

Guided wave thickness measurement with EMATs

W Luo and J L Rose

Paper submitted 25 September 2003

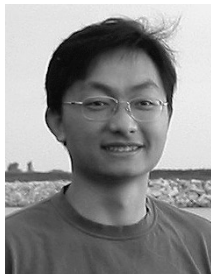
Guided waves can be used for the thickness measurement of a stainless steel vessel. Commonly used piezoelectric transducers for guided wave generation are often not suitable because of potential couplant contamination. Therefore, a non-contact electromagnetic acoustic transducer (EMAT) can be used for non-contact measurements. A sample stainless plate with four different thicknesses was made for the study. A direct and an indirect measurement method based on the relationship between the peak frequency shift and the thickness change were developed. Great accuracy for the thickness measurement was realised.

Introduction

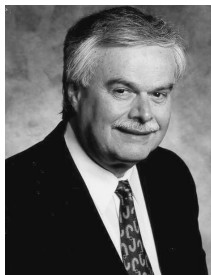
Ultrasonic guided wave inspection is an efficient NDE method compared with traditional point-by-point NDE methods. It can realise fast inspection over long distances from a single position. In many cases with limited access, inspection is still possible for such inspection objects under coating, water, insulation and also for multilayer structures^[1-3].

There are many ways to generate guided waves, for example piezoelectric transducers and electromagnetic acoustic transducers (EMATs). The limitation of piezoelectric transducers is often the need to use a couplant; couplants can possibly contaminate the test object. EMATs are non-contact and easy to use. They can be applied

Wei Luo is currently a PhD candidate and research assistant in the Ultrasonic NDE Lab at the Department of Engineering Science and Mechanics, Pennsylvania State University. He received an M.S. degree in Mechanical Engineering in June, 2001 and a B.S. degree in Mechanical Engineering in June, 1998, both from Tsinghua University, Beijing, China. He is a member of ASNT. His research interests include ultrasonic guided wave NDE, FEM/BEM wave propagation simulation, signal processing and EMAT applications.



Dr Joseph L Rose is the Paul Morrow chaired professor in the Engineering Science & Mechanics Department of Pennsylvania State University. Dr Rose received his PhD from Drexel University in 1970. He received a variety of awards and was a finalist in the 1995 Discover Awards for technological innovation in Aviation and Aerospace for the development of a hand-held probe for aging aircraft inspection. He was also the recipient of a University Faculty Scholar Medal for achievement in Engineering in 1996, an outstanding research award in 1997, and a premier research award in 2002. He was also the ASNT Mehl Honor Lecture recipient in 2001. Dr Rose is a fellow of ASNT and ASME.



Dr Rose is author of over ten patents, four text books, and over 400 articles on ultrasonic NDE, wave mechanics, medical ultrasound, adhesive bonding, concrete inspection, pipe and tubing inspection, and composite material inspection.

Contact address: Department of Engineering Science & Mechanics, the Pennsylvania State University, University Park, PA 16802, USA; Phone: 814-863-8026; Email: jlrsm@engr.psu.edu

to structures with coatings, rough surfaces and moreover, for special requirements such as high temperature with no contamination. EMATs are able to excite not only longitudinal and shear waves but also surface waves, Lamb waves and shear horizontal (SH) waves. Its operational principle and characteristics can be found in the literature^[4-5]. EMATs are commercially available.

Guided wave thickness measurement and inspection have been studied by some researchers. Some examples can be found in the literature^[6-11]. Some EMATs applications for thickness measurement are given^[12-17]. However, most are for bulk waves. In this study, EMAT guided waves are used for a thickness

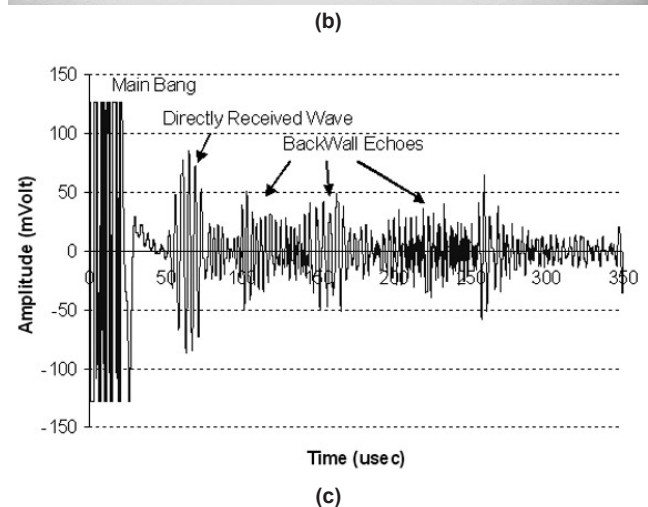
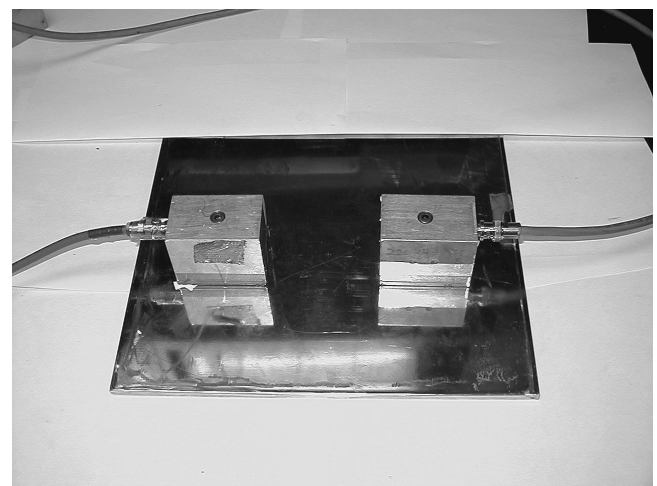
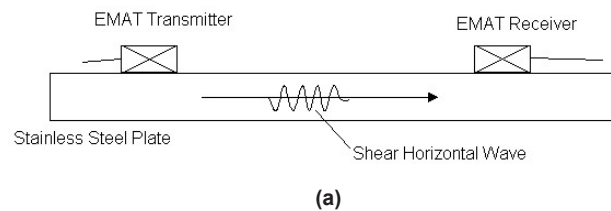
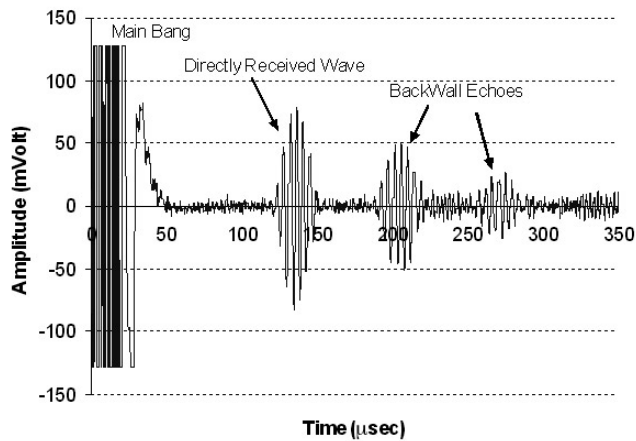


Figure 1. Pitch-catch testing, (a) schematic diagram, (b) set-up, (c) received signal, using 13 mm-wavelength SH EMATs at 235 KHz for the n_0 mode on the stainless plate



(a)



(b)

Figure 2. Pitch-catch testing, (a) set-up, (b) received signal, using 13 mm wavelength SH EMATs at 235 KHz on the stainless steel pipe with the transmitter and receiver placed on the outside

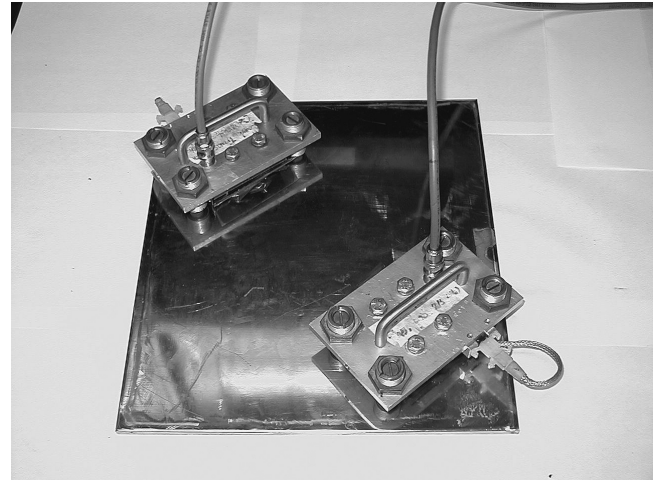
measurement of a vessel. Some experiments were carried out on a sample plate and/or a short sample tube. EMAT shear horizontal and Lamb type waves were used for thickness measurement employing a peak frequency approach where the EMAT excitation line intersects the phase velocity dispersion curves for generation of a specific wave mode. Peak frequency is the frequency at which the maximum amplitude is observed as a tone burst wave is swept over a particular frequency range. A thickness measurement method based on a shift of the peak frequency with the thickness change was developed. The measured thickness values agreed quite well with the actual thicknesses.

Evaluation of EMAT capability

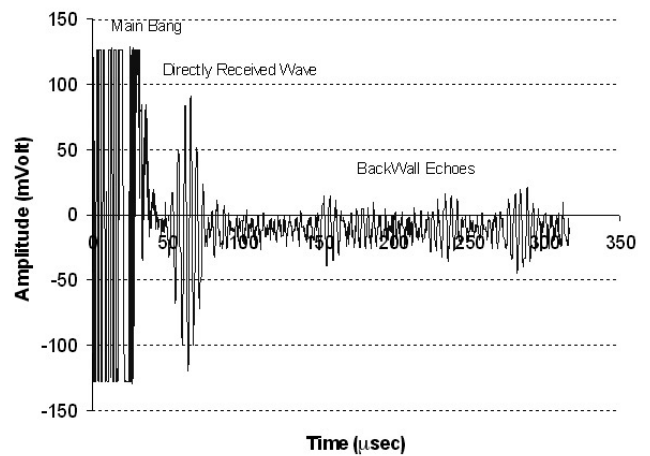
Some experiments were conducted first to see if EMATs could work on stainless steel materials. Figure 1 shows the pitch-catch schematic diagram, testing set-up and the received signal of the n_0 mode generated at 235 KHz by 13 mm-wavelength SH EMATs on a stainless plate with a 6.15 mm thickness. The stainless plate is not magnetic, but it is electrically conductive. The fact that it is electrically conductive makes it possible to generate in the material some ultrasonic waves. Some additional tests were conducted on stainless steel pipes typical of those used in heat exchangers. A pitch-catch test is illustrated in Figure 2 with an EMAT transducer on one end of the structure and the receiver on the other end. In this case, there was no need to remove the plastic wrapping material. Note that the presence of wrapping material does not affect the ultrasonic wave propagation characteristics from one sensor to

another. In this case, scratches on the surface can be avoided.

In addition to the shear horizontal wave propagation studies, some experiments were conducted with Lamb EMATs on both the stainless plate and pipe as shown in Figures 3 and 4. Again, excellent results were obtained. Note that one of the two wave modes, SH or Lamb, might actually be more sensitive to certain kinds of defects, and also one might be more accurate than the other with respect to the thickness determination scheme. This is because the wave structure or displacement field characteristics across the thickness of the test specimen dependant on mode choice and frequency^[18].



(a)



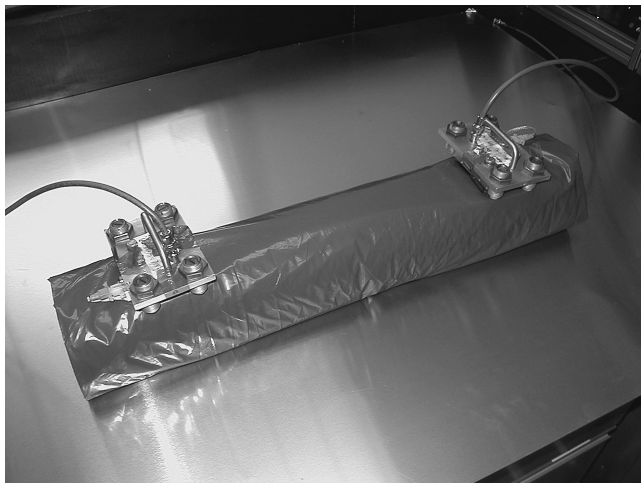
(b)

Figure 3. Pitch-catch testing, (a) set-up, (b) received signal, using 17 mm-wavelength Lamb EMATs at 245 KHz on the stainless plate

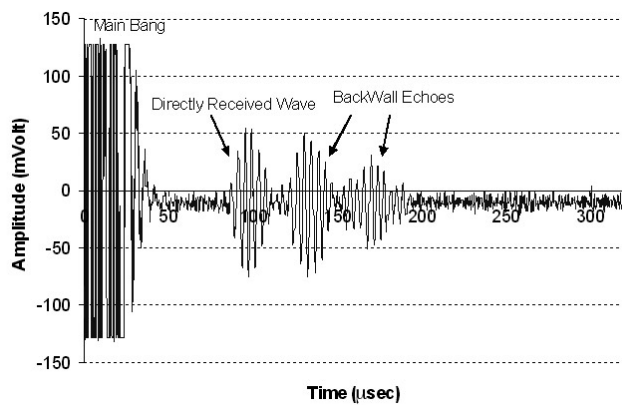
Dispersion curves

Experiments were also conducted to determine the material constants of the stainless steel material which came out to be very close to those already listed in various Tables. A bulk longitudinal wave and shear wave measurement was taken at various positions inside the plate. Guided wave group velocity measurements were also taken at various angles throughout the plate. Isotropy was assumed because variation in group velocity was small enough to be negligible in different propagation directions.

From the elastic constants obtained, dispersion curves were generated for the shear horizontal and Lamb waves for the stainless steel plate, having a thickness of approximately 6.15 mm. Computational scheme are presented in the literature^[18]. The shear horizontal dispersion curves are illustrated in Figure 5 showing phase and group velocities. The Lamb wave dispersion curves for the stainless steel plate are presented in Figure 6. They will be critical to the studies for thickness measurement.



(a)



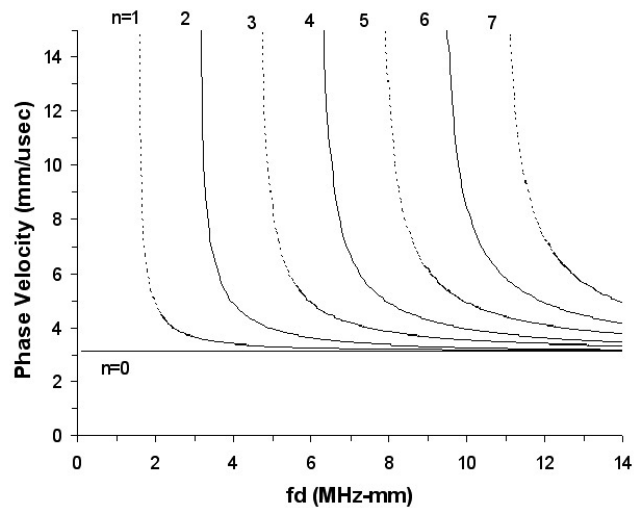
(b)

Figure 4. Pitch-catch testing, (a) set-up, (b) received signal, using 17 mm-wavelength Lamb EMATs at 245 KHz on the stainless pipe

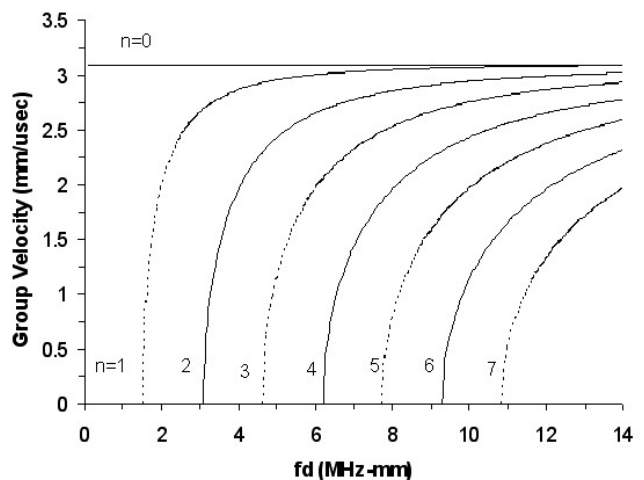
Rather than use the group velocity measurement technique directly, which has been studied by many groups^[7-11], presented here is a simpler technique that could be applicable to both Lamb type and SH waves based on measuring the peak frequency value, and then comparing with a reference dispersion curve. A sample SH measurement is presented in this paper.

Thickness measurement methods

It was decided to carry out a thickness measurement experiment to study the thickness measurement method using a shear horizontal EMAT. As shown in Figure 7, the stainless plate with an original 6.15 mm thickness 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. Figure 8 shows the experimental set-up for thickness measurements using the frequency sweep method. The transducers are shear horizontal EMATs with a 13 mm wavelength. The phase velocity dispersion curves of the SH wave for these four plate sections with different thicknesses are shown in Figure 9. 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 an excitation line across the dispersion curve of phase velocity *versus* frequency as shown in Figure 9. The slope of the excitation line is just the wavelength of the EMAT. When the excitation line crosses the dispersion curve, a peak in detected amplitude will occur and the corresponding frequency is called *peak frequency*. For a different thickness, the dispersion curve will shift right or left. This will result in different peak frequencies.



(a)



(b)

Figure 5. The (a) phase velocity (b) group velocity dispersion curve of shear horizontal wave for the stainless plate

A tone-burst function generator that performs a frequency sweep was used to do the thickness measurement. The amplitudes of the received signals were recorded as the frequencies were swept from low to high. Figure 10 shows the results of frequency sweeping for the four different sections of the plate. It can be seen from Figure 10 that the peak frequency shifts right when the thickness decreases, as predicted in Figure 9.

An interesting phenomenon is that frequency for the n_0 mode does not shift as the thickness changes. This is because the n_0 curve is non-dispersive and independent on the thickness changes, as shown in Figure 9. Therefore, the peak frequency for the n_0 mode is fixed for all the thicknesses, thus making the n_0 mode unsuitable for thickness measurements. The peak frequency of n_0 is only decided by the wavelength of the EMAT and the n_0 phase velocity which is also the shear wave velocity in the material and hence decided by the material property. Once knowing the material and the EMAT, this peak frequency is the same for all thicknesses. This fact is encouraging and valuable because it can be used to discriminate which mode a certain peak frequency belongs to. For example, when we do the thickness measurement on an unknown thickness plate by sweeping frequency, we cannot predict the peak frequency values for n_1 , n_2 or higher modes. We cannot therefore directly know which mode a certain peak frequency is. However, we are able to know the mode by comparing the peak frequency with the fixed n_0 frequency. If the peak is the first one observed after n_0 , the peak should be n_1 mode; if second, it should be n_2 , and so on.

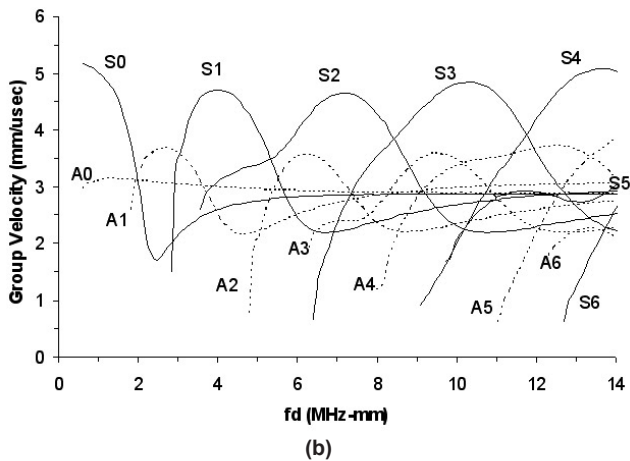
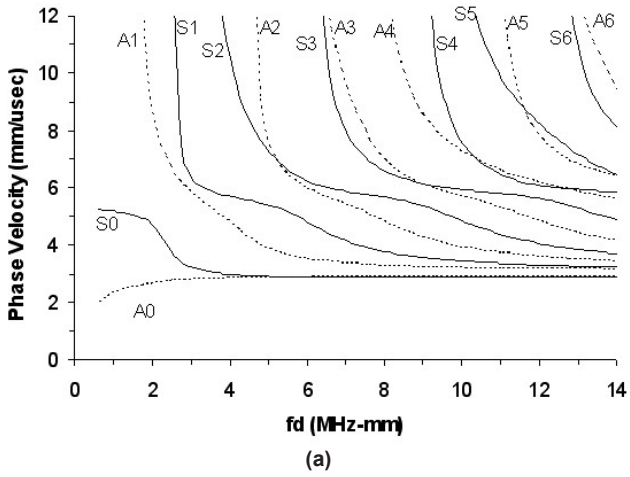


Figure 6. The (a) phase velocity (b) group velocity dispersion curve of Lamb wave for the stainless steel plate

Knowing the peak frequency and wavelength, the phase velocity can be calculated by the product of the peak frequency and wavelength. Then the $f \cdot d$ (the product of frequency and thickness) value can be decided from the phase velocity *versus* $f \cdot d$ dispersions curves as shown in Figure 5(a), by the calculated phase velocity and known mode type. Therefore, by dividing the $f \cdot d$ value by the peak frequency we get the thickness of the plate, thus using the guided waves for thickness measurement. This method is called the *direct method*. The result of this method is shown in Table 1. 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 multi-solution problem which

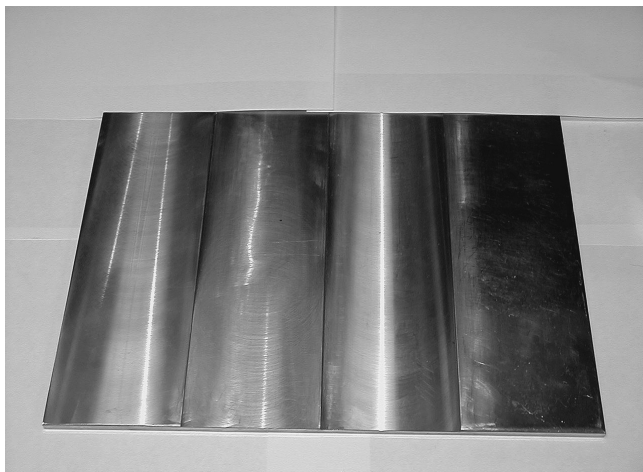


Figure 7. The stainless steel plate was machined to four sections with different thicknesses. From left to right, 5% reduction, 10% reduction, 20% reduction and original

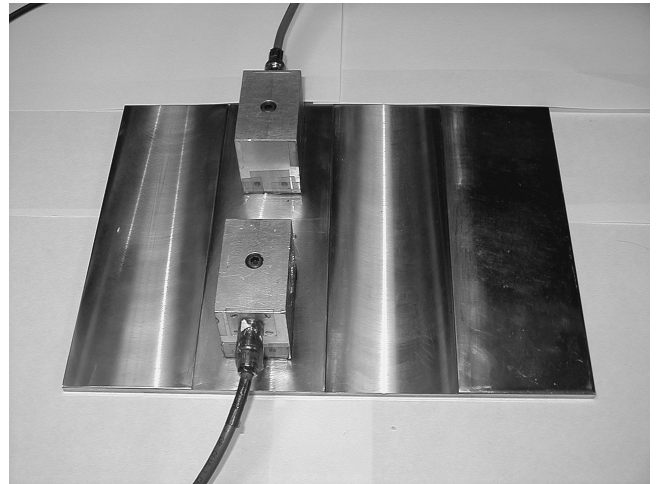


Figure 8. Experimental set-up for thickness measurements using the frequency sweep method. The EMATs shown are shear horizontal EMATs with 13 mm wavelengths

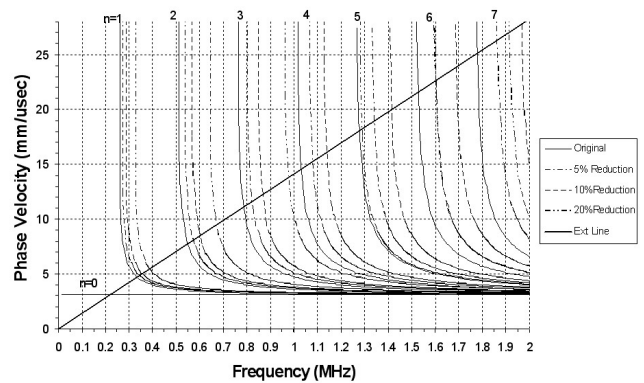


Figure 9. Phase velocity dispersion curve for shear horizontal waves for four plate sections with different thicknesses, showing the excitation line for a 13 mm-wavelength EMAT for the 6.15 mm stainless plate

means that there are many $f \cdot d$ 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.

We can see that the errors for the n_1 mode are larger than others, but still not so bad. Other errors are to be around 1%. This is

Table 1. Thickness measurement results by the direct method

Plate Type	Mode	Frequency (MHz)	Real Thickness (mm)	Calculated Thickness (mm)	Error
Original	n_1	0.3300	6.146	6.6311	7.880%
5% Reduction	n_1	0.3450	5.864	6.0913	3.696%
10% Reduction	n_1	0.3575	5.548	5.7167	2.744%
20% Reduction	n_1	0.3900	4.884	4.9574	1.194%
Original	n_2	0.5575	6.146	6.1251	-0.340%
5% Reduction	n_2	0.5700	5.864	5.9635	1.617%
10% Reduction	n_2	0.6050	5.548	5.5564	0.137%
20% Reduction	n_2	0.6800	4.884	4.8565	-0.447%
Original	n_3	0.7825	6.146	6.2302	1.369%
5% Reduction	n_3	0.8150	5.864	5.9592	1.548%
10% Reduction	n_3	0.8725	5.548	5.5352	-0.208%
20% Reduction	n_3	0.9800	4.884	4.8894	0.088%
Original	n_4	1.0225	6.146	6.2331	1.416%
5% Reduction	n_4	1.0675	5.864	5.9569	1.510%
10% Reduction	n_4	1.1500	5.548	5.5106	-0.608%
20% Reduction	n_4	1.2750	4.884	4.9507	1.365%

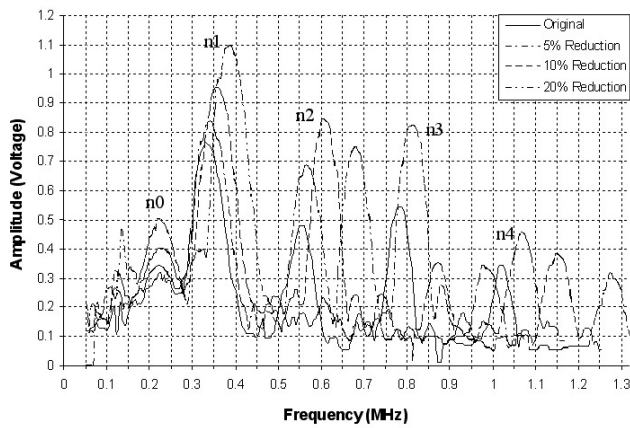


Figure 10. Frequency sweep results for four plate sections with different thicknesses

reasonable. As we know, the more dispersive the dispersion curve, the less error it will generate in deciding the $f \cdot d$ value according to the phase velocity. For the n1 mode, the curves are less dispersive at the crossing points of the excitation line and the dispersion curves so that larger errors occur. Therefore, the higher modes have more accuracy for thickness measurement.

However, we are able to improve the accuracy of the n1 mode by using an indirect method for the n1 mode in calculating the thickness. First, calibrate the measurement for the original thickness and make the error for this case very small by adjusting slightly the measured n1 peak frequency value for the original thickness. Then adjust the n1 frequencies of other thicknesses according to their differences from the initial frequency of the original thickness listed in the Table so that the thicknesses can be calculated by these adjusted relative frequencies. The relative frequency is helpful in removing some unknown errors so that the result could be more accurate. This is why the method is called a *relative method* or *indirect method*. The results are shown in Table 2. We can see that the errors become smaller. The accuracy of n2 and higher modes can also be improved by calibration and using the relative frequency.

Table 2. Thickness measurement results by the indirect method for n1 mode

Plate Type	Mode	Frequency (MHz)	Real Thickness (mm)	Calculated Thickness (mm)	Error
Original	n1	0.3435	6.146	6.1403	~ 0%
5% Reduction	n1	0.3520	5.864	5.8744	0.170%
10% Reduction	n1	0.3645	5.548	5.5301	-0.290%
20% Reduction	n1	0.3970	4.884	4.8236	-0.981%

Summary and concluding remarks

It has been demonstrated in this study that EMATs are capable of performing non-contact thickness measurement of stainless steel materials. Phase velocity and group velocity dispersion curves of both Lamb wave and SH wave of the stainless plate were calculated and applied to the thickness measurement. A sample stainless plate with four sections of different thickness was used for the study. A method based on peak frequency shifts of the SH waves along with the thickness change was developed. It has been found that the n1, n2 and higher modes could be used for thickness measurement while the n0 mode was useful for mode discrimination. Compared with the n1 mode, the n2 and higher modes are more accurate. An indirect method utilising relative frequencies has been studied to improve the measurement accuracy.

References

1. J L Rose, *Ultrasonic Waves in Solid Media*, Cambridge University Press, 1999.
2. J L Rose, 'A Baseline and Vision of Ultrasonic Guided Wave Inspection Potential', *Transactions of the ASME, Journal of Pressure Vessel Technology*, 124, pp 273-282, 2002.
3. J L Rose, 'Standing on the Shoulders of Giants – An Example of Guided Wave Inspection', Mehl Honor Lecture, *Materials Evaluation*, Vol 60, No. 1, pp 53-59, 2002.
4. R B Thompson, 'Physical Principles of Measurements with EMAT Transducers', *Physical Acoustics*, Vol 16, Academic Presses, pp 157-200, 1990.
5. X Zhao, 'Electromagnetic Acoustic Transducer (EMAT) development', Susquehanna Valley Section of the ASNT meeting, November 2001.
6. Y Cho, 'Guided wave monitoring of thickness variation for thin film materials', *Materials Evaluation*, v 61, n 3, pp 418-422, March 2003.
7. F Jenot, M Ouafouh, M Duquennoy, M Ourak, 'Corrosion thickness gauging in plates using Lamb wave group velocity measurements', *Measurement Science and Technology*, v 12, n 8, pp 1287-1293, August 2001.
8. Moreno, Eduardo; Acevedo, Pedro, Thickness measurement in composite materials using Lamb waves, *Ultrasonics*, v 35, n 8, Jan, 1998, p 581-586.
9. Gao, Weimin; Glorieux, Christ; Thoen, Jan, Laser ultrasonic study of Lamb waves: Determination of the thickness and velocities of a thin plate, *International Journal of Engineering Science*, v 41, n 2, January, 2003, p 219-228.
10. Pei, Jun; Levent Degertekin, F; Khuri-Yakub, Butrus T; Saraswat, Krishna C, In situ thin film thickness measurement with acoustic Lamb waves, *Applied Physics Letters*, v 66, n 17, Apr 24, 1995, p 2177.
11. Sun, Keun J, Kishoni, Doron; Johnston, Patrick H, Feasibility of using Lamb waves for corrosion detection in layered aluminum aircraft structures, *Proceedings of the IEEE Ultrasonics Symposium*, v 2, 1993, p 733-736.
12. M Gori, S Giamboni, E D'Alessio, S Ghia, F Cernuschi, 'EMAT transducers and thickness characterization on aged boiler tubes', *Ultrasonics*, v 34, n 2-5, pp 339-342, June 1996.
13. P Crowther, C Edwards, S B Palmer, S D Kenny, 'Ultrasonic thickness measurement of power station boiler tubes using electromagnetic acoustic transducers', *Insight: Non-Destructive Testing and Condition Monitoring*, v 39, n 9, pp 618-621, September 1997.
14. S Dixon, C Edwards, S B Palmer, 'High accuracy non-contact ultrasonic thickness gauging of aluminum sheet using electromagnetic acoustic transducers', *Ultrasonics*, v 39, n 6, pp 445-453, October 2001.
15. R J Dewhurst, P R Murray, 'Application of a laser/EMAT system for using shear and LS mode converted waves', *Ultrasonics*, v 40, n 1-8, pp 771-776, May 2002.
16. S B Palmer, S Dixon, C Edwards, 'Non-contact ultrasonic thickness gauging of aluminum sheet with sub-micron accuracy using Electromagnetic Acoustic Transducers (EMATs)', *Proceedings of SPIE - The International Society for Optical Engineering*, v 4704, pp 187-195, 2002.
17. M Hirao; H Ogi, 'SH-wave EMAT technique for gas pipeline inspection', *NDT & E International*, v 32, n 3, pp 127-132, April 1999.
18. J L Rose, *Ultrasonic Waves in Solid Media*, Cambridge University Press, p 200-240, 1999.