Submitted September 2003

Lamb Wave Thickness Measurement Potential with Angle Beam and Normal Beam Excitation

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ABSTRACT

It is shown that guided waves can be effectively used for thickness measurement. The measurement gives an estimate of thickness value over some distance, therefore it is valuable for large area thickness measurement or monitoring. In this paper, lamb wave thickness measurement was studied utilizing guided waves generated from normal beam and angle beam transducers. A stainless steel plate with four sections of different thickness was used for the experiments. Experiments were carried out for studying the thickness measurement potential by using peak frequency shifts and group velocity changes. A broadband shock excitation system and a narrowband tone burst excitation system were used for guided wave generation. It was found that normal beam transducers and angle beam transducers with small incident angles were good for the peak frequency shift method while the group velocity method was suitable for angle beam transducers with large incident angles. A difference study of angle beam and normal beam transducer utilization was carried out by using source influence theory.
Keywords: *lamb wave, thickness measurement, peak frequency shift, group velocity, source influence.*

INTRODUCTION

As a fast and efficient nondestructive testing (NDT) technique, ultrasonic guided waves have been widely used in the testing and health monitoring of large area structures, such as pipes, rails, vessels and aircraft. The main benefit of guided waves is the fast testing over a long distance from a single sensor position (Rose, 2002a; Rose, 2002b). When structures age, some thickness degradation or loss may occur due to various field conditions such as corrosion and erosion. Thickness measurement or monitoring is becoming an important aspect of structural health monitoring. Traditional point by point thickness gages utilizing bulk waves are inefficient and can easily miss some critical points in large area structures. Guided wave thickness measurement gives an estimate of the thickness value over a wave propagation distance and therefore achieves a fast and reliable test.

Guided wave thickness measurement has been studied by some researchers. Some examples can be found in Jenot et al. (2001), Pei and Khuri-Yakub (1997), Hayashi et al. (1999), Moreno and Acevedo (1998), Gao et al. (2003), Pei et al. (1995), Moreno et al. (2000) and Sun et al. (1993). Most are for the study of group velocity or phase velocity. In this study, lamb waves are used for thickness measurement of a plate. Experiments were carried out on a stainless steel plate with four sections of different thickness. Thickness measurement methodologies based on peak frequency shifts and group velocity changes were studied. Normal beam transducers and angle beam transducers with different angles were studied with both a tone bust system and a shock excitation system. The theory of source influence was used for a difference study of normal beam and angle beam transducers.

EXPERIMENT SETUP

As shown in Figure 1, a stainless plate with an original 6.15 mm (0.2 in.) thickness was used for the thickness measurement study. The plate was ground to four sections with different thicknesses. From left to right, the thicknesses are 95, 90, 80 and 100%, respectively, of the original thickness. Some experiments were carried out with normal beam and angle beam transducers to test the thickness measurement potential by using peak frequency shifts and group velocity changes. Some broadband 500 kHz normal beam and angle beam piezocomposite transducers were used. A pair of normal beam transducers and a pair of angle beam transducers working in through transmission mode on the sample plate are illustrated in Figure 2.

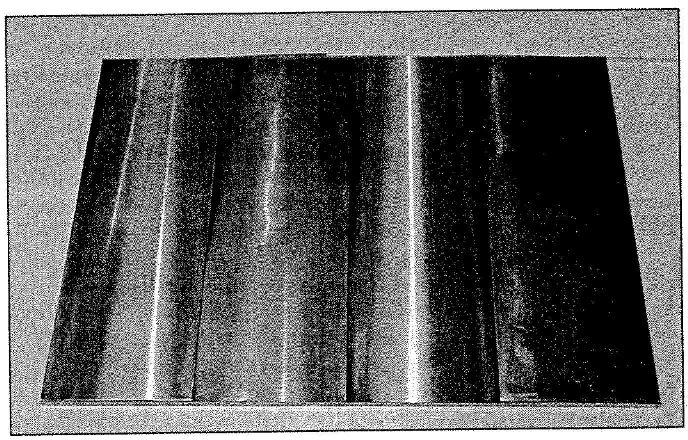

Figure 1 — The stainless steel plate was machined to create four sections with different thicknesses (from left to right: 5% reduction; 10% reduction; 20% reduction; original thickness).

DISPERSION CURVES

Shown in Figure 3 are phase and group velocity dispersion curves for the stainless steel plate used in the study. Computational schemes to achieve the curves are presented in Rose (1999). The results are shown for plates of four different thicknesses. A discussion will follow on how to find special regions of the dispersion curve that are particularly sensitive to thickness variations for peak frequency shifts and then for group velocity changes. Excitation lines for a 13 and 35 degree incident angle used in this study are drawn

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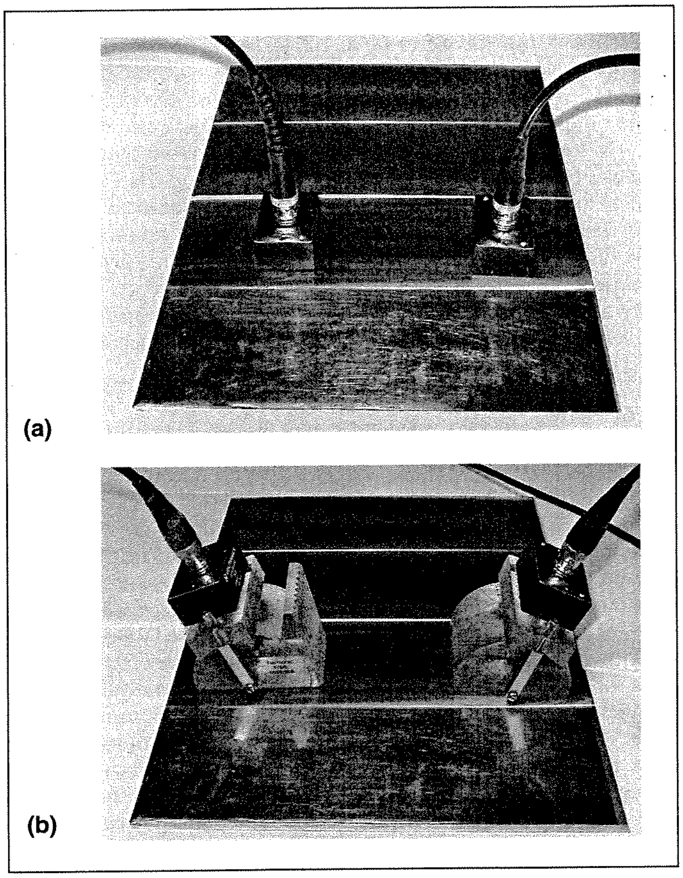

Figure 2 — Thickness measurement experiment setup for the sample plate: (a) 500 kHz normal beam transducers; (b) 500 kHz angle beam transducers working in through transmission mode.

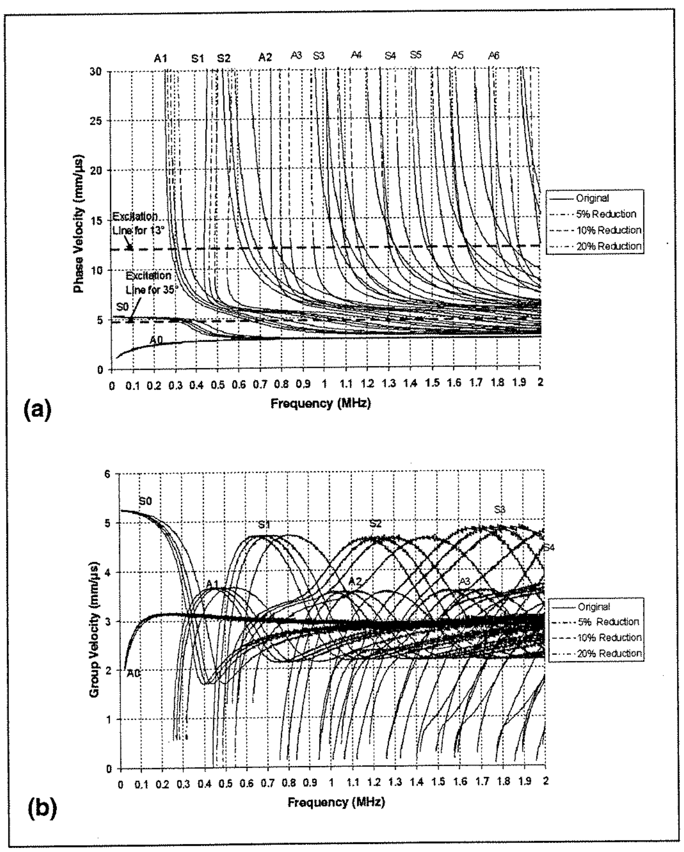

Figure 3 — Dispersion curves for a stainless steel plate with four different thicknesses: (a) phase velocity; (b) group velocity.

in Figure 3a as well. The relationship between incident angle and phase velocity can be established through Snell's law. The phase velocity of an angle is fixed by the acrylic shoes, then producing a horizontal excitation line across the phase velocity dispersion curve. A normal beam transducer has a zero incident angle and therefore has a theoretically infinite phase velocity. A peak will occur when the excitation line intersects with a phase velocity dispersion curve. The frequency at this peak is called the peak frequency. Keep in mind that implicit in all of this work is an understanding of the source influence that is the phase velocity spectrum variation for a transducer as a result of change in incident angle and diameter of the transducer over a particular frequency range (Rose, 1999). The source influence will be considered in this work.

Note that the X axis denotes frequency in Figure 3a. Therefore, the dispersion curves shift right as the thickness decreases for each mode. The peak frequencies will shift right as well. This correlation between thickness changes and frequency shifts allows the lamb wave thickness measurement to be possible. Different modes have different sensitivities to thickness changes. We can see from the figure that the A_0 and S_0 waves show no apparent shifting; hence, they are not useful for finding peak frequency shift. For A_1, S_1 and higher modes, the shifting becomes apparent. There is a monotonic increasing relationship between the thickness deduction and the shifting. Furthermore, the shifting is larger for higher modes. Therefore, higher modes are more sensitive to thickness changes.

For the broadband 500 kHz transducers, A_1, S_1, S_2 and A_2 are all possible for evaluating peak frequency shift. It is easy to find that the shifting measurement would be more accurate when the phase velocity is high, say 30 mm/μs (1.2 in./μs). A normal beam transducer is capable of generating a high phase velocity, so this is good for monitoring peak frequency shift. It will be shown later that the 500 kHz normal beam transducer works at about 25 mm/μs (1 in./μs) as well.

However, there is a limitation on the peak frequency method for solving the inverse problem, which is to calculate the thickness according to the peak frequency. We can see that the S_1 curve with a large thickness reduction, say 20% or more, will shift right very far and mix with the S_2 curve group. Therefore, for the inverse problem, if the wave mode is unknown, it is difficult to tell whether it is the S_1 or S_2 mode. So the inverse problem has multiple solutions. However, in some cases, such as in corrosion monitoring, if we are able to know the initial monitored thickness and the modes of the impinging waves, the solution becomes unique. Also, if the thickness changes are not very large, the method still works. For the measurement of a completely unknown thickness, this method cannot be used to find a unique solution unless the wave mode can be determined, which could often be obtained with an angle beam sensor.

Similarly, the shifting phenomenon also occurs with the group velocity dispersion curves as shown in Figure 3b. Since the fastest wave is the most reliable and the easiest to detect when testing, the mode and frequency for high group velocities are more useful. From the figure, it can be seen that the symmetric modes have higher group velocities than the antisymmetric modes, so they could be used more reliably for thickness measurement. Within the frequency range of 0 to 1 MHz, the 300 kHz S_0 mode and 850 kHz S_1 mode are two good regions for measuring a thickness change via group velocity change. The group velocity of the 300 kHz S_0 mode has a monotonic increasing relationship with the thickness deduction, which makes the solution of the inverse problem unique. However, this is not true for the 850 kHz S_1 mode when considering a greater thickness loss, because its curves may mix with the curves of other modes. On the other hand, the 850 kHz S_1 mode is more sensitive to a thickness change than the 300 kHz S_0 mode. We could use the 300 kHz S_0 mode, then, to measure any value of a thickness deduction, especially for large thickness changes up to 100%. For the requirement of a more accurate measurement, such as 20% or less, we could use the 850 kHz S_1 mode. Note here that the dispersion curves are special for the four thicknesses because the X axis is frequency. For other thicknesses, the suitable frequency regions may be different.

SOURCE INFLUENCE

The theoretical dispersion curves were developed on an ideal assumption that an infinite plane wave can produce a particular phase velocity at a certain frequency. Indeed, the transducer, experimental and instrumentation parameters have some effects on the dispersion curve. The effect of these parameters is called the source influence. Some source influence studies for guided wave applications are given in Rose (1999) and Ditri and Rose (1994). It was found that the transducer diameter and the incident angle were two critical factors for source influence. The phase velocity spectrum improves (becomes narrower) as the transducer diameter increases or the incident angle increases. Figure 4a shows a typical illustration of the phase velocity spectrum of an angle beam excitation. Ideally, the spectrum should be a vertical line (the horizontal excitation line shown before). However, the spectrum has a bandwidth because of the source influence. Shown in Figure 4b is the phase velocity spectrum of a normal beam excitation. Note the phase velocity is very high, which is suitable for finding peak frequency, but the spectrum is very broad, which make the isolation of a particular mode and frequency quite difficult. More details can be found in the references.

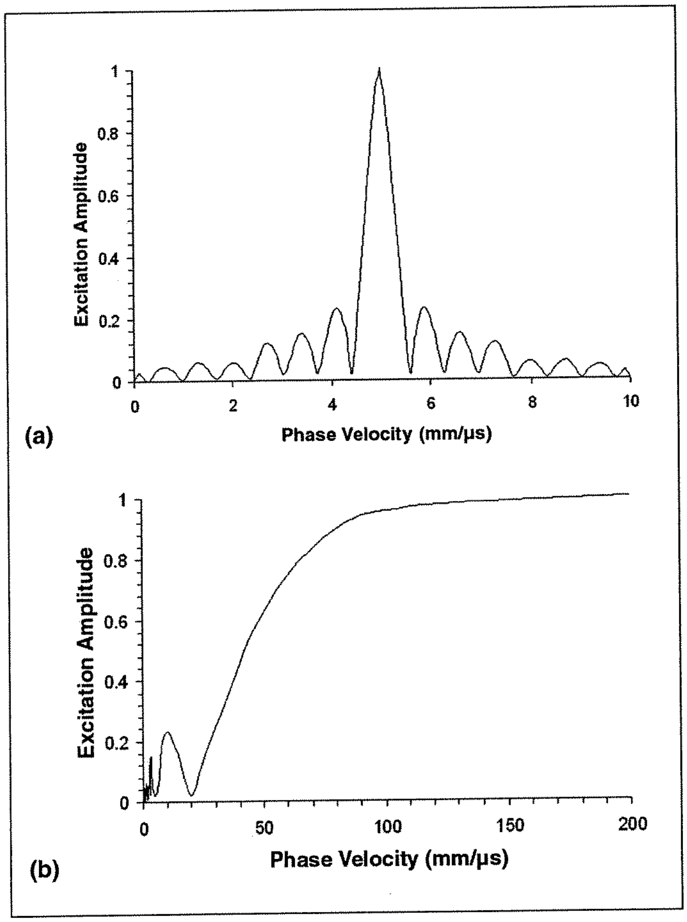

Figure 4 — Phase velocity spectra: (a) angle beam excitation; (b) normal beam excitation.

METHODOLOGY: PEAK FREQUENCY STUDY

Normal Beam

A shock excitation system was used to generate a pulse signal with a very broad frequency band. Then a Fourier transform was used to analyze peak frequency shifts of the received signals. The experimental setup using the 500 kHz normal beam transducer is shown in Figure 2a. Results are shown in Figure 5 and outlined in Table 1. Obvious changes in group velocity were not evident. There were indeed, though, some nice shifting in the peak frequencies to the right with a decrease in plate thickness. Note that only the fastest wave, the wave from 0 to 100 µs in Figure 5a, was considered. Comparing the peak frequency values with the dispersion curve in Figure 3a, it is easy to see that the S_2 mode was dominant while other modes were not apparent. In Table 1, the theoretical phase velocity is indicated as well. This came about by looking at the peak frequency value that was measured and then drawing a vertical line to an intersection point with the theoretical phase velocity dispersion curve. This gave us a point of activation that had a fairly high phase velocity value, which was expected according to the source influence studies. At this point, the theoretical group velocity at that particular frequency value was compared with the measured group velocity. The comparison was reasonable, but indicated no reasonable trend with thickness variation.

Angle Beam

Compared with normal beam transducers, angle beam transducers have narrower phase velocity spectra according to source influence theory. The narrow spectrum is helpful for generating fewer modes or even a unique mode. Experiments were carried out to study the difference between angle beam and normal beam transducers by using a shock excitation system. Because the spectrum width is also related to the incident angle, therefore, different incident angles such as 13 and 35 degrees were used in this study.

Shown in Figure 6 are the signals and their Fourier transform results for 13 degree angle beam transducers. The analysis of peak frequency, phase velocity and group velocity are summarized in Table 2. The signals shown in Figure 6a become simpler with respect to the signals of the normal beam transducers shown in Figure 5a because of the narrower phase velocity spectrum of the 13 degree angle beam transducers. It can be seen in Figure 6b and the peak frequencies in Table 2, that the S_2 mode is still dominant but with a little component of the S_1 mode. The difference is that the peak frequencies are larger than those for normal beam transducers. This is because when the excitation line becomes lower for the angle beam transducers, the intersection points shift right, which makes the peak frequency values larger. That is also why the theoretical phase velocity values become smaller. The measured group velocities also agree with the theoretical group velocities quite well.

Similar experiments were carried out with a 35 degree incident angle and excellent results were obtained for that peak frequency shift value, with a very nicely controlled narrow phase velocity bandwidth. The results are shown in Figure 7 and summarized in Table 3. In this case, the S_0 and A_1 modes became dominant instead of the S_2 mode in the prior two cases. This can also be seen from the intersection area of the 35 degree excitation line and the dispersion curves shown in Figure 3a.

An interesting phenomenon which can be observed in Figures 5b, 6b and 7b is that the width of the frequency spectrum profile increased as the incident angle changed from 0 to 13 degrees and then to 35 degrees. This can be explained as follows. For 0 degrees, the phase velocity is very high and the corresponding dispersion curve is very dispersive so that the excitation line intersects with the dispersion curve almost orthogonally. But when the angle increases to 35 degrees, it can be seen from Figure 3a that the dispersion curve become much less dispersive at the intersection area with the excitation line, which results in a very broad frequency band. It is not difficult to find that the accuracy of determining the peak frequency will decrease when the frequency spectrum profile becomes wider or the incident angle increases along with an increase of phase velocity. This can be demonstrated from the larger error between the measured and theoretical group velocities for this case shown in Table 3. Therefore, the normal beam transducer is more suitable for finding peak frequencies. However, to consider the simplicity of the signal and the accuracy together, the 13 degree angle beam would be a better choice. Other angles could certainly be considered in further studies.

METHODOLOGY: GROUP VELOCITY STUDY

Group velocity was also studied for thickness measurement using a narrowband tone burst excitation system. Normal beam and angle beam transducers were studied and the results were

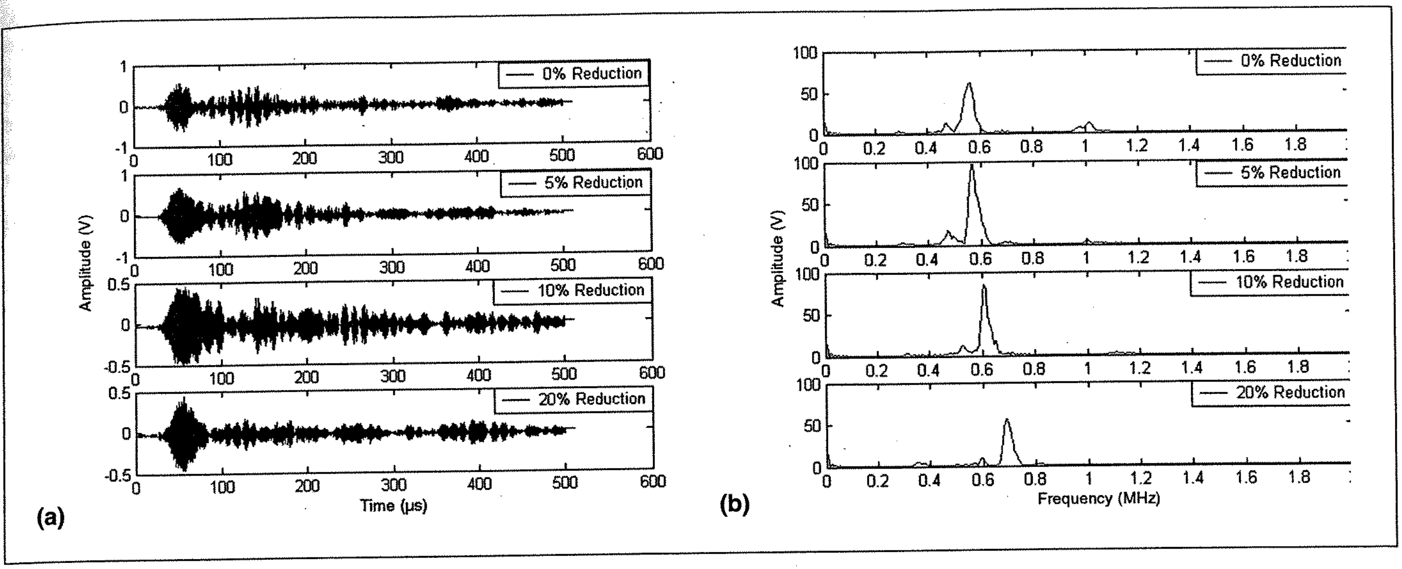

Figure 5 — Normal beam transducer peak frequency study results: (a) the signal; (b) Fourier transform of the fastest arriving wave, the S_2 mode, 0 to 100 µs; acquired by the shock excitation method for stainless steel plates with four different thicknesses, using 500 kHz normal beam transducers. Note the shift in peak frequency to the right with decreasing plate thickness.

Table 1 S_2 mode velocity analysis at the peak frequency for shock excitation using the 500 kHz normal beam transducers (showing peak frequency shift with thickness change but no reasonable trend with group velocity)

	0% Reduction	5% Reduction	10% Reduction	20% Reduction
Peak frequency	561 kHz	566 kHz	609 kHz	689 kHz
Theoretical phase velocity	18.3 mm/µs (0.72 in./µs)	25.2 mm/µs (0.99 in./µs)	22.5 mm/µs (0.89 in./µs)	20.9 mm/µs (0.82 in./µs)
Theoretical group velocity	2.58 mm/µs (0.102 in./µs)	2.33 mm/µs (0.09 in./µs)	2.46 mm/µs (0.097 in./µs)	2.53 mm/µs (0.10 in./µs)
Measured group velocity	2.38 mm/µs (0.094 in./µs)	2.26 mm/µs (0.089 in./µs)	2.42 mm/µs (0.095 in./µs)	2.46 mm/µs (0.097 in./µs)

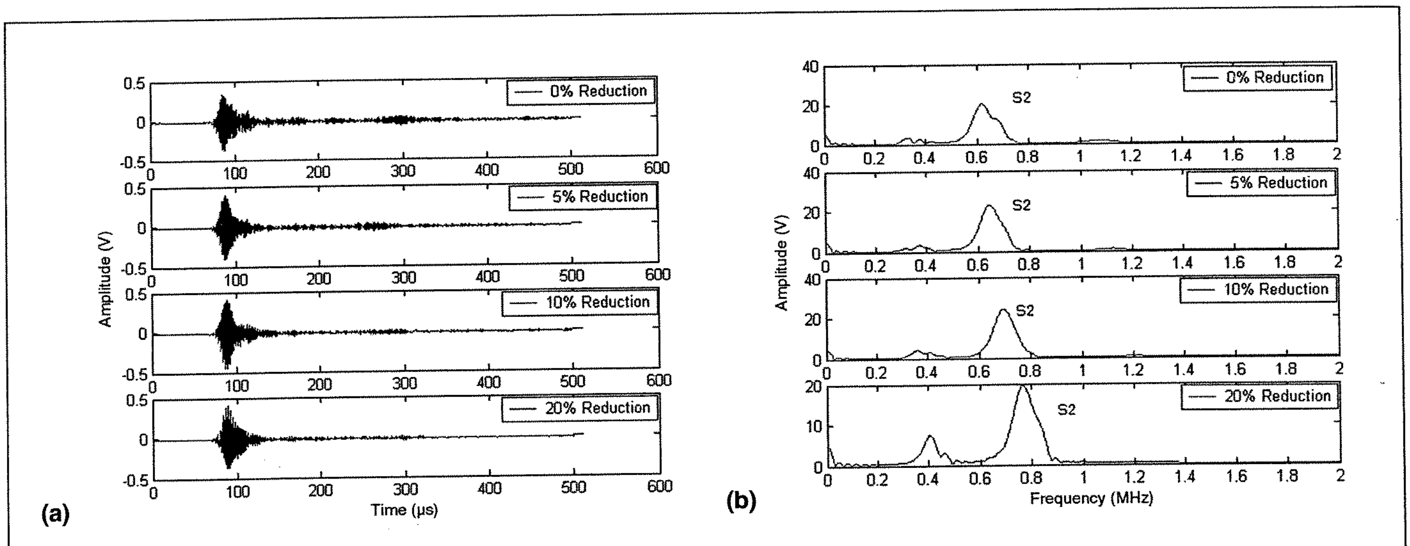

Figure 6 — Angle beam transducer peak frequency study results: (a) S_2 mode signals; (b) Fourier transform of the first arrival signal; acquired by the shock excitation method for stainless steel plates with four different thicknesses using angle beam transducers with 13 degree incident and receiving angle. (Lower frequency mode not useful; note the shift in peak frequency for thickness reduction.)

Table 2 S_2 mode velocity analysis at the peak frequency for shock excitation using 13 degree 500 kHz normal beam transducers (showing peak frequency shift with thickness change)

	0% Reduction	5% Reduction	10% Reduction	20% Reduction
Peak frequency	619 kHz	645 kHz	695 kHz	768 kHz
Theoretical phase velocity	12.0 mm/µs (0.47 in./µs)	12.4 mm/µs (0.49 in./µs)	11.6 mm/µs (0.46 in./µs)	12.3 mm/µs (0.48 in./µs)
Theoretical group velocity	2.95 mm/µs (0.116 in./µs)	2.92 mm/µs (0.115 in./µs)	2.99 mm/µs (0.118 in./µs)	2.94 mm/µs (0.116 in./µs)
Measured group velocity	2.99 mm/µs (0.118 in./µs)	2.87 mm/µs (0.113 in./µs)	2.90 mm/µs (0.114 in./µs)	2.83 mm/µs (0.111 in./µs)

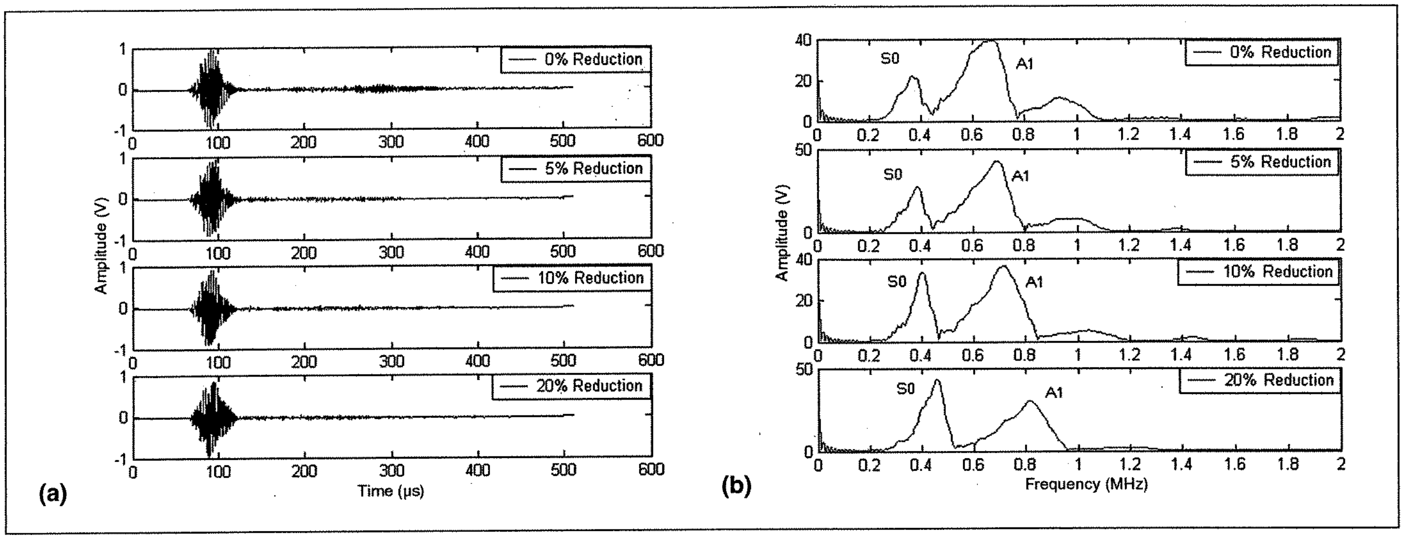

Figure 7 — Angle beam transducer peak frequency study results: (a) the signal; (b) Fourier transform of the first arrival signal; acquired by the shock excitation method for stainless steel plates with four different thicknesses using angle beam transducers with 35 degree incident and receiving angle. (Note the peak frequency shift for thickness change for both S_0 and A_1 modes.)

Table 3 Velocity analysis at the peak frequency for shock excitation using 35 degree 500 kHz normal beam transducers (showing peak frequency shift with thickness change for both S_0 and A_1 modes)

	0% Reduction mm/μs (in./μs)		5% Reduction mm/μs (in./μs)		10% Reduction mm/μs (in./μs)		20% Reduction mm/μs (in./μs)	
Peak frequency	S_0 (367 kHz)	A_1 (672 kHz)	S_0 (387 kHz)	A_1 (691 kHz)	S_0 (402 kHz)	A_1 (723 kHz)	S_0 (461 kHz)	A_1 (816 kHz)
Theoretical phase velocity	4.25 (0.167)	4.65 (0.183)	4.23 (0.167)	4.75 (0.187)	4.31 (0.17)	4.79 (0.189)	4.22 (0.166)	4.77 (0.188)
Theoretical group velocity	1.95 (0.077)	2.36 (0.093)	1.94 (0.076)	2.46 (0.097)	2.05 (0.081)	2.50 (0.098)	1.91 (0.075)	2.50 (0.098)
Measured group velocity*	2.60 (0.102)		2.50 (0.098)		2.51 (0.099)		2.62 (0.103)	

* not measured independently for each mode

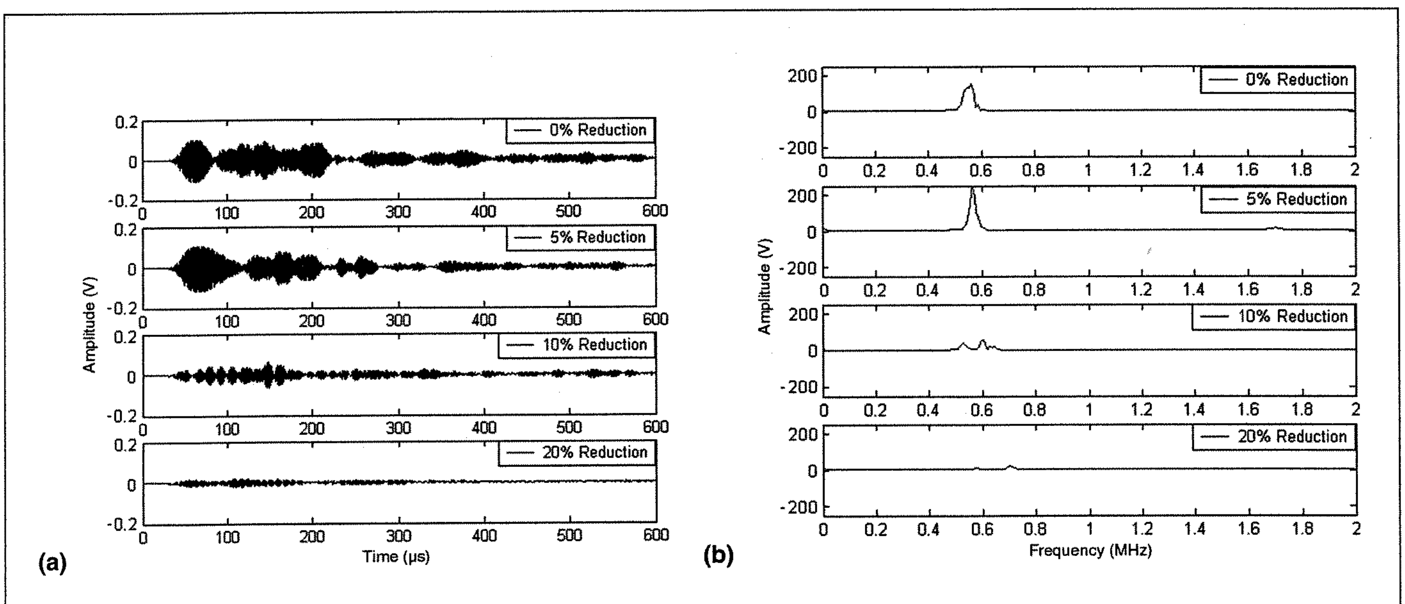

Figure 8 — Normal beam transducer group velocity study results: (a) received signals; (b) Fourier transform of the fastest arriving signal; from a 550 kHz tone burst wave for stainless steel plates with four different thicknesses using normal beam transducers.

Table 4 Group velocity measurements for a 300 kHz tone burst wave using angle beam transducers with a 35 degree incident angle and tuning receiver angle to find the fastest wave, the S_0 mode (showing group velocity increase with thickness deduction)

	0% Reduction	5% Reduction	10% Reduction	20% Reduction
Measured	3.80 mm/μs (0.15 in./μs)	3.90 mm/μs (0.154 in./μs)	4.14 mm/μs (0.163 in./μs)	4.36 mm/μs (0.172 in./μs)
Theoretical for S_0	3.67 mm/μs (0.14 in./μs)	3.97 mm/μs (0.156 in./μs)	4.20 mm/μs (0.165 in./μs)	4.50 mm/μs (0.177 in./μs)

compared with those of the peak frequency study. From Figure 3 it is shown that the group velocity becomes lower when the phase velocity curve is more dispersive. But in practice, only the fast wave is considered for studying group velocity. Therefore, normal beam transducers working at high phase velocities are not suitable, while larger incident angles such as 35 degrees should be better for group velocity studies.

Normal Beam

Some experiments were carried out with a normal beam transducer using a tone burst system at 550 kHz, which was found to be the best frequency working for the original thickness in this case. The mode excited at this frequency was S_2 according to the phase velocity dispersion curves shown in Figure 3a. Results in Figure 8a show that this frequency didn't work well for the 10 and 20% reductions in thickness, whose excitation frequencies shift right. The reason for this, of course, is associated with too narrow a bandwidth of the tone burst waveform. Therefore, it is difficult to measure the group velocities for all the thicknesses at one certain frequency. However, a Fourier transform of the fastest arriving signals, shown in Figure 8b, shows some changes in the peak frequency shift, although the amplitudes are very low for the 10 and 20% reduction thicknesses. If the thickness changes are very large, which means a large shift, this peak frequency shift may not be seen due to the narrow band of the tone burst system. In this sense, the shock excitation is better for the peak frequency shift method because of the broad bandwidth. The group velocity method is not suitable when using normal beam transducers.

Angle Beam

We also considered angle beam excitation using a tone burst system at 300 kHz, which is a good frequency for group velocity thickness measurement. The results for a 35 degree incident angle are shown in Figure 9 and Table 4. In this case, the group velocity results worked out beautifully, but we did tune the receiver angle in order to find the fastest wave. Table 4 shows the measured and theoretical group velocity values of the fast mode. From Figure 3b, the group velocity dispersion curve, it can be seen that the S_0 mode was the fastest mode at 300 kHz. The measured group velocities were reasonable compared with the theoretical values. In looking at the peak frequency shifts, the Fourier transform of the first signal to arrive didn't work well at all, again because of the narrow frequency bandwidth of the tone burst waveform.

A frequency sweep was also carried out for different thicknesses. The result is shown in Figure 10. The angle beam transducers worked very well in demonstrating the peak frequency shift from one thickness to another, this being associated of course with traversing a specific mode in phase velocity dispersion curve space. So it turns out that the frequency sweep idea works beautifully for a tone burst while the fast Fourier transform is not very useful, unless a shock excitation is used.

CONCLUDING REMARKS

Lamb wave thickness measurement was studied using a peak frequency shift method and a group velocity method. Normal beam transducers and angle beam transducers were studied for both of these two techniques by considering the source influence on the phase velocity spectra. It was found that normal beam transducers or angle beam transducers with small incident angles utilizing a shock excitation and a Fourier transform worked quite well for the peak frequency shift method. The peak frequency shifts right as the thickness decreases. The limitation of this method is the requirement of recognizing the signal modes, which allows the inverse problem to have a unique solution. Sometimes the mode recognition is difficult. However, this method is still useful provided the degradation is not very large or signal modes are recognizable. On the other hand, angle beam transducers with large incident angles using a tone burst excitation were most suitable for the group velocity method. The relationship between group velocity changes and thickness changes was established based on the group velocity dispersion curves, provided the right mode, frequency and incident angle were chosen. The 300 kHz S_0 mode is suitable for any

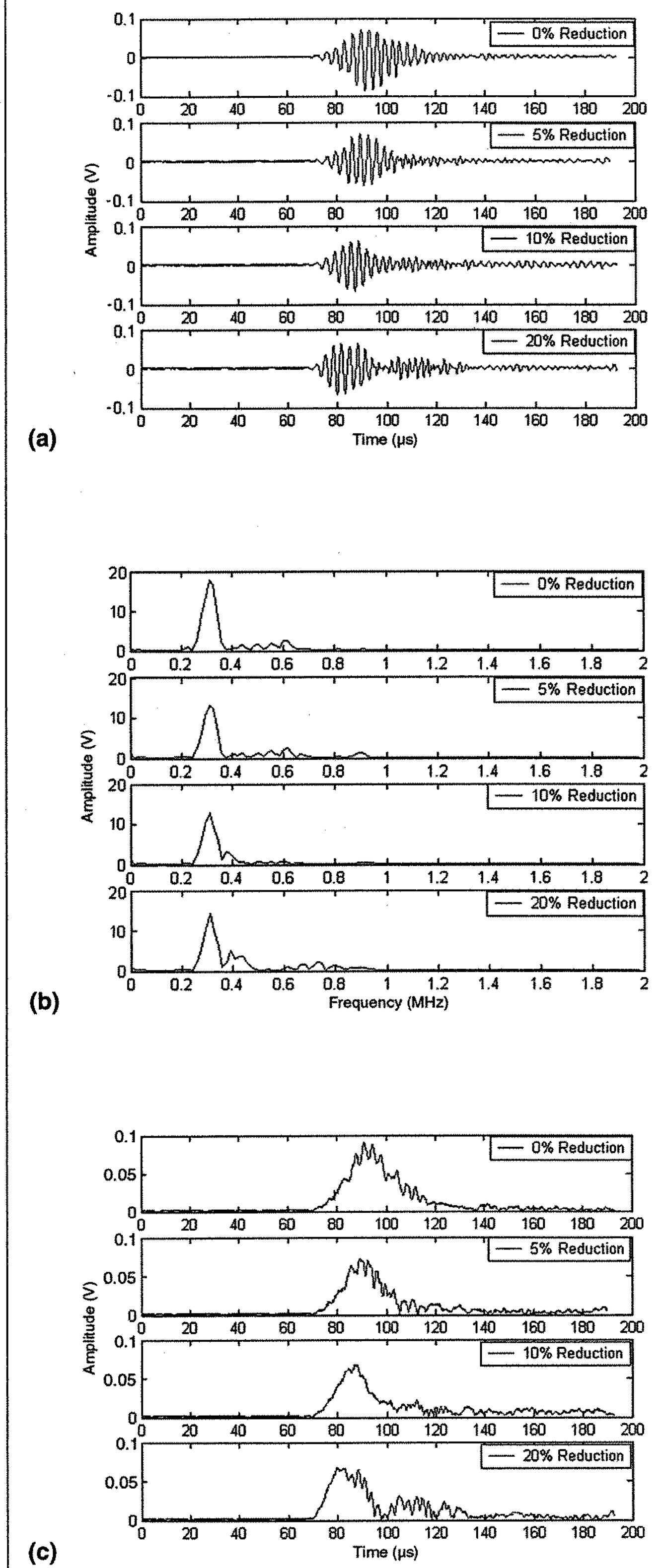

Figure 9 — Angle beam transducer group velocity study results: (a) received signals; (b) Fourier transform of the first arrival signal; (c) Hilbert transform of the received signal of 300 kHz tone burst wave for stainless steel plates with four different thicknesses using angle beam transducers with a 35 degree incident angle and tuning the receiver angle to find the fastest wave, the S_0 mode.

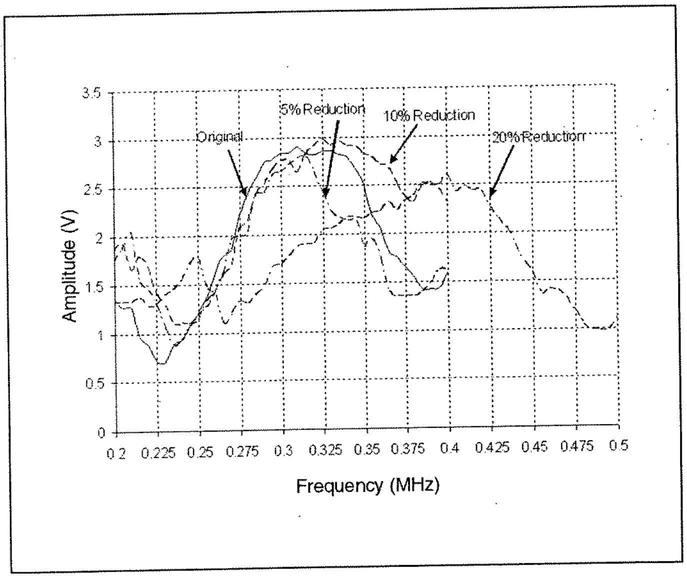

Figure 10 — Frequency sweep results for stainless steel plates with four different thicknesses using angle beam transducers with a 35 degree incident and receiver angle (note that peak frequency shifts with thickness change).

large thickness changes because the S_0 group velocity curves do not mix with the curves of other modes at this frequency. Peak frequency shift phenomena were also observed for the tone burst excitation by sweeping frequency. The source influence theory played an important role in the whole methodology development.

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