electronics were removed by using previously measured calibrations. The effects of multiple reflections were minimized by choosing specimen geometries with very large dimensions which approximated a semi-infinite half-space or an thick infinite plate. The impulse response functions (or Green's functions) for these geometries were calculated theoretically and used to eliminate the geometrical effects from the waveforms. The resulting waveforms were then interpreted in terms of moment tensor analysis. The waveforms were from measurements at several locations on the specimen. The results yield the time response and directionality of the AE source.

This approach has led to better methods for calibrating AE transducers and a better understanding of AE source mechanisms. Currently, however, it is of limited applicability for practical AE monitoring of damage in structures. One limitation is the need for absolutely calibrated wide band transducers and detection electronics. Another is the sensitivity of the deconvolution algorithms to noise. Probably the biggest limitation complexity in calculating impulse response functions for even the known simple geometries, much less for the more complicated geometries.

Another approach to obtaining quantitative information about AE sources from measured AE signals has been investigated recently. Gorman (1990) used broad band sensors to detect signals from simulated AE events (lead pencil breaks) in aluminum and graphite/epoxy composite plates. It was demonstrated that in these thin plates, only the lowest order extensional and flexural plate modes were detected. Furthermore, it was shown that the

amplitudes of the extensional and flexural modes were different when the lead break AE source was applied on the surface versus when it was broken on the edge of the plate. Thus, it was postulated that interpretation of the AE signals in terms of plate waves may be useful in determining source orientation.

Classical plate theory was used to predict the velocities of the modes and good agreement with experimental measurements was exhibited. Gorman and Prosser (1990) used classical plate theory to predict the low frequency portion of the out-of-plane displacement component of the flexural mode for a finite plate. Good agreement with experiment was demonstrated.

Further research by Gorman and Ziola (1990) has shown that AE signals from a real AE source (transverse matrix cracking) also contained plate waves. They also discussed the effects that the different modes can have on locating AE sources. Most AE location techniques assume a single velocity of propagation. When multiple modes with different velocities occur, erroneous location results can be obtained.

While the applicability of plate wave analysis only to plate geometries is a limitation, this approach is still useful since most practical structures to be tested have one dimension that is much smaller than the other two. Examples of this include aircraft structures, such as wing and fuselage skins, and pressure vessels, whose walls are usually thin. Prosser, Gorman, and Dorigi (1990) illustrated that these modes were present in a thin-walled graphite/epoxy tube of a type similar to that proposed to be used in NASA's Space Station. Even though the tube had less than a two-inch radius of curvature, plate theory accurately predicted the extensional and flexural mode velocities.

In this paper, the effect of source orientation was investigated further. For source motion at 0, 30, 60, and 90 degrees to the plane of the plate, both the in-plane and out-of-plane displacement components were measured. It is shown that the amplitudes of both components of the two modes were dependent on the source orientation angle. At the smaller angles, for which

largest component of the source motion was in the plane of the plate, the extensional mode was larger. For larger angles, the flexural mode was dominant.

Theory

Waves propagating in plates have been studied theoretically by numerous authors (Graff, 1976 and references therein).

Displacements for waves propagating in plates are governed by Lamb's homogeneous equations. The solutions to these equations are called Lamb waves and consist of an infinite number of modes. In the case when the wavelength is much larger than the thickness of the plate, the equations of motion can be reduced to a much simpler form using classical plate theory. In this case the resulting waves are called plate waves and there exist only two modes, extensional and flexural.

The extensional mode in an isotropic material is governed by the equations:

$$\frac{\partial^2 u^0}{\partial x^2} + \frac{(1-\nu)}{2} \frac{\partial^2 u^0}{\partial y^2} + (1+\nu) \frac{\partial^2 v^0}{\partial x \partial y} = \frac{\rho}{A} \frac{\partial^2 u^0}{\partial t^2} \quad (1)$$

and

$$\frac{\partial^2 v^0}{\partial y^2} + \frac{(1-\nu)}{2} \frac{\partial^2 v^0}{\partial x^2} + (1+\nu) \frac{\partial^2 u^0}{\partial x \partial y} = \frac{\rho}{A} \frac{\partial^2 v^0}{\partial t^2} \quad (2)$$

where x and y are the coordinate axes in the plane of the plate, u and v are the displacements along these axes respectively, ν is the Poisson's ratio, ρ is the density, and A is given by

$$A = \frac{Eh}{(1-\nu^2)} \quad (3)$$

where E is the Young's modulus and h is the thickness. The

superscript 0 indicates that these equations are for the motion of the midplane of the plate. These equations predict the in-plane displacement for the extensional mode. However, this is only an approximation. Due to the Poisson effect, the extensional mode also consists of an out-of-plane displacement. The velocity c_e of the extensional mode is given by

$$c_e = \sqrt{\frac{E}{\rho(1-\nu^2)}} \quad . \quad (4)$$

The flexural motion is governed by

$$D\nabla^4 w + \rho \frac{\partial^2 w}{\partial t^2} = 0 \quad (5)$$

where w is the displacement along the z axis which is normal to the plate, and D is the bending stiffness given by

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad . \quad (6)$$

In this case, only an out-of-plane displacement component is predicted. However, the same argument used previously suggests that an in-plane displacement component of the flexural mode should also exist. The velocity of this mode is dispersive, with the higher frequencies traveling faster than the lower frequencies, and is given by

$$c_f = \sqrt[4]{\frac{D}{\rho h}} \sqrt{\omega} \quad (7)$$

where ω is the frequency.

Experiment

AE signals were produced by pencil lead breaks (Hsu-Neilsen

sources) at 0, 30, 60, and 90 degrees with respect to the plane of the plate on a set of aluminum plates and the amplitudes of the displacement measured. At each angle, the break was repeated ten times to determine the variability of the magnitude of the impulse applied to the plate. The dimensions of the plates were 0.508 meters in width, 0.381 m. in length, and 0.00635 m. in thickness. The lead break normal to the plate (90 degrees) was positioned at the center width of the plate and at a length of 0.127 m. from the plate edge. For the case of 30 and 60 degree lead breaks, slots were machined into the plate at the same position as the 90 degree break to allow the lead to be broken at an angle. A plan view of the plate showing the positioning of the slot is presented in Figure 1. A cross sectional view of the plate and slot is shown in Figure 2. For the case of the 0 degree break, where the source motion is parallel to the plane of the plate, the break was positioned on the edge of the plate at the center of the width.

The waveforms were detected by two 3.5 MHz ultrasonic transducers (Panametrics). These transducers offer relatively flat frequency response over the 20 kHz to 1 MHz frequency range of AE signals in comparison to conventional low frequency resonant AE transducers. One transducer measured the out-of-plane displacement component and was positioned on the surface of the plate. For the 30, 60, and 90 degree sources, this transducer was placed at the center of the width and at a distance of 0.254 m. from the plate edge (or 0.127 m. from the source location). In Figures 1 and 2, this transducer is designated as the out-of-plane transducer and its position is shown. For the 0 degree case, where the source was broken on the plate edge, the source to receiver distance was maintained at 0.127 m. and thus it was positioned along the center width 0.127 m. from the edge.

The second transducer was used to determine the in-plane displacement component and was placed on the opposite edge of the plate at the center width, Figures 1 and 2. Thus the source to receiver distance for all of the breaks except the 0 degree break was 0.254 m. From Figure 2, it can be seen that, for the 0 degree

break, the propagation length was longer (0.381 m.). So this break was carried out on a separate plate that was only 0.254 m. in length. This was done in order to compare the wave amplitudes from all of the sources for the same propagation distance.

A third sensor was placed next to the source and was used to trigger the transient recorder (LeCroy 6810) used to digitize the waveforms. This sensor is also indicated on Figure 1. After being amplified and filtered in a preamp (Physical Acoustics Corp. 1220A with 20 kHz high pass filter), the waveforms were digitized at a sampling rate of 5 MHz on the transient recorder which had a vertical resolution of 12 bits. The signals were then stored on a computer for further analysis and display. A block diagram of the setup is presented in Figure 3.

Results and Discussion

A typical out-of-plane displacement waveform due to a lead break source on an aluminum plate is shown in Figure 4. The extensional and flexural modes are identified in this figure. The measured velocities of the two modes agree with the theory which confirms that these are the plate modes. This waveform was detected by the broad band transducer. When a typical narrow band resonant AE transducer is used, the two modes are indistinguishable because of the ringing in the transducer.

The out-of-plane displacement components of the waves created by the lead breaks at the four source angles are presented in Figure 5. The waveform shown at each angle was from a lead break with a peak amplitude nearest the average peak amplitude for the ten breaks. For the source motion in the plane of the plate (0 degree or edge break), it can be seen that the extensional mode has its largest peak amplitude while the flexural mode has its minimum. As the source angle increases, the extensional mode peak amplitude decreases. For increases in source angle toward normal to the

plate, the flexural peak amplitude increases except for the 60 to 90 degree cases where the 60 degree flexural amplitude is slightly larger than that of the 90 degree break. At present it is unknown why this anomaly occurred but, it is being investigated.

The average peak amplitude of the out-of-plane displacement components of the flexural and extensional modes are plotted versus source angle in Figure 6. The standard deviations of the ten measurements are plotted as the error bars in this figure. The increasing amplitudes of the flexural mode and decreasing amplitudes of the extensional mode with increasing source angle are as expected. For a 90 degree source, most of the source motion is normal to the plate which should produce flexural motion. The only in-plane component of the source motion is the result of the Poisson effect which is much smaller and thus produces a very small extensional mode. For the case of a 0 degree source, the opposite is true with source motion primarily in plane. This creates a larger extensional mode and a smaller flexural mode. At the intermediate angles, the amount of source motion in the plane and out of the plane of the plate is proportional to the appropriate vector component of the source force. Thus as the angle increases, there should be an increasing flexural mode and decreasing extensional mode which is as observed.

Examples of the in-plane displacement components for the four source angles are shown in Figure 7. Again, it is pointed out that the 0 degree measurement was made on a separate plate with a length of 0.254 m. to maintain a constant source to receiver distance. In these waveforms, the extensional amplitude again decreases with increasing source angle. However, it is interesting that the in-plane component of the flexural mode is not detected even for large source angles where it should be largest. Recall that the out-of-plane component of the extensional mode is observed for all source angles. The average in-plane peak amplitudes of the extensional mode versus source angle is plotted in Figure 8. The standard deviation is indicated

by error bars.

These measurements demonstrate the effect of simulated AE source orientation on plate modes in thin plates. It is expected that quantitative source information can be obtained by the measurement of the amplitudes of the components of the plate modes due to real sources. One example is of the case of impacts, particularly hypervelocity impacts which are a concern to spacecraft such as the proposed space station. Measurements of the amplitudes of the plate modes should allow determination of the angle of the impact and the energy of the impact which will allow a better estimate of damage. Consideration of plate wave propagation will also yield more accurate source location.

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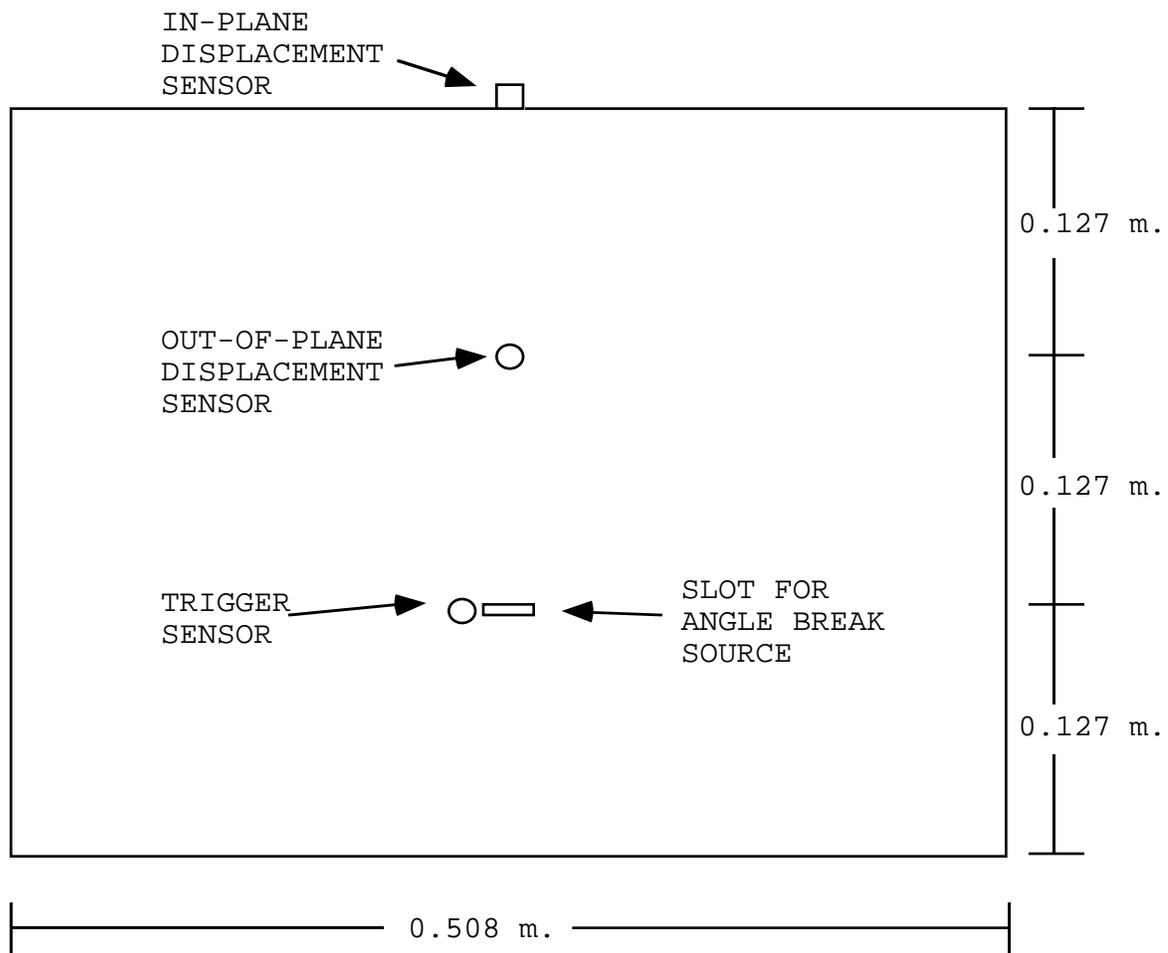


Fig. 1 Plate dimensions and positioning of sensors and source.

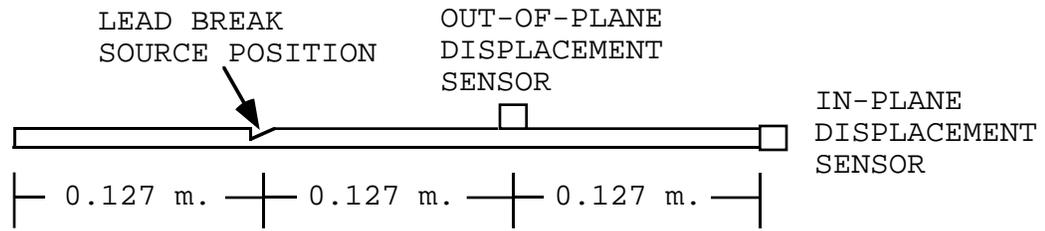


Fig. 2 Cross sectional view along center of plate detailing slot and location of transducers.

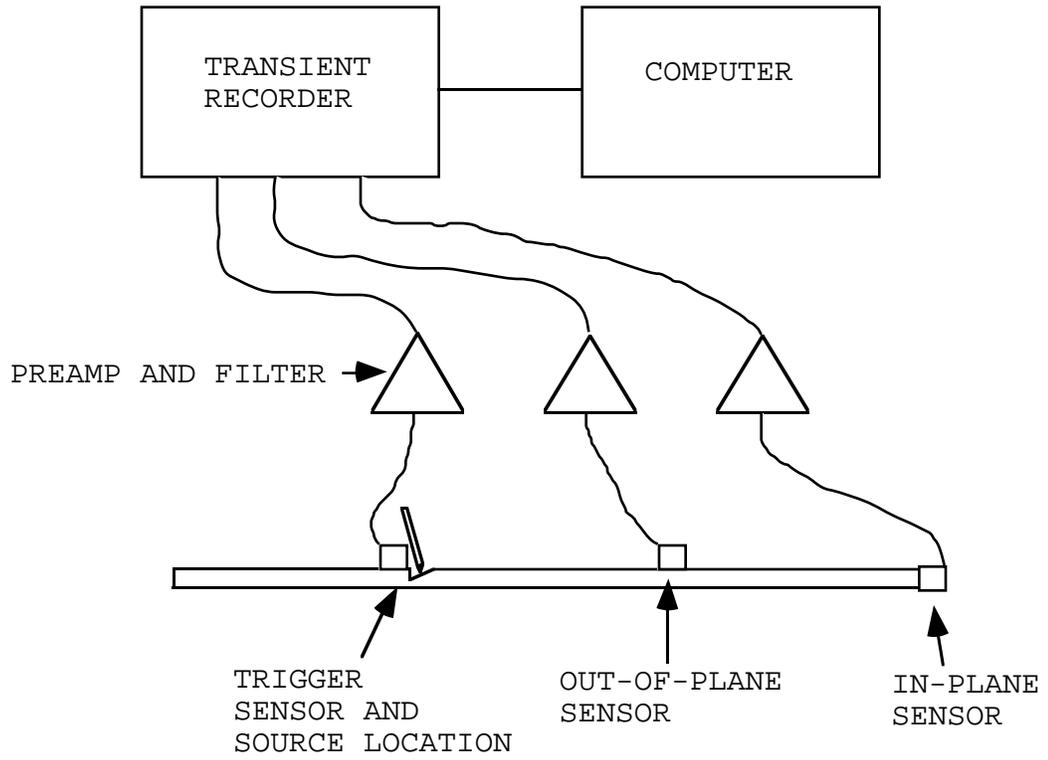


Fig. 3 Experimental setup.

Fig. 4 Typical plate waveform indicating flexural and extensional modes.

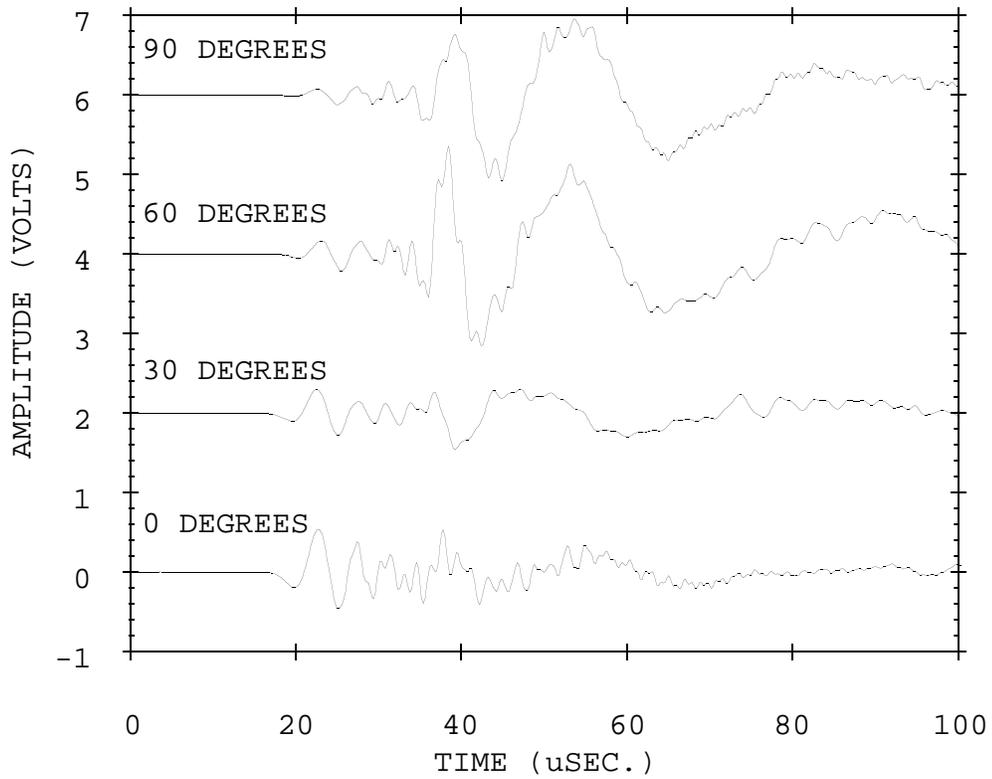


Fig. 5 Out-of-plane displacement components for the waves generated by sources at different angles with respect to the plane of the plate. Each waveform is offset by two volts to allow comparison.

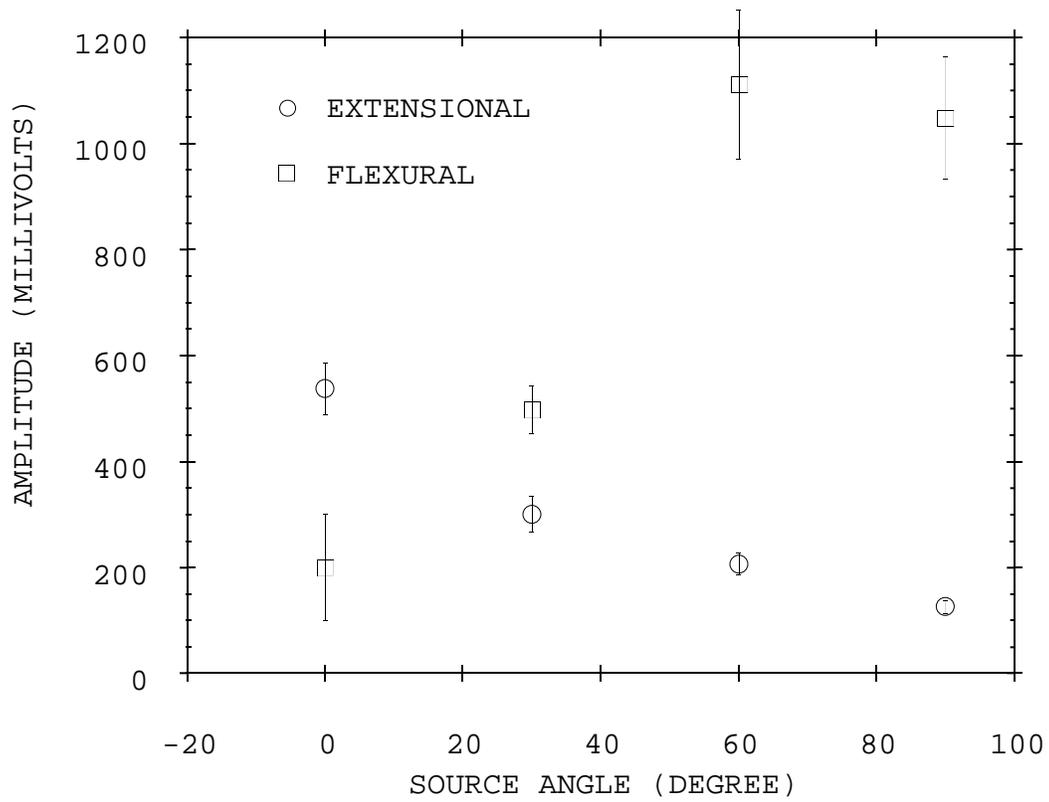


Fig. 6 Average peak amplitudes of out-of-plane extensional and flexural modes for sources at different angles. The error bars are +/- one standard deviation.

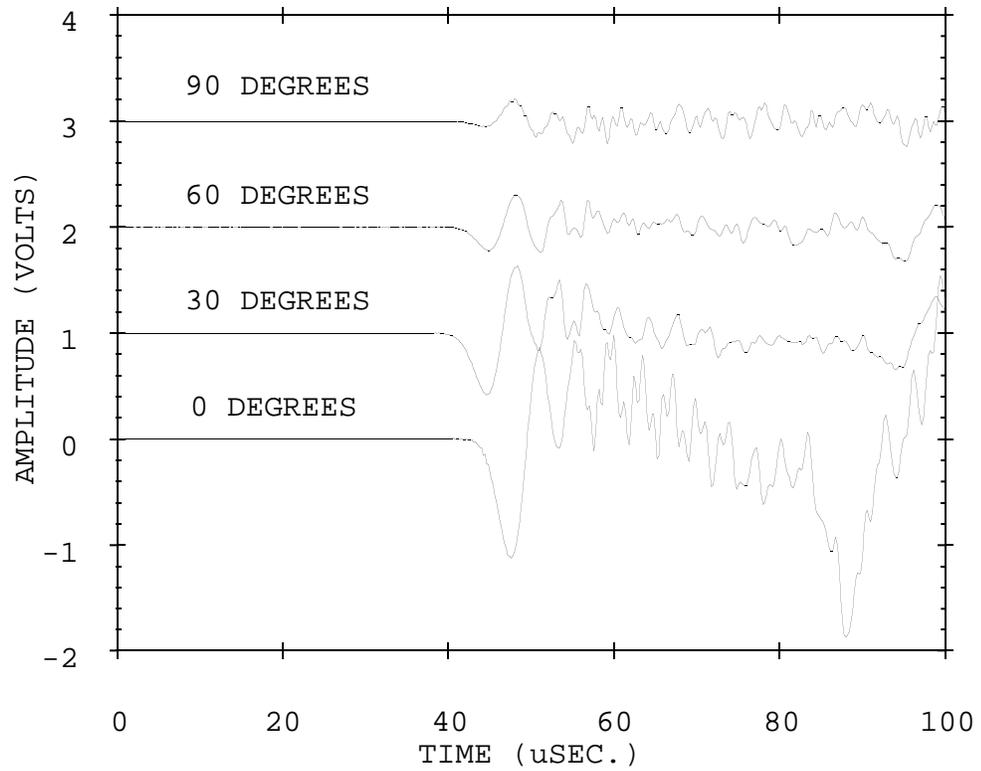


Fig. 7 In-plane displacement components for the waves generated by sources at different angles with respect to the plane of the plate. Each waveform is offset by one volt to allow comparison.

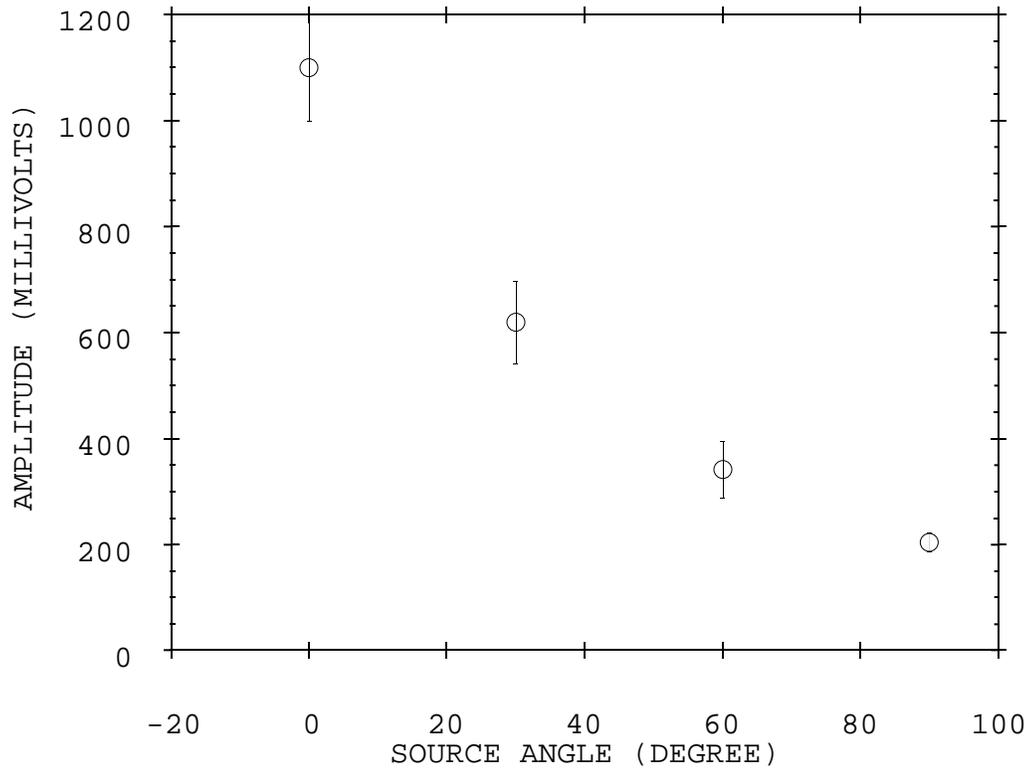


Fig. 8 Average peak amplitudes of in-plane extensional mode for sources at different angles. The error bars are +/- one standard deviation.