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H. L. DUNEGAN

MODAL ANALYSIS OF ACOUSTIC EMISSION SIGNALS

INTRODUCTION

Over three decades ago Worlton published his paper (Ref 1) “Experimental Confirmation of Lamb Waves at Megacycle Frequencies.” This work was received with great enthusiasm by researchers using ultrasonic techniques for Nondestructive Testing, and the results of this work finds continuing use today in ultrasonic applications. Researchers in Acoustic Emission testing which began a few years later largely ignored applications of Lambs Theory to analyzing acoustic emission data. One reason this occurred is due to the fact that most of the early AE experiments were conducted on small coupon specimens, where the theory is not applicable. The second reason is that Ultrasonic researchers can transmit a harmonic wave to select the mode desired for a given plate thickness, while AE researchers are faced to dealing with waves generated by a transient event and therefore such selection is denied. In 1990 Gorman (Ref 2) published “Plate Wave Acoustic Emission,” where he discussed the use of plate wave theory to the testing of thin plate- like specimens with acoustic emission. According to the theory there are two modes of propagation. One is called the extensional and the other the flexural mode. The extensional mode is non-despersive and the flexural mode is despersive. This work and following work by Gorman and Prosser (Ref 3) sparked a great interest on the part of the author in starting an experimental program to study the wave modes in plates. Most of the prior published experimental data was obtained from thin composite plate specimens. The author’s primary interest was in finding out if the theory was applicable to thicker plates constructed from steel and aluminum. Experiments were conducted on 6.25mm and 12.5mm thick steel bars 1.2 M in length (Ref 4). It was discovered from the start of this experimental work that a signal traveling at the shear velocity of steel was present in most of the data. It was also found in this study that analog filtering of the signal into two frequency bands- 100Khz-1Mhz and 20Khz-70Khz would allow for separation of the extensional and flexure wave. The extensional wave and shear wave always appear in the high frequency bandpass and the flexure wave in the low frequency bandpass. The purpose of this report is to show results of a more intensive study on the presence and detectability of shear waves in plates, as well as show the results of a study to determine the despersive nature of plates in the thickness range between 3.13mm and 12.5mm.

PROCEDURE

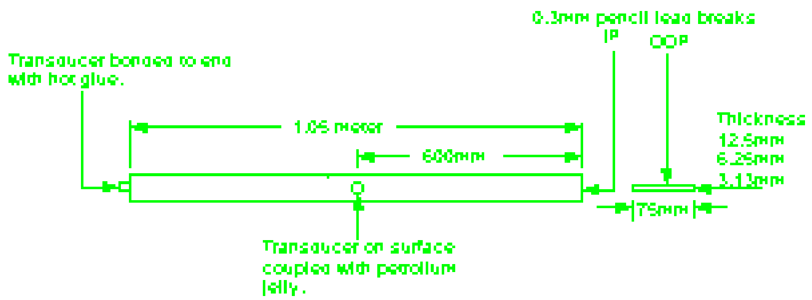


Figure 1- Schematic showing placement of transducers on steel bars, and location where pencil lead breaks are made on bars.

The specimens chosen for the study (figure 1) were three steel bars 1.05M in length, by 75mm in width , with three different thickness- 12.5mm, 6.25mm and 3.13mm. The first experiment conducted on these steel bars was to bond a high fidelity broadband transducer to one end of each bar and break 0.3mm pencil lead breaks both in-plane (IP) and out-of-plane (OOP) at the other end of the bar.

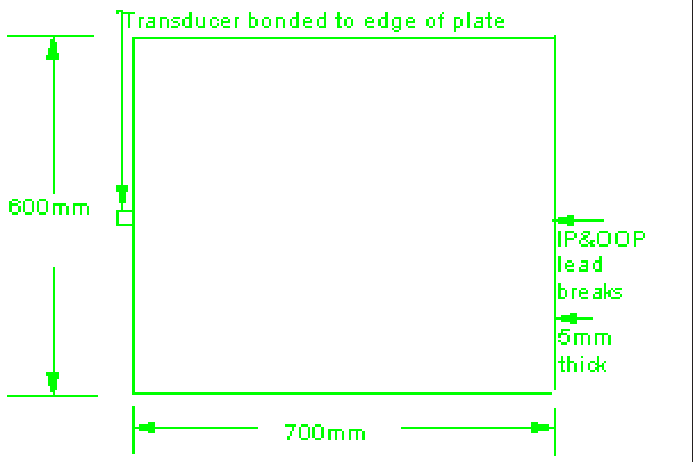
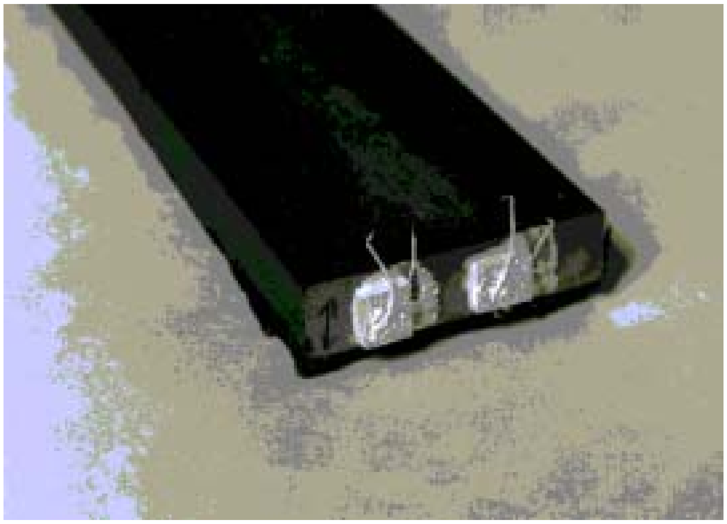


Figure 2-Schematic of aluminum plate used in experiments.

Prior experimental results (Ref 4) has shown that the different modes present in plates can more easily be observed by splitting the signal from the AE transducer into two frequency components: 100Khz -1Mhz and 20Khz-70Khz. The AESMART 2000 instrument is designed to split the AE signal into these two frequency bands. Amplified and filtered AE signals from these high and low frequency channels were recorded by a digital oscilloscope and Paintbrush was used to present the data. It was observed in the previous study that the extensional mode and a wave traveling at the shear velocity were observed primarily in the high frequency channel. The antisymmetrical (flexure wave) mode seemed to be predominately in the lower frequency channel. For the 12.5mm thickness plate used in the previous study the arrival time of the high frequency shear wave very closely matched the arrival time of the low frequency flexure wave and it was initially thought that the high frequency wave was simply the high frequency components of the flexure wave. What seemed to contradict this scenario was the fact that the high frequency wave traveling at the shear velocity was still present when pencil lead breaks were made in the exact center of the edge of the plate. The symmetry produced by this condition does not produce flexure wave components in the plate. Consideration was given to the finite width of the bars being used, as a possible reason for the presence of this high frequency wave. Therefore another experiment was chosen using a large aluminum plate 5mm in thickness. The dimensions of the plate are shown in figure 2. Again a SE1000-H high fidelity transducer was bonded to the center 600mm edge and both IP and OOP pencil lead breaks were made at the opposite 600mm edge, giving 700mm of travel for the simulated AE signal.

A third experiment was conducted in order to determine the efficiency of a transducer coupled to the surface of the plate in detecting shear waves of different polarization traveling in the plate. Two piezoelectric shear plates were constructed and bonded to the end of a 12.5mm thick steel bar, 1.2 meters in



length (figure 3). The bar had damping material on the bottom side. One of the shear plates was oriented such that particle displacement was vertical to the plane of the bar and the other with particle displacement parallel to the plane of the bar. OOP and IP 0.3mm Pencil lead breaks were made at the opposite end of the plate, the signals from each of the shear plates were recorded for these different sources. The shear plates were then used as transmitters by connecting a 50V spike pulse to each in turn. Receiving transducers were placed at 600 mm on the surface of the bar and coupled with petroleum jelly.

EXPERIMENTAL RESULTS

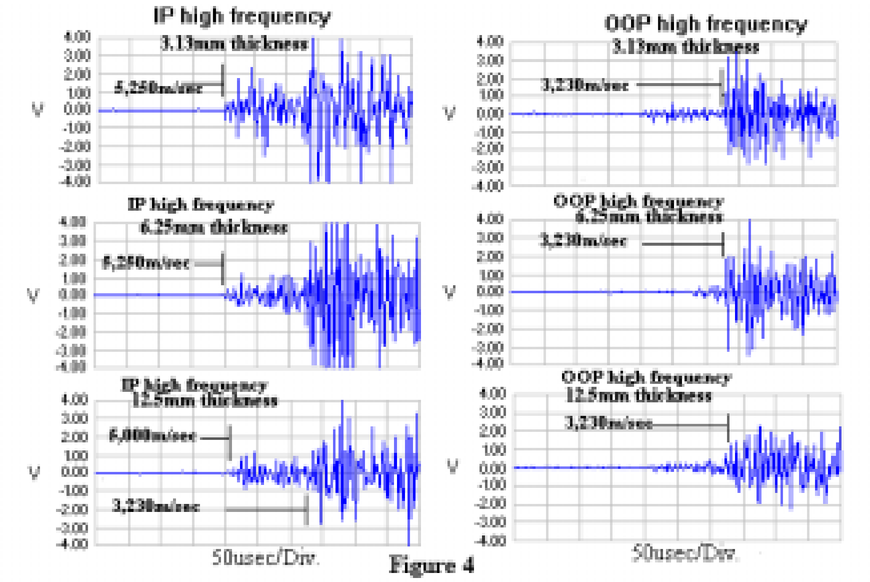


Figure 4

SE1000-H transducer bonded to the end of 3 steel bars 1.05M in length and varying thickness as indicated above. IP and OOP 0.3mm pencil lead breaks were made at the opposite ends of the bars. Note that a signal arriving at a velocity of 3,230m/sec. is present in all the data regardless of thickness.

Figure 4 shows the data obtained from the SE1000-H high fidelity transducer which was bonded to the end of three different thickness steel bars. IP and OOP 0.3mm pencil lead breaks were made at the opposite end of each bar. Note that some dispersion is observed in the first arrival signal (extensional wave) in the high frequency in-plane (IP) channel as a function of thickness of the bars. Also note the presence of a large signal arriving at approximately 325 microseconds from each of the bars. Since this signal arrives at the same time regardless of the thickness of the bar and exhibits a velocity equal to the shear velocity of steel, one must assume that it is a shear wave and not a high frequency flexure wave. Note from the OOP high frequency channels that only faint evidence of the extensional wave is present, and similar to the IP channels a large signal traveling at the shear velocity in steel is observed from each of the bars. An OOP pencil lead break apparently produces a vertically polarized shear wave in addition to the large amplitude flexure wave more clearly observed at lower frequencies. Again arguments for this wave being a shear wave comes about by the fact that the arrival time of the signal is the same regardless of the thickness of the bar. If this were a high frequency flexure wave, which is despersive, one would expect to see arrival times that differ as a function of plate thickness.

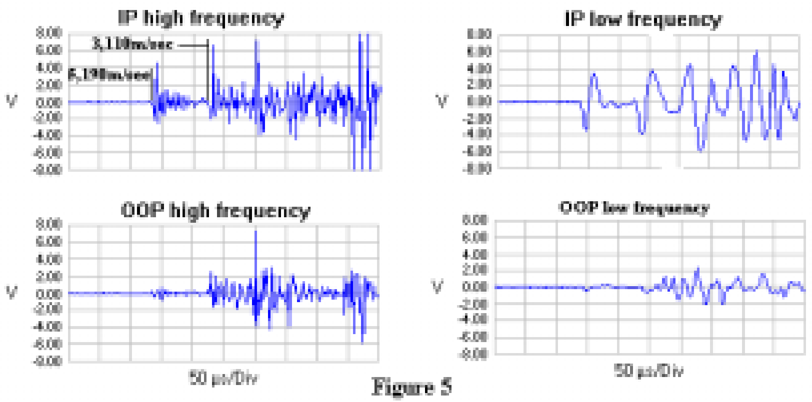


Figure 5

SE1000-H bonded to center 600mm edge of a 600mm X 700mm aluminum plate, 5mm in thickness. IP and OOP 0.3mm pencil lead breaks were made at opposite edge from transducer resulting in 700mm of travel for the stress waves. Note that both high and low frequency IP signals, and the OOP high frequency signal show the arrival time of an extensional wave and a shear wave in the plate. 60dB gain AESMART 2000.

All of the steel bars were 75mm in width. In order to test whether or not the arrival of what appears to be a shear wave was not an artifact due to side reflections from the finite width of the bar, the large aluminum plate shown in figure 2 was utilized. It is wide enough to prevent any side reflections from reaching the transducer prior to the arrival time for the shear wave. The data from the aluminum plate is shown in figure 5. Note that the IP and OOP high frequency channels, and the IP low frequency channel show the arrival times of an extensional wave and the shear wave. Note the lack of signal strength from the OOP low frequency channel. Apparently the small aperture high fidelity transducer (SE1000-H) bonded to the edge of the plate is fairly unresponsive to the large low frequency flexure wave generated by an OOP source, but is responsive to the low frequency components of the shear wave from the IP source.

Further confirmation of the presence of a shear wave in the steel bars, and the ability of AE transducers in detecting the shear waves of different polarization was the motive for conducting experiments on the bar shown in figure 3. Two shear plates were fabricated from PZT-5 material and bonded to the end of a 12.5mm thick steel bar 1.2 meters in length. The bottom side of this bar was coated with a damping material. 0.3mm IP and OOP pencil lead breaks were made at the opposite end. A trigger transducer was located adjacent to the pencil lead break region in order to provide a time trace to measure velocities. Figure 6 shows the response of the shear plates to the pencil lead breaks. First of all note the difference in vertical scale. The horizontal poled crystal gave more than twice the signal as the vertical poled crystal. One reason for this is the damping material on the bottom of the bar attenuated the Sv wave but had minimal influence on the Sh wave as would be expected. Another

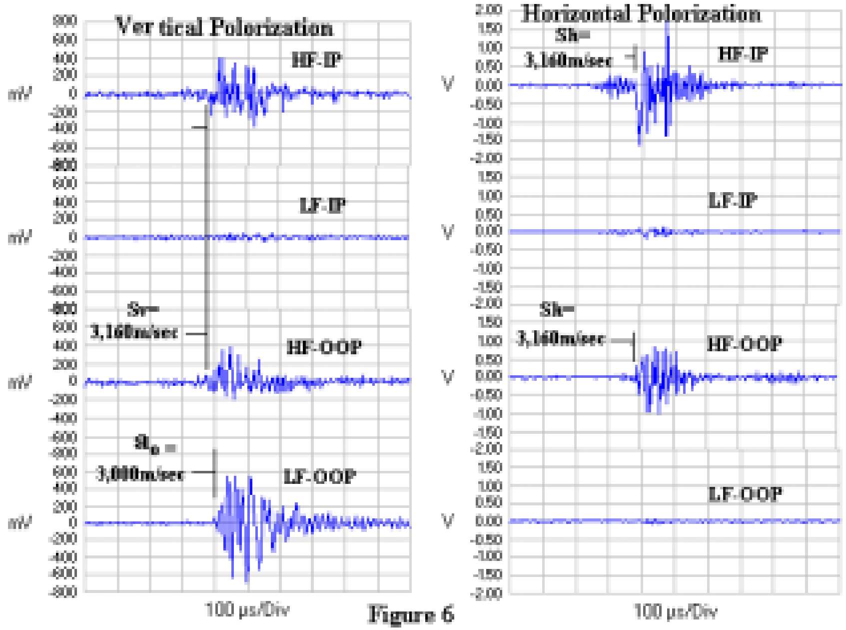


Figure 6

Vertical and Horizontal shear plates were bonded to the end of a 1.2M steel bar, 12.5mm thick. Out of plane(OOP) and in-plane(IP) 0.3mm pencil lead breaks were made at the opposite end. Signals recorded in two frequency ranges, HF=100-1000Khz, LF=20-70Khz. Trigger transducer for digital scope was adjacent to lead breaks. Note vertical scale difference. 40dB gain.

reason is that some of the energy of this shear wave is mode converted into a low frequency flexure wave as evidenced by the large signal detected in the low frequency channel. Note the lack of signal in the low frequency (LF) channel of the crystal with horizontal polarization. The OOP source created a low frequency flexure wave in the bar which was detected by the vertical poled crystal as would be expected. The LF-OOP channel from the horizontal poled crystal was not responsive to this flexure wave since the particle motion was 90 degrees from the poling direction. A slight hint of a shear wave arrival is present in the both LF-IP channels. Most of the Sh energy is displayed in the high frequency (HF-IP) channel for the horizontal polarized crystal. Note that the antisymetrical wave (LF-OOP) from the vertical poled channel, has a velocity very close to the shear velocity measured by both the vertical and parallel poled high frequency channels. Also note that a small signal traveling at the extensional velocity precedes the arrival of the Sh wave in the HF-IP horizontal poled channel. It is almost impossible to fabricate a "pure" shear crystal from PZT plates, so a certain amount of cross coupling is to be expected.

DETECTING SHEAR WAVES WITH SURFACE MOUNTED TRANSDUCERS

It was shown in Figure 6 that both IP and OOP pencil lead breaks produce shear waves in the steel bars. The next step in the experimental program was to determine how effectively an AE transducer mounted on the surface could detect shear waves having polarization parallel to the plate. Again an SE1000-H high fidelity transducer was coupled with petroleum jelly at 600mm on the 1.2M bar on which the shear plates were bonded. Each of the shear plates were pulsed with a 50V spike pulse and detected by the SE1000-H. Figure 7 shows the results of this experiment. One of the surprising results of this experiment was the presence of the high amplitude signal from the horizontal poled crystal. Since the particle

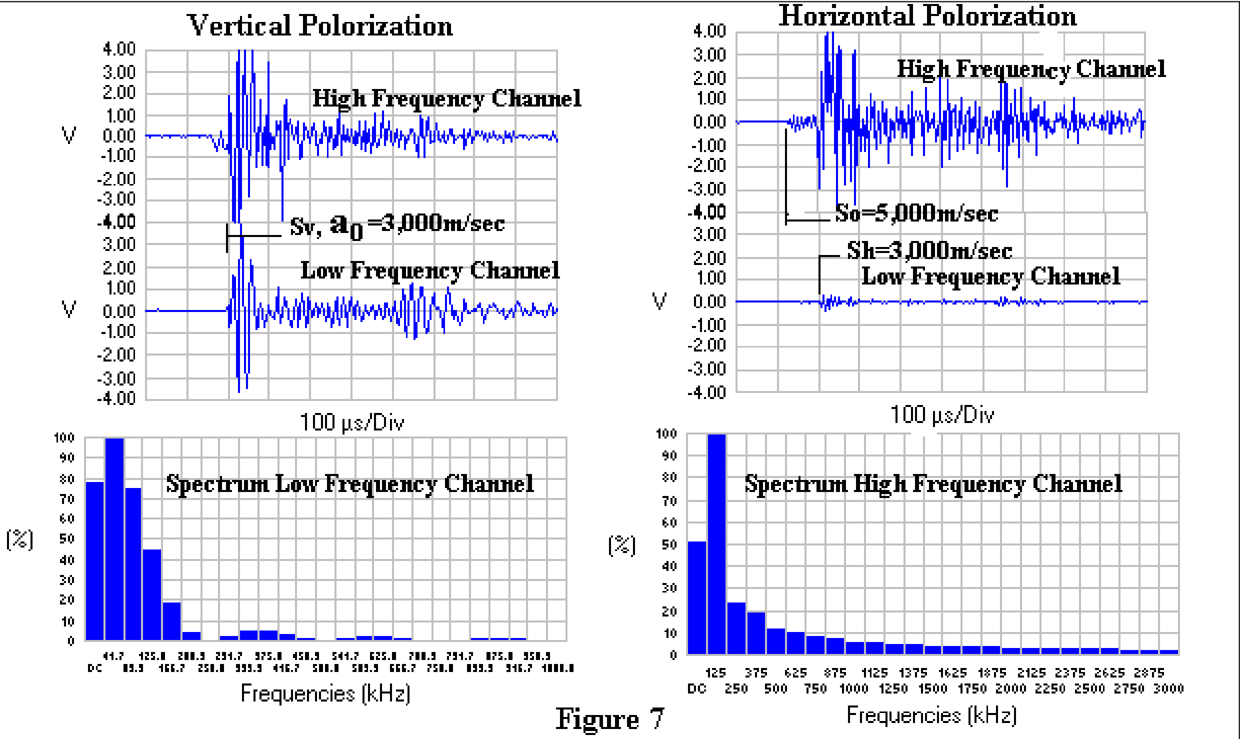


Figure 7

Vertical and horizontal polorized shear plates were bonded to the end of a 1.2M steel bar 12.5mm thick with damping material on the bottom side. An SE1000-H high fidelity transducer was coupled to the bar with petrolium jelly at 600mm distance from the shear plates. Each shear plate was excited with a 50 volt spike pulse in turn. High frequency and low frequency components of the signal were detected to allow measurement of velocities and frequency content.

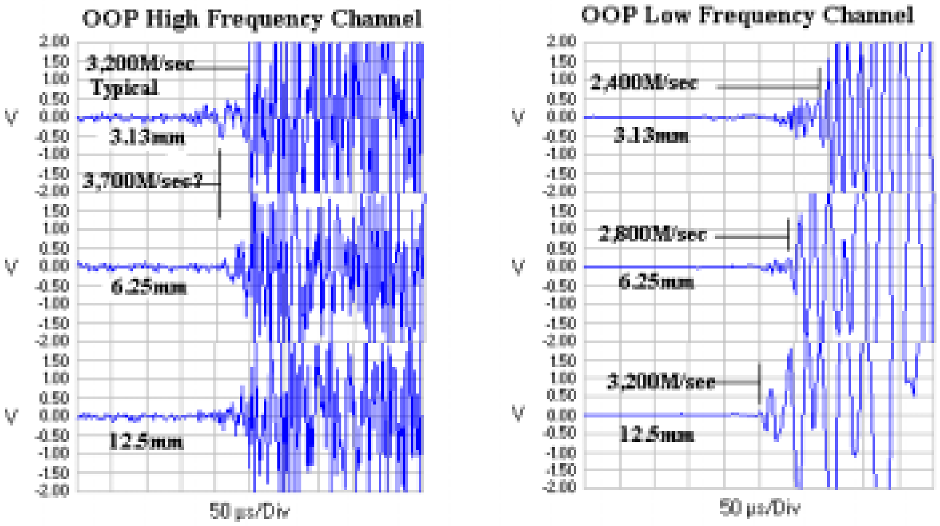


Figure 8

SE1000-HI @ 800mm on three steel bars of varying thickness. Out-of-plane (OOP) 0.3mm pencil lead breaks were made at the end of each bar. Response from high and low frequency channels of AESMART 2000 @ 40dB gain. Showing shear wave and mystery wave in high frequency channel, and despersive antisymmetrical lamb wave in low frequency channel.

motion is parallel to the surface on which the transducer is mounted it was expected that not much signal would couple through the petroleum jelly. The low frequency channel in figure 7 did not detect the Sh wave very effectively. A hint of a signal is present in the low frequency channel with arrival time corresponding to the Sh wave, but it is insignificant compared to the amplitude of the high frequency Sh wave. Again a hint of an extensional wave arrival is present in the high frequency channel. The frequency spectrum of this channel shows a predominant peak at 125Khz.

The SE1000-H responded to signals from the vertical poled crystal in both the high frequency and low frequency channels. It is apparent that the Sv wave excites the low frequency flexure wave as would be expected. The data suggests that the high frequency response is a direct measure of the Sv wave. As seen previously both the Sv wave and the low frequency flexure wave have approximately the same arrival time velocity for this thickness plate. The frequency spectrum of the low frequency channel shows maximum response in the 50Khz range of frequencies which correlates with previously observed frequencies of the low frequency flexure wave.

The next experiment involved attaching a SE1000-HI transducer at 800mm on each of the three thickness bars. (This longer distance was used in order to obtain more accurate velocity measurements). IP and OOP pencil lead breaks were made at the ends of each bar. Figure 8 shows the high frequency and low frequency response on the three bars to OOP pencil lead breaks. A voltage range on the oscilloscope was chosen at a high sensitivity in order to detect the leading edge of the signals for purpose of making velocity measurements on the different waves. Note that on the high frequency channel for each bar a signal with a velocity of 3,200m/sec is observed from all three bars. This constant velocity regardless of thickness along with a value of 3,200m/sec shows these waves to be shear waves. Note in the high frequency data a small amplitude signal having a velocity of 3,700M/sec. The question mark following the velocity value indicates that the mode for this wave is unknown. It might possibly be a 1st order antisymmetrical lamb wave.

The signals observed on the Low frequency channel have a varying velocity which is dependent on plate thickness. This is the type of results one would expect from the zero order antisymmetrical Lamb wave.

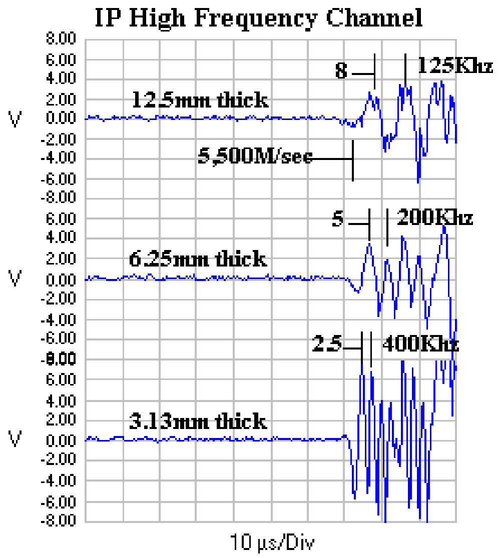


Figure 9

SE1000-HI @ 400mm on three different thickness bars. Showing a constant extensional wave velocity but varying frequency response to 0.3mm in-plane IP pencil lead breaks at the end of the bar. High frequency channel of AESMART 2000, 60dB system gain.

There was also interest in determining if the primary frequency content of the IP and OOP source signals could be determined easily. The transducer was repositioned to 400mm on the bars and the time base was expanded in order to show more detail of the leading few cycles of the signals. Figure 9 shows the response of the SE1000-HI to in-plane(IP) pencil lead breaks at the opposite end of each bar. One can see from this data that there is no apparent change in the extensional velocity as a function of plate thickness.

There is a definite difference in the frequency content of the signals. The frequency of the signal was estimated by measuring the time in microseconds between the first two positive going peaks and dividing this value into 1. Note that the thinner the plate the higher the frequency content, and the higher the amplitude of the signal of these extensional waves. The primary frequencies measured in this manner were: 125Khz for the 12.5mm bar, 200Khz for the 6.5mm bar, and 400Khz for the 3.13mm bar.

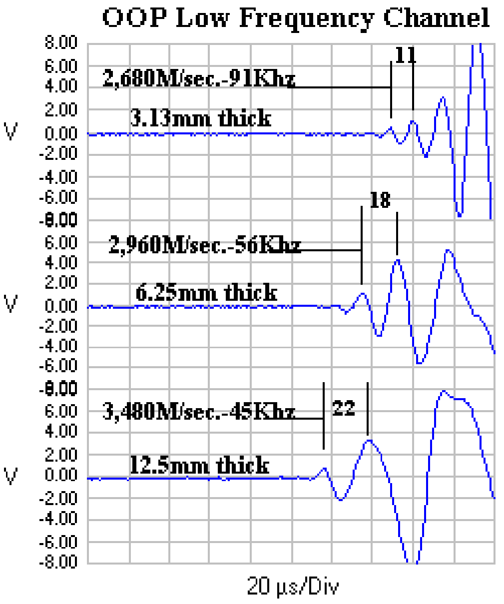
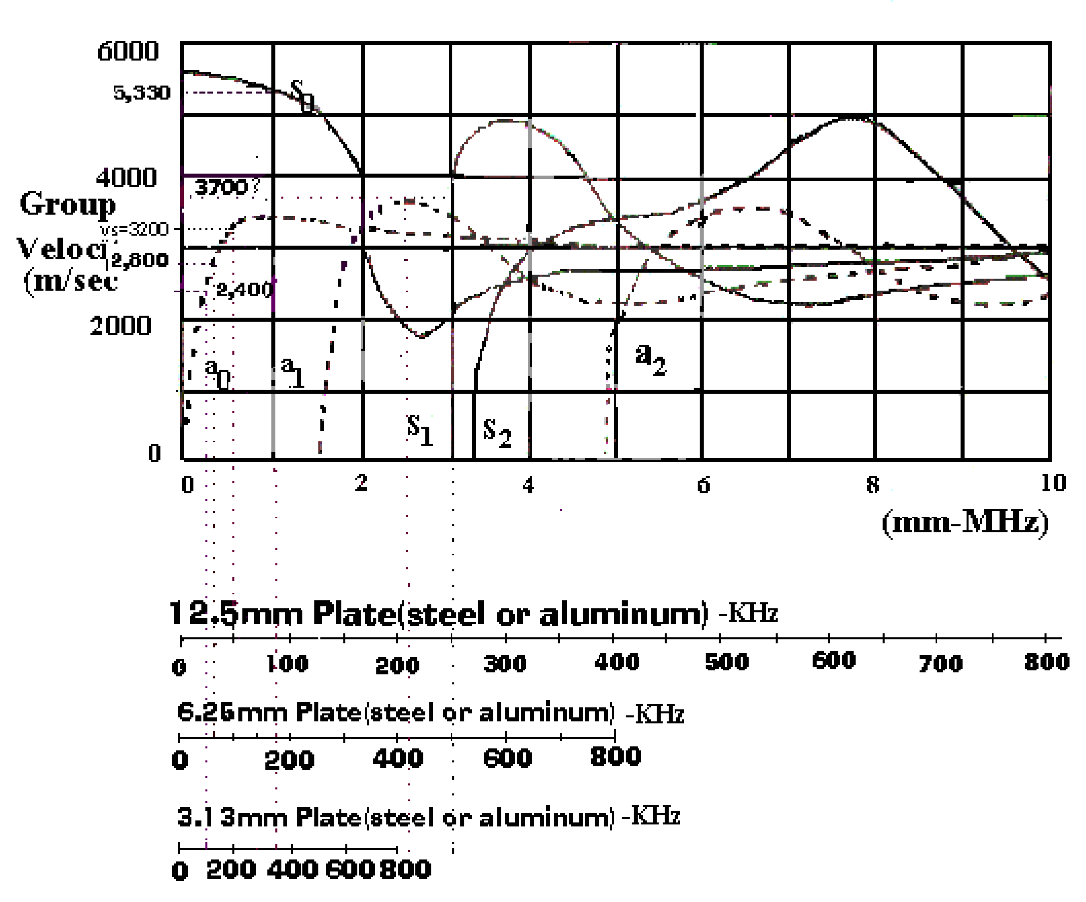


Figure 10

SE1000-HI @ 400mm on three different thickness steel bars. Response to OOP 0.3mm pencil lead breaks at the end. Showing velocity and frequency for each thickness bar. Low frequency channel of AESMART 2000-system gain 40dB.

The same procedure was repeated with the exception that OOP pencil lead breaks were made at the end of the bar in order to create a low frequency flexure wave in each bar. Again the time in microseconds was measured between the first two positive peaks in order to estimate frequency content. This data is shown in figure 10. Observe that the frequency content and amplitude of the signals increases as the bar gets thinner. This is similar to results for extensional waves. The primary difference in the low frequency data is the velocity despersion not present in the high frequency extensional wave data. This increase in amplitude as the bar gets thinner for both the extensional waves and flexure waves is an indicator that the surface displacement is greater in the thinner bars. The velocity despersion of this low frequency wave as a function of thickness shown in figure 8 is repeated in this data. The velocity measurements in figure 10 differ from those in figure 8 by approximately 200M/sec., but the relative differences remain in the same proportion. Note at this sensitivity, that the high frequency precursor for the two thinner plates present in figure 8 are absent from this data. The primary



frequencies measured for the data were: 45Khz for the 12.5 mm bar, 56Khz for the 6.5mm bar and 91Khz for the 3.13mm bar.

Figure 11 shows the group velocities for the first three modes of the Symmetrical (So) and antisymmetrical (ao) Lamb waves in (mm-MHz). Below these curves are corresponding values in Kilocycles for the three steel bars used in these experiments. The smaller numbers on the ordinate are group velocities measured in this study (figures 8 and 9). These values were projected horizontally until they intersected with the proper wave mode. Projections (small dotted lines) from these intersections were then made vertically until intersection was made with the bar from which the velocities were measured. Some interesting observations can be made from this data. Note that the zero order symmetrical mode velocity (So) for all three thickness plates is constant and its projection to the three different plate thickness results in a frequency of approximately 70Khz for the 12.5mm plate, 140Khz for the 6.25mm plate and 280Khz for the 3.13mm plate. These values favorably compare with the measured values in figure 9 considering the possible errors present in only measuring the time between the first two cycles of the signals. Observe that the zero order antisymmetrical mode (ao) for the same bars decreases in velocity such that projection onto the respective bars yields a frequency of 100Khz for the 3.13mm bar, 60Khz for the 6.5mm bar and 50Khz for the 12.5mm bar. These results also compare favorably with the measured results in figure 10.

DISCUSSION OF RESULTS

The stress wave produced in a plate by an impulse source such as breaking of a 0.3mm pencil lead break appears from the data in this report to partition the majority of its energy into three primary waves as it travels away from the source: The So symmetrical lamb wave (extensional), the antisymmetrical lamb wave ao (flexural) and a shear wave. The amount of energy carried by the extensional and flexure waves and therefore their amplitudes when detected depends strongly on whether or not the source direction is in-plane (IP) or out-of-plane with respect to the plate dimensions. The amplitude of the shear wave is not so dependent on source orientation, since it can travel in the plate with different polarization's. For OOP sources a strong flexure wave is produced with very little extensional component, and for IP sources a strong extensional wave is produced with lesser amounts of the flexure wave component depending on the depth in the plate where the source originates (Hamstad ref. 6).

Figure 4 shows the dependence of the extensional wave on source orientation. For the OOP case the extensional wave components are very weak, but note that the shear wave amplitude is approximately the same for both source inputs in the high frequency range. Another example of the effect of orientation is shown by figure 8 which shows a lack of extensional component in the OOP high frequency range and a strong shear wave. The OOP low frequency range for this figure shows a strong flexure wave and a lack of extensional and shear wave components. This is further indication that the extensional and shear waves are high frequency phenomenon and do not have frequency components below 100Khz in plates of the thickness used in this study. This statement is contradicted by the data shown in the IP low frequency range of figure 5. Both extensional and shear waves having low frequency components were detected in this example. The transducer used in the test (SE1000-H) is a high fidelity displacement transducer bonded to the edge of the plate. It was capable of detecting low frequency extensional and shear waves in the plate due to its high sensitivity to displacement and broad frequency response. From a practical standpoint it would be rare that access to the edge of a plate would be available, since in most instances the transducer is placed on the surface of the plate. It has been observed throughout this study that the shear wave is present for both IP and OOP sources and its amplitude is much higher than the amplitude of the extensional wave which leads to the following hypothesis. For IP sources both Sh and Sv shear waves are launched by the pencil lead break at the edge of a plate. The Sv wave will lose energy due to any damping material on the surfaces and due to transfer of energy through mode conversion to a flexure wave. The Sh wave which has particle motion parallel to the plate surface will propagate without mode conversion. This is evidenced by the data in figure 6 which indicates that the Sh wave has more than three times the amplitude of the Sv wave. For the OOP source in figure 6, a strong flexural wave is detected by the vertical polarized crystal in the low frequency channel, while no such wave is detected by the horizontal poled crystal in the same frequency band. Further evidence of this partitioning of energy between modes is shown in figure 4. For an IP source at the center edge of the plate a partitioning of energy is shown by the IP high frequency channel between the extensional and shear wave (no low frequency flexure wave is created by this source). The OOP high frequency amplitude of the shear wave is less than the IP high frequency amplitude due to energy partition to a low frequency flexure wave (not shown). Therefore it appears that one can expect higher amplitude shear waves from IP sources than for OOP sources. If one assumes that the IP pencil lead break truly represents the growth of a crack, the Sh wave is the strongest high frequency wave produced and is probably the predominate wave detected in most field tests using AE instrumentation with high pass filtering above 100Khz , resonant sensors, and large transducer spacing. The data in figure 7 shows that it does not matter whether or not a displacement at the surface is present in order to detect stress waves, a shear wave with polarization parallel (Sh) to the surface will excite the transducer as well as a displacement of the surface if the coupling material has enough stiffness to couple the shear wave to the transducer. Apparently a thin layer of petroleum jelly is sufficient to transfer the energy to the transducer for higher frequency - shorter wavelength signals but not for signals having frequencies below 100Khz, as evidenced by a lack of data in the low frequency channel. The same transducer was used for the data in figure 7 and in figure 5 where a low frequency shear wave was apparently detected. For the situation of figure 5 where the transducer was on the end of the bar as opposed to being on the surface of the bar (figure 7), the detected wave corresponding to the shear wave velocity could have been mode converted signals that created a displacement at the end of the bar.

The data in figures 4 and 5 show a comparison of the SE1000-H high fidelity transducer bonded to the end of three steel bars and the large aluminum plate. Both sets of data show the arrival of the extensional wave and shear wave. The data from the aluminum plate is "cleaner," due to a lack of any edge reflections prior to approximately 500 micro seconds. There is some evidence of side reflections from the bar data, but it occurs after the arrival of the shear wave. Therefore if one is only interested in study of the extensional and shear wave arrival in the high frequency range, and the flexure mode in the low frequency range the finite width bars are suitable subjects for investigating plate waves. The width to thickness ratio for the three bars used in this study ranged from 12 for the thicker bar to 48 for the thin bar. There is no obvious difference in the appearance of the signals in figure 4 due to this wide difference in ratio.

The data in figure 9 shows that the extensional wave velocity remains constant for the three thickness bars used in this study. This is only obvious when increasing sensitivity to view the leading edge of the signals. When viewing the signals such that the shear wave signal remains on scale, there is an "apparent " decrease in velocity when going from the 6.25mm to the 12.5mm bar (fig. 4). The data in figure 10 shows the frequency and velocity variation of the ao wave as a function of bar thickness. The frequency differences are small and are only measurable due to the high fidelity response of the SE1000-HI transducer used in these measurements. Favorable correlation of these frequencies to those obtained from the measured velocities and projection from the group velocity curves to each bar in figure 11 further shows that splitting the signal into a high and low frequency range prior to making velocity measurements allows a high degree of accuracy in measuring the velocity of the slower flexure waves.

CONCLUSIONS

Results of this investigation have shown that for transient signals produced by breaking of 0.3mm pencil lead breaks on plates of thickness ranging from 3 to 12.5mm, that useful signals from the acoustic emission standpoint are only present from extensional waves, zero order antisymmetrical lamb waves, and a shear wave. Researchers in Ultrasonic wave propagation have been able to make use of the higher order Lamb waves due to the ability to transmit harmonic waves having frequency content of the higher mode of interest and in this manner selecting the mode to study. Acoustic emission testing involves detecting waves generated by a transient displacement covering a broad range of frequencies. Higher modes are generated by such an event, but most of the energy appears to be transmitted by the three waves mentioned above. For example note from figure 11 that the first order antisymmetrical mode has a higher velocity and higher frequency content than the zero order mode for a given plate thickness. This higher mode was not detected in this study to any certainty, although there is a hint that a signal having this velocity may be present in some of the data (figure 4). It is shown by the dotted line in figure 11 having a velocity of 3,700M/sec. Note from figure 11 that for plate thickness greater than 3.1mm that the first two zero order Lamb modes are predominate at frequencies below 200 Khz. Plate wave theory only predicts two waves for thin plates: A nondespersive extensional wave, and a despersive flexure wave. This study shows that a strong shear wave is generated in a plate by both OOP and IP pencil lead breaks. This signal unlike the normal Lamb modes associated with wave propagation in plates is nondespersive and therefore travels at a constant velocity regardless of plate thickness and frequency. It is consistently higher in amplitude than the extensional wave, and in the author's opinion is the primary wave detected by AE transducers in field testing of large structures when working at frequencies above 100Khz. This report has shown that an AE transducer is capable of detecting both Sv and Sh waves and that the Sv waves lose energy due to mode conversion and damping material on the plate surface while the Sh wave is not effected by either. It is further shown that the shear wave has very little frequency content below 100Khz Therefore it is postulated that it is the Sh wave that is detected from crack growth as well as noise from impact and friction (since it is generated by both IP and OOP sources) on large plate-like structures such as pressure vessels, piping, and bridges by AE transducers with large spacing. Since the larger aperture resonant AE transducer has a higher sensitivity in detecting the high frequency shear wave over a smaller aperture high fidelity sensor (Ref.4, 5), its use for field testing of large structures is justified. Since the shear wave is generated by both (OOP, noise sources) and (IP, crack growth sources) figures 7,8 , the resonant transducer alone will not provide the type of data needed to separate crack-like signals from noise. The best identifier of OOP (noise) sources is the zero order antisymmetrical Lamb wave ao. If one is interested in using this wave as a tell-tale to identify noise sources, as well as detect the high frequency shear waves, a hybrid transducer the SE9125-M and the AESMART 2000 instrumentation has been developed to separate crack-like signals (IP sources) from extraneous noise (OOP sources) by calculating the ratio of the amplitudes of the two waves to identify whether or not the signal came from crack growth or noise. It is further shown in this report that finite width bars can be used effectively for the study of the zero order plate modes and the shear mode without influence from side reflections since they arrive later than the shear wave in the high frequency channel and higher order Lamb wave modes are not present in the low frequency channel.

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