A PEAK FREQUENCY SHIFT METHOD FOR GUIDED WAVE THICKNESS MEASUREMENT AND ITS REALIZATION BY DIFFERENT TRANSDUCER TECHNIQUES

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Abstract: Ultrasonic guided wave inspection is much more efficient than traditional point-by-point examination. Guided waves can propagate over long distances from a single position, and therefore is a good method of evaluating thickness degradation, especially for large-area structures such as pipes and vessels. In this paper, guided wave thickness measurement potential is studied utilizing a peak frequency approach. Because guided wave velocities are functions of the product of the frequency and the structure thickness, the dispersion curve of phase velocity vs. frequency will shift as the thickness changes, and the mode excitation frequency, which is called peak frequency, will also shift. The relationship between peak frequency shifts and thickness changes can be used for guided wave thickness measurement. Both Lamb waves and shear horizontal (SH) guided waves were studied. Experiments were carried out on plates with different thicknesses. Phase velocity dispersion curves and their changes with the thicknesses variations were calculated theoretically. Peak frequency shifting information was acquired experimentally by signal analysis for establishing an algorithm of calculating thicknesses from peak frequency shifts. Different guided wave transducer techniques, such as piezoelectric and electromagnetic acoustic transducer (EMAT) technique, were studied and compared for realization of the thickness measurement method.

Introduction: Ultrasonic guided waves can propagate over a long distance from a single point, and therefore present a fast and efficient NDE method for large area structures, such as pipes, rails, vessels, and aircraft [1-2]. 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 gauges utilizing bulk waves are inefficient, for example, for the inspection cases with limited access, and also can easily miss some critical points in large area structures. Guided wave thickness measurement gives an estimate of the thickness value over the wave propagation distance, and therefore realizes a fast and reliable inspection, even for objects with limited access.

Guided wave thickness measurement has been studied by some investigators. But most concentrate on the studies of Lamb wave group velocity or phase velocity. For example, Pei et al. [3] proposed a method utilizing dry contact transducers to detect the thickness variations by the changes in the velocity of the Lamb wave A_0 mode, and then studied tomographic reconstruction of thickness variations using Lamb wave velocities [4]. Moreno et al. [5] evaluated the possibility of thickness measurement for composites by studying the phase velocity of the Lamb wave A_0 mode at a low frequency range, followed by a study of the viscoelastic effect [6]. Hayashi et al. [7] studied the group velocity method using the A_0 mode of laser generated Lamb waves, in which group velocities were estimated experimentally by the wavelet transform. Jenot et al. [8] presented a corrosion thickness gauging method by measuring the group velocity of the Lamb wave S_0 mode. Other studies can be found from the work of Gao et al. [9] and Sun et al. [10].

However, the velocity method usually works at low frequencies for lower order modes, but it is sometimes difficult to measure the velocity for a certain mode because of the superposition of different modes. In this study, a different method considering of a peak frequency shift is presented for both Lamb wave and SH wave thickness measurement of a plate. Some of the ideas presented in this paper were taken from [11] and [12]. Experiments were carried out on various thickness stainless steel plates. Based on an analysis of the acquired wave signals, thickness measurement methodologies were studied employing a peak frequency approach, where the transducer excitation line intersects the phase velocity dispersion curves for generation of a specific wave mode. Different guided wave transducer techniques, such as piezoelectric and EMATs techniques were studied and compared for the realization of this method.

Lamb Wave Method via Piezoelectric Transducers: Figure 1 shows the experiment schematic diagram of thickness measurement on stainless plates with 4 different thicknesses, original 6.15mm, 95%, 90% and 80% of the original thickness. Experiments were carried out with piezoelectric transducers to evaluate the thickness measurement potential by using peak frequency shifts. Some broad band 500 kHz normal beam piezocomposite transducers were used.

Shown in Figure 2 are Lamb wave phase velocity dispersion curves for the stainless steel plates with the four different thicknesses. Lamb wave theory and computational schemes to achieve the curves are presented in [13]. Excitation lines for a certain incident angle, say 13°, are drawn in Figure 2 for illustration. 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 Plexiglas 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 theoretical 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

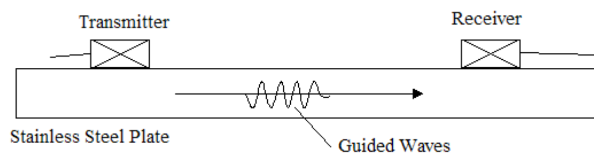


Fig. 1. Experiment schematic diagram of thickness measurement experiments for a plate.

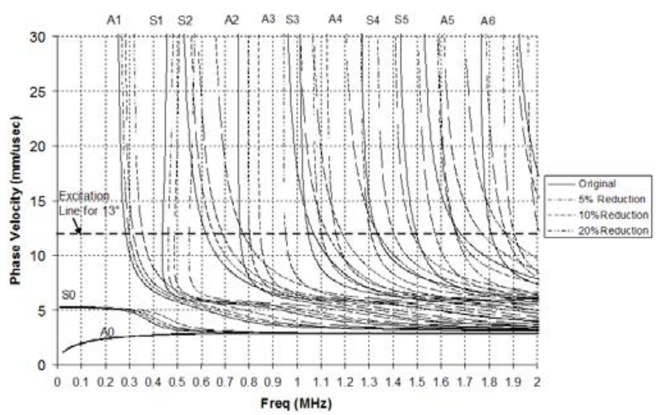


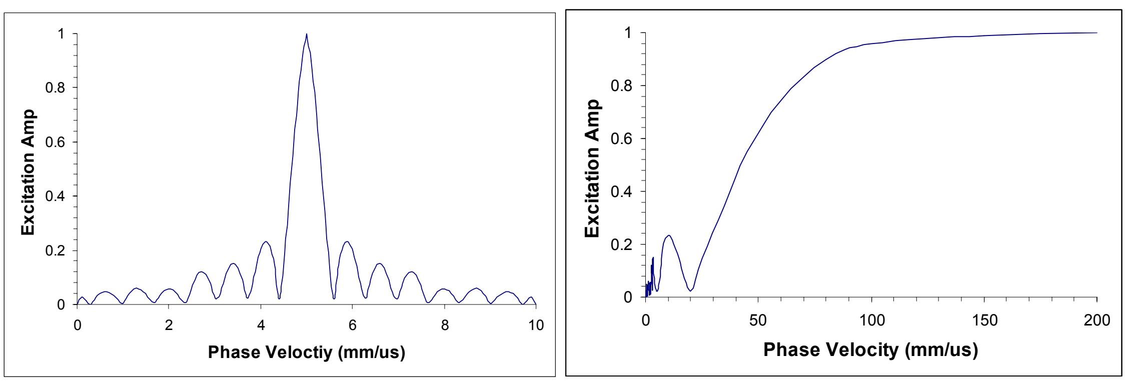
Fig. 2. Phase Velocity Dispersion Curves for a Stainless Steel Plate with four different thicknesses: original, 5%, 10% and 20% reductions

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. See [13]. The source influence will be considered in this work.

Note that the x-axis is frequency in Figure 2. So the dispersion curves shift right as the thickness decreases for each mode. The peak frequencies will shift right as well. This relates thickness changes and frequency shifts together. 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, and hence 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 broad band 500 KHz transducers, A_1, S_1, S_2 and A_2 are all possible in the peak frequency shift approach. It is easy to find that the shifting measurement would be more accurate when the phase velocity is high, say 30 mm/μsec. A normal beam transducer is capable of generating a high phase velocity, so this is good for a peak frequency shift. It will be shown later that the 500 kHz normal beam transducer works at about 25mm/μsec as well.

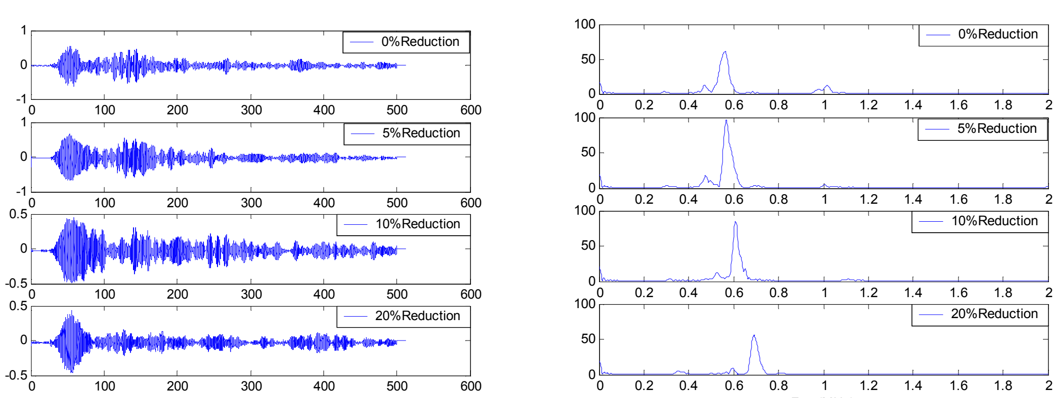
However, there is a limitation on the peak frequency method for solving the inverse problem, which is to calculate the thickness according to the peak frequency. We can see that the S_1 curve with a large thickness reduction, say 20% or more, will shift right quite far and hence mix with the S_2 curve 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.

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 [13-14]. 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 and/or the incident angle increases. Figure 3(a) 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 in Figure 2). However, the spectrum has a bandwidth because of the source influence. Shown in Figure 3(b) 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 makes the isolation of a particular mode and frequency quite difficult. More details can be found in the references.



(a) (b)

Fig. 3. Phase velocity spectra of (a) angle beam excitation, (b) normal beam excitation.



(a) (b)

Fig. 4. (a) The signal; (b) Fourier Transform of the fastest arriving wave, the S_2 mode, 0 to 100 µsec; acquired by the shock excitation method for stainless steel plates with 4 different thicknesses, using 500 kHz Normal Beam Transducers. Note the shift in peak frequency to the right with decreasing plate thickness.

For the experiments, 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. Results are shown in Figure 4 and outlined in Table 1. There were indeed some nice shifts 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 microseconds in Figure 4(a), was considered. Comparing the peak frequency values with the dispersion curve in Figure 2, 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. Data of thickness and peak frequency is also cast into a useful decision chart in Figure 5, in which the 13° angle beam transducer is also considered.

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)

	Original	5% reduction	10% reduction	20% reduction
Peak Frequency (MHz)	0.561	0.566	0.609	0.689
Theoretical Phase Velocity (mm/µsec)	18.3	25.2	22.5	20.9

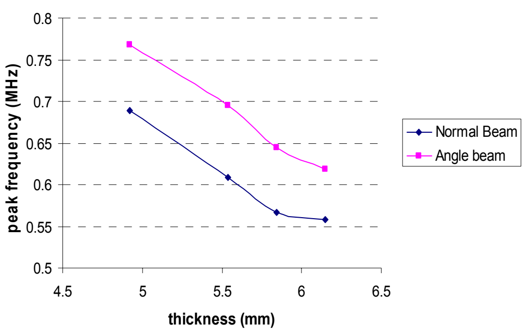


Fig. 5. Experimental curves of peak frequency value vs. thickness, for both normal beam and 13° angle beam transducers

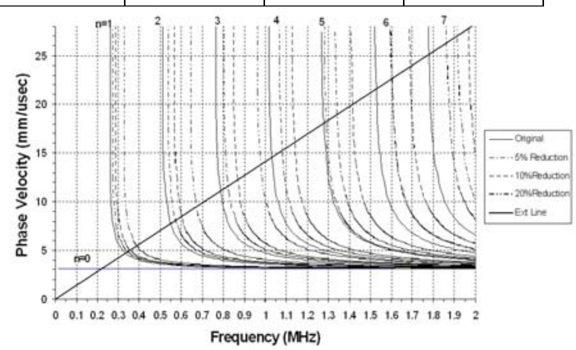


Fig. 6. Phase velocity dispersion curve for SH waves for plates with 4 different thicknesses

SH Wave Method via EMATs: It has been shown that piezoelectric transducers work well for thickness measurement. However, the limitation of piezoelectric transducers is often the requirement of using a couplant. Couplants can possibly contaminate the test object. EMATs are non-contact and easy to use. They can be applied to structures with coatings, rough surfaces and moreover, for special requirements such as high temperature with no contamination. Its operational principle and characteristics can be found in [15]. Some EMATs applications for thickness measurement are given in [16-19]. However, most are for bulk waves.

In this study, experiments using SH wave EMATs were carried out on the same sample plates. The phase velocity dispersion curves of the SH wave are shown in Figure 6. It can be seen that the dispersion curves shift right as the thickness decreases. The phase velocity equals the product of wavelength and frequency. The wavelength of the SH wave is fixed by the magnet spacing of the SH EMAT, therefore, effectively producing a excitation line across the dispersion curve of phase velocity vs. frequency as shown in Figure 6. The slope of the excitation line is just the wavelength of the EMAT. For a different thickness, the dispersion curve will shift right or left. This will result in different peak frequencies.

A tone-burst function generator that performs a frequency sweep was used here instead of the shock excitation system in which the pulse signal has too short duration and low energy to generate EMAT guided waves. Compared with the shock excitation method, the frequency sweeping using a tone-burst function generator is more time-consuming. The amplitudes of the received signals were recorded as the frequencies were swept from low to high. Figure 7 shows the results of frequency sweeping for the 4 thicknesses. It can be seen from Figure 7 that the peak frequency shifts right when the thickness decreases as predicted in Figure 6. An interesting phenomenon is that frequency for the n_0 mode doesn't shift as the thickness changes. This is this because the n_0 curve is non-dispersive and independent on the thickness changes as shown in Figure 6. The peak frequency of n_0 is only decided by the wavelength of the EMAT and the n_0 phase velocity dependent on the material property. Therefore, it can be used for discriminate which mode a certain peak frequency belongs to by comparing the peak frequency with the fixed n_0 frequency.

Knowing the peak frequency and wavelength, the phase velocity can be calculated by multiplying the peak frequency and wavelength. Then the f*d (the product of frequency and thickness) value can be decided from the theoretical phase velocity vs. f*d dispersion curves, by the calculated phase velocity and known mode type. Then, by dividing the f*d value by the peak frequency, we get the thickness of the plate. Some calibrations were carried out on the n_1 mode with the original thickness. The result of this method is shown in Table 2. Four modes, n_1 to n_4, were used to measure the four different thicknesses.

Note here that if we do not know the mode of the peak frequency, the problem becomes a

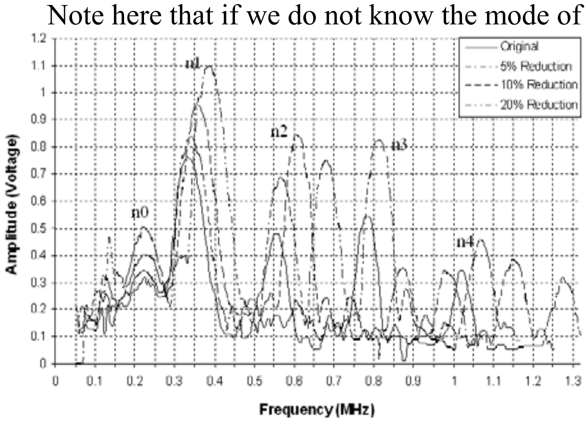


Fig. 7. Frequency sweep results for 4 plate sections with different thicknesses

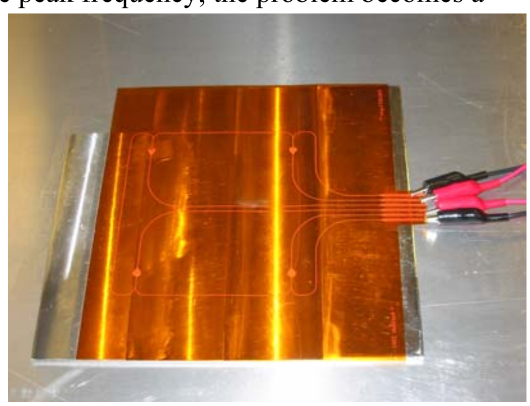


Fig. 8. Thickness measurement experiment using a sensor network embedded into a thin film

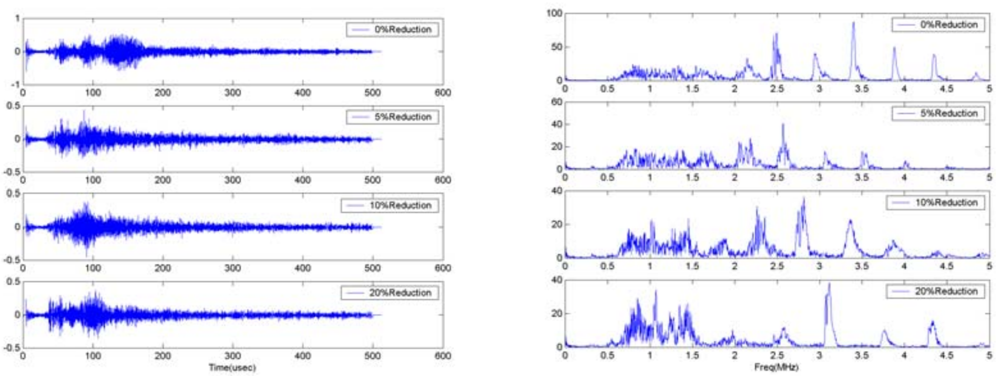
Table 2. EMAT Thickness measurement results, calibration was carried out on n_1 mode and original thickness.

Thickness Reduction	Mode	Freq (MHz)	Real Thickness (mm)	Calculated Thickness (mm)	Error
Original	n_1	0.3435	6.146	6.146	0%
5%	n_1	0.3520	5.864	5.874	0.17%
10%	n_1	0.3645	5.548	5.530	-0.29%
20%	n_1	0.3970	4.884	4.824	-0.98%
Original	n_2	0.5575	6.146	6.125	-0.34%
5%	n_2	0.5700	5.864	5.964	1.62%
10%	n_2	0.6050	5.548	5.556	0.14%
20%	n_2	0.6800	4.884	4.857	-0.45%
Original	n_3	0.7825	6.146	6.230	1.37%

5%	n_3	0.8150	5.864	5.959	1.55%
10%	n_3	0.8725	5.548	5.535	-0.21%
20%	n_3	0.9800	4.884	4.889	0.09%
Original	n_4	1.0225	6.146	6.233	1.42%
5%	n_4	1.0675	5.864	5.957	1.51%
10%	n_4	1.1500	5.548	5.511	-0.61%
20%	n_4	1.2750	4.884	4.951	1.37%

multi-solution problem which means that there are many f*d values for one phase velocity and therefore many thickness possibilities. Although the n_0 is not used directly for the thickness measurement, it allows the method to have a unique solution.

Application of a piezoelectric sensor network: We have shown that piezoelectric normal beam transducers and EMATs work well for guided wave thickness measurement using the peak shift method. However, for some cases, such as the health monitoring of an aircraft wing, those two kinds of transducers are not suitable because of their sizes. A piezoelectric sensor network was studied here for such applications with respect to thickness measurement. Shown in Figure 8 is a sensor network embedded into a thin dielectric layer [20]. The sensor network is composed of several distributed piezoelectric sensors. Each sensor is like a normal beam transducer but with a very small dimension (6.35 mm diameter and 0.254 mm thickness). Therefore, the working theory for the peak frequency shift method is the same as that of the Lamb wave method. The layer can be mounted on the structure surface or integrated into the structure during fabrication process. The sensor itself can also be mounted on a structure surface by using conductive epoxy glue.



(a) (b)

Fig. 9. (a) signals; (b) Fourier Transform of the whole signals; by shock excitation method for stainless steel plates with 4 different thicknesses original, 5%, 10% and 20% reductions, using a piezoelectric smart layer.

Figure 9 shows the testing results for two sensors in the network using the peak frequency method on the sample plates. Broad band shock wave excitation was used here. It can be seen that the peak frequency observation is also a function of thickness changes. Experimental curves for thickness vs. peak frequency can be established by doing more calibration experiments on more thicknesses. The benefit of using the sensor network is the realization of area monitoring in which different sensors can work with each other, thus improving the testing reliability. Further more, the tomographic technique can be utilized to reconstruct the thickness variations of the monitoring area as long as suitable sensor networks are designed.

Summary and Conclusion Remarks: Guided wave thickness measurement was studied utilizing the peak frequency shift method in which both Lamb waves and SH waves were used. Piezoelectric transducers were studied for Lamb waves by considering the source influence on the phase velocity spectra. It was found that normal beam transducers utilizing a shock excitation and a Fourier transform worked quite well for the peak frequency shift method. But 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 at the starting points. A requirement of using a couplant is also a limitation of piezoelectric transducers. SH EMATs are capable of performing non-contact thickness measurement. It has been found that the n1, n2 and higher modes could be used for thickness measurement. The n_0 mode was useful for mode discrimination and allows the inverse problem to have a unique solution. Great accuracy for the thickness measurement was realized. A summary and comparisons of Lamb and SH methods is shown in Table 3. A sensor network layer was also applied for thickness measurement and/or monitoring. Results show great potential in its practical use in structural health monitoring.

Table 3. Comparisons between Lamb and SH thickness measurement methods

Item	Lamb Wave Method	SH Wave Method
Transducer	Piezoelectric transducers	EMATs
Couplant	Required	Non-contact
Excitation method	Shock wave	Tone-burst
How to find peak frequency	Fourier Transform	Frequency Sweeping
Speed	Fast	Slow
Inverse problem	May have multi-solution	Unique solution
Thickness Calculation Method	Experimental thickness vs. frequency curves	Theoretical phase velocity dispersion curve

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