LASER GENERATION OF RAYLEIGH AND LAMB WAVES FOR ULTRASONIC NONDESTRUCTIVE TESTING

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INTRODUCTION

Laser ultrasonics has been the focus of several research efforts over the last two decades. The main advantage of the technique is its noncontact nature which alleviates the problem of sensor coupling inherent in conventional techniques. However, laser ultrasonics has some limitations When operated in the thermoelastic regime, where no damage is inflicted on the surface of the specimen, the signal-to-noise ratio (SNR) is very small, particularly when compared with conventional piezoelectric generation.[1] Several authors have proposed increasing the SNR by producing a source with spatial periodicity designed to enhance a particular wavelength. Royer and Dieulasaint [2] have used a periodic mask, Wagner *et al.* [3] have used a lenticular array, Vogel [4] and Berthelot and Jarzynski [5] have used an array of optical fibers. Cielo *et al.* [6] increased the SNR by increasing the displacement by geometrical focusing. They detected the displacement of surface waves at the center of an anular source and demonstrated that it was 20 times greater than that of a spot source.

The objective of the present study is two-fold. First, a new method is proposed to improve the SNR. It consists in using a Fresnel lens to create on the surface of the specimen an array of curved line sources (arcs of circles) with adjustable length and spacing. A greater SNR is achieved by reducing the bandwidth of the signal of interest (spatial periodicity) and by increasing the signal amplitude by focusing (curved line sources). This "Fresnel-array" method offers the advantages of low cost and convenience.

The second objective of the study is to demonstrate how dispersion curves for Lamb waves in plates can be determined experimentally by laser ultrasonics. Most of the material published so far on the subject has dealt with very thin plates in which only the lowest symmetric and antisymmetric modes were excited. The method presented here is essentially the same as that described by Alleyne and Cawley [7] but it is here obtained with laser ultrasonics. Several potential applications of the technique are discussed. In particular, it is believed that this type of frequency-wavenumber technique can be applied to study Love waves in layers and composites.

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

FRESNEL ARRAY

Ultrasound was generated with a pulsed ruby laser. By Q-switching, pulse durations of 60 ns with pulse energies of 120 mJ were attained, with variations of approximately 12 mJ. Neutral density filters were employed to attenuate the pulse energy in order to avoid ablating the specimen. The signals were detected with a Valpey-Fisher pinducer, the diameter of which was 1.3 mm. A typical signal produced by a laser generated Rayleigh wave on an aluminum block is shown in Fig. 1a. This signal was digitized with a Tektronix 420 digital oscilloscope and transferred to a micro-computer via GPIB.

The array was created by placing the Fresnel lens in front of the specimen so that the beam from the pulse ruby laser passed through it. This causes the beam cross section to transform into an array of concentric arcs as it strikes the surface of the specimen. The spacing between the arcs can be adjusted by varying the distance between the lens and the specimen. The lens was positioned relative to the beam and the pinducer so that the pinducer lay at the center of the concentric circles described by the arcs. By creating an array of sources the bandwidth was decreased and by placing the pinducer at the "focal point" of the array the displacement was increased. Thus, SNR was improved since Wagner *et al.* [3] have shown that the SNR is proportional to the square of the displacement of the surface wave and inversely proportional to the bandwidth.

By experimentation, it was determined that the optimum amplitude was achieved when the Fresnel lens was placed 22 cm from the specimen. A typical waveform and its spectrum is shown in Fig. 1b. The smaller amplitude cycle in the middle of the signal indicates that the laser beam was probably not truly Gaussian across its section.

The particular Fresnel lens used in this experiment had a focal length of 2.54 cm and 3.94 lines per mm. Using geometrical arguments, it was calculated that there were about 12 arcs in the array. This compared favorably with the number of cycles in the signal, as shown in Fig. 1b. The spacing between arcs was calculated to be 1.95 mm using similar geometrical arguments. It was then determined that the frequency at which the spectrum was a maximum was approximately 1.52 MHz. If we consider that the line spacing is equal to a wavelength of the Rayleigh wave, and consider the relation $\lambda f=c$, where λ is the wavelength, f is the frequency, and c is the Rayleigh wave speed, then we calculate a Rayleigh wave speed of 2964 m/s. This agrees very well with accepted values of the Rayleigh wave speed and appears to validate the technique.

Using this technique to construct arrays offers a couple of advantages. The first is convenience. Constructing a thermoelastic array with the Fresnel lens is very easy. The second is affordability. Fresnel lenses can be purchased for $50 or less.

ANALYSIS OF DISPERSION CURVES

In this section it is shown that the modes in a plate can be determined by taking a 2 dimensional Fast Fourier transform (2-D FFT) of a series of waveforms recorded at various positions on the specimen. The time/frequency and position/wavenumber FFT's allow the visualization of the signals in the frequency-wavenumber domain. Alleyne and Cawley first demonstrated this technique using conventional wedge transducers and the coincidence effect for the generation and detection of Lamb waves.[7] It will be shown here that this method can be used in conjunction with the more broadband thermoelastic laser source in which several modes are excited at once. The laser based technique is well suited for this type of experiment because coupling with the sample is not an issue.

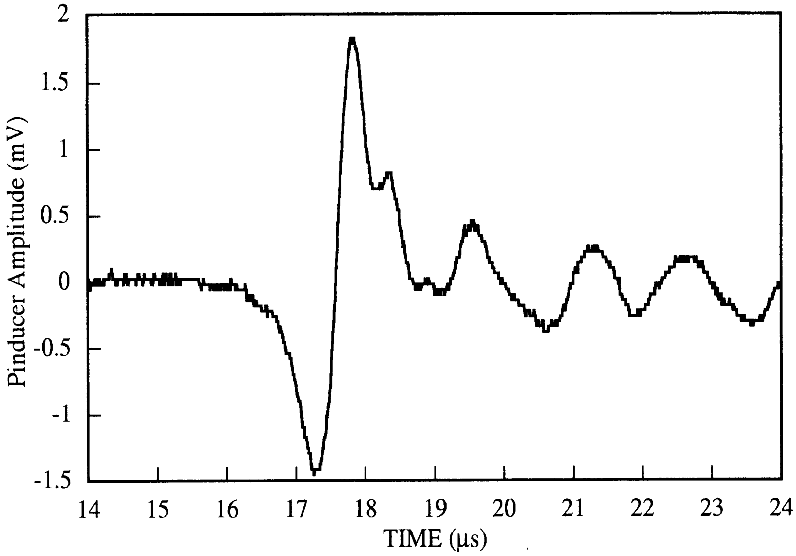

Fig. 1a Laser generated Rayleigh wave on aluminum block.

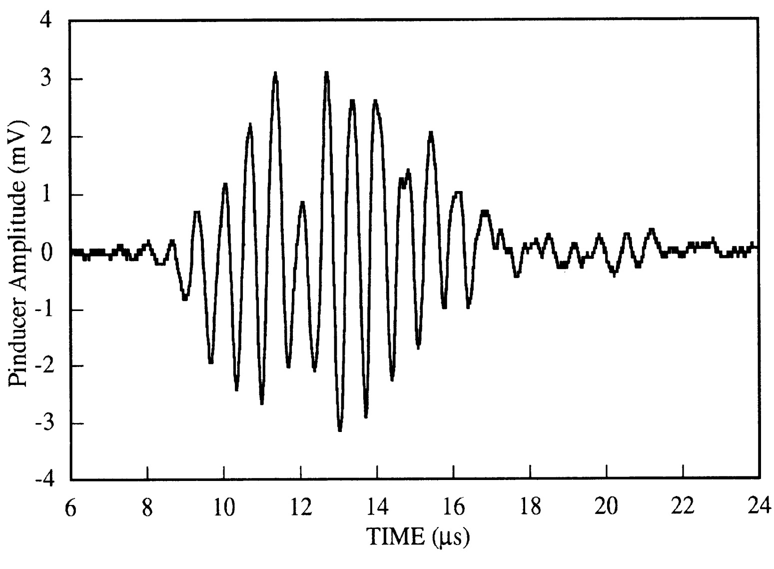

Fig. 1b Rayleigh wave generated with Fresnel array.

To implement this technique, a series of temporal waveforms were recorded at a series of source-receiver separations. In these experiments, the pinducer was attached to the specimen so that both were translated with respect to the incident laser beam. This had the advantage of avoiding any variability in the pinducer-specimen coupling that would have occurred had the pinducer been moved with respect to the specimen. Since this has the effect of sampling the signal spatially, the separations were incremented by an amount that would satisfy the Nyquist criteria.

A matrix was created with this data in which the columns were the temporal waveforms at each successive spatial increment. A 2-D FFT was taken of this matrix. The result of this operation was a complex valued matrix of the same size as the original in which the columns represent the Fourier transform with respect to time and the rows represent the Fourier transform with respect to the spatial direction. Then, the magnitude of each of the values in this matrix was taken to create a 2-D spectrum. This matrix was considered as a surface and represented as a contour plot, one axis of which was the wavenumber and with the other being frequency.

In order to verify the procedure, this experiment was performed first on an aluminum block. Rayleigh waves propagating on the surface of an aluminum block are not dispersive. The frequency-wavenumber contour plot should therefore exhibit a straight line whose slope is the Rayleigh wave speed. Since in our experiment most of the energy in the Rayleigh wave is contained at frequencies below 2 MHz, a separation distance of 0.5 mm between source positions should be adequate to avoid spatial aliasing. This is particularly true when taking in consideration the finite width of the pinducer. A total of 45 signals were recorded over a total travel distance of 22.0 mm. The temporal sampling rate was 100 MHz with a record length of 2500 points. Each time waveform was averaged over 5 signals to improve the signal-to-noise ratio.

This procedure produced a 2500 by 45 matrix. The resulting contour plot in the frequency-wavenumber domain is shown in Fig. 2a. The plot reveals that the dispersion relation for Rayleigh waves is indeed linear. Each column in the results matrix is a function of frequency and each row is a function of wavenumber. In Fig. 2b, the maximum in each column has been found and replotted against the same axes. A linear least squares fit to these points reveals a Rayleigh wave speed of 2870 m/s with a standard deviation of 38 m/s, which is very close to the accepted value. Admittedly, this would be a cumbersome procedure just to find the Rayleigh wave speed. Indeed, by using time of flight measurements, the Rayleigh wave speed was found to be 2950 m/s. However, it does serve to validate this technique.

The real value of this technique is to determine the dispersion relations in waveguides which are highly dispersive. To show this, the experiment was repeated in a 1.016 mm (0.040 in.) thick plate. Fifty-one waveforms were recorded with a spatial sampling interval of 1.0 mm. The temporal sampling rate was 25 MHz with a record length of 4096, with each waveform being averaged 5 times. This resulted in a 4096 by 51 matrix. One of these waveforms is shown in Fig. 3. Both the lowest order symmetric and antisymmetric modes can be seen in this figure. The antisymmetric mode is clearly dispersive.

The 2-D FFT was applied to this matrix. As can be seen in Fig. 3, the symmetric mode is of lower amplitude than the antisymmetric mode. As a result, the resulting magnitudes on the 2-D spectrum surface were small. In order to enhance their contribution to the contour plot, the logarithm base 10 was taken of each value of the spectrum matrix after one was added to it to produce always positive contour values. The resulting contours are shown in Fig. 4a.

The local maxima in each column were found in the original 2-D spectrum matrix, i.e., without adding one and taking the logarithm. These were plotted against the theoretically determined dispersion curves. These curves were calculated using the values of 6300 m/s for the compressional wave speed and 3100 m/s for the shear wave speed. The results are shown in Fig. 4b. The results are very encouraging.

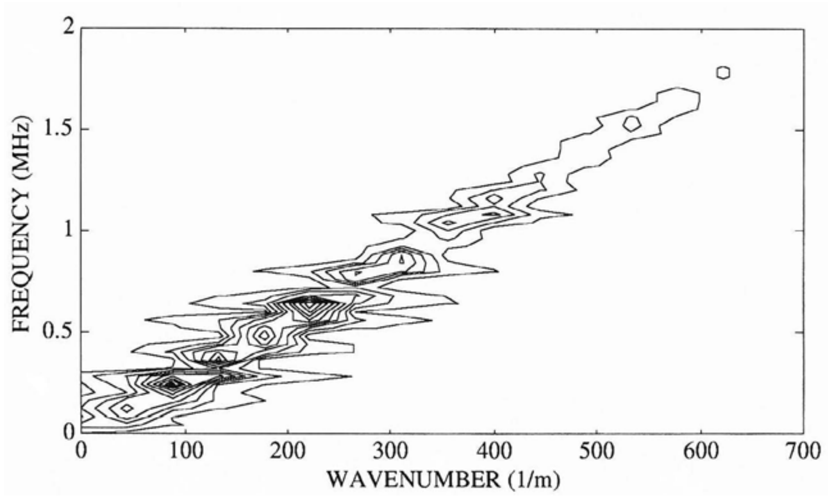

Fig. 2a Contours of magnitude of 2-D FFT for Rayleigh waves on an aluminum block.

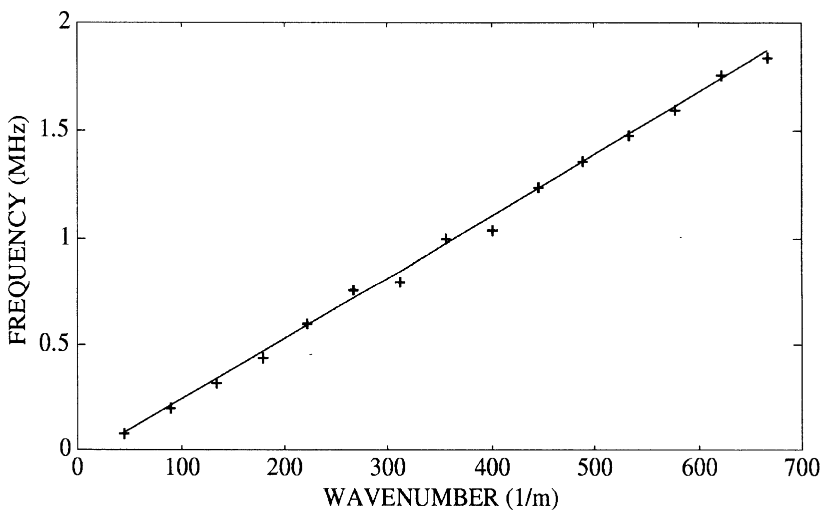

Fig. 2b Maxima from contour plot and least squares fit giving Rayleigh wave speed of 2870 m/s with a standard deviation of 38 m/s.

This technique has several potential applications. By comparing the experimentally determined dispersion curves with those obtained from theory, the plate's thickness and its material properties could be determined. This could be considered a generalization of a method in which Hutchins, Lundgren, and Palmer used laser generation in very thin plates to determine their thickness and material properties.[8] However, using a 2-D FFT to determine the plate's dispersion curves, the thickness and material properties of thicker plates could be determined. In another potential application, different modes could be isolated using wave-vector filtering.[9] These modes could be utilized to investigate different types of flaws.

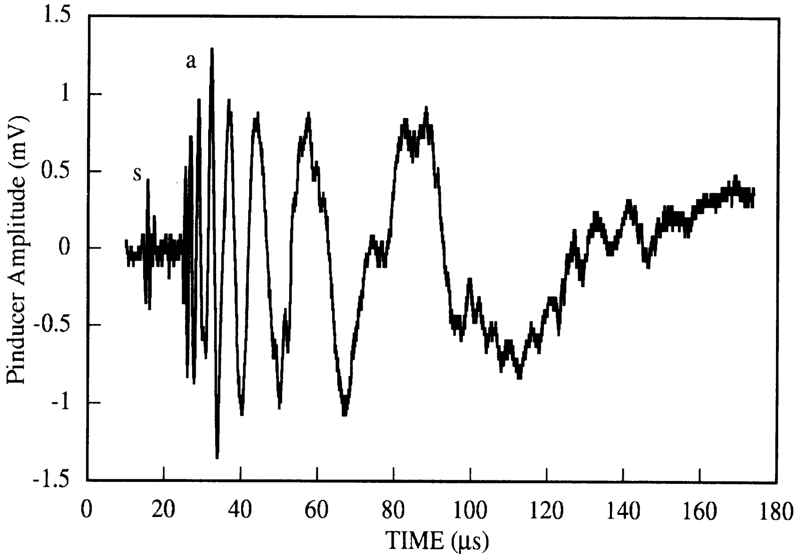

Fig. 3 Laser generated Lamb waves in 1.016 mm thick aluminum plate with source-pinducer separation of 81 mm. Lowest order antisymmetric and symmetric modes are denoted a and s, respectively.

SUMMARY

The Fresnel lens is a convenient and cost effective method to improve the SNR of laser generated Rayleigh waves. A Fresnel lens can be used to create an array of curved arc sources on the surface of the sample. A greater SNR is achieved by reducing the bandwidth of the signal (spatial periodicity) and by increasing the signal amplitude by focusing (curved line sources).

A 2-D FFT method can be applied to the laser generation of Lamb waves in plates to determine experimentally the dispersion curves and the propagating modes. There was excellent agreement between the experimental dispersion curves and those calculated from theory and several promising applications of this technique were briefly discussed.

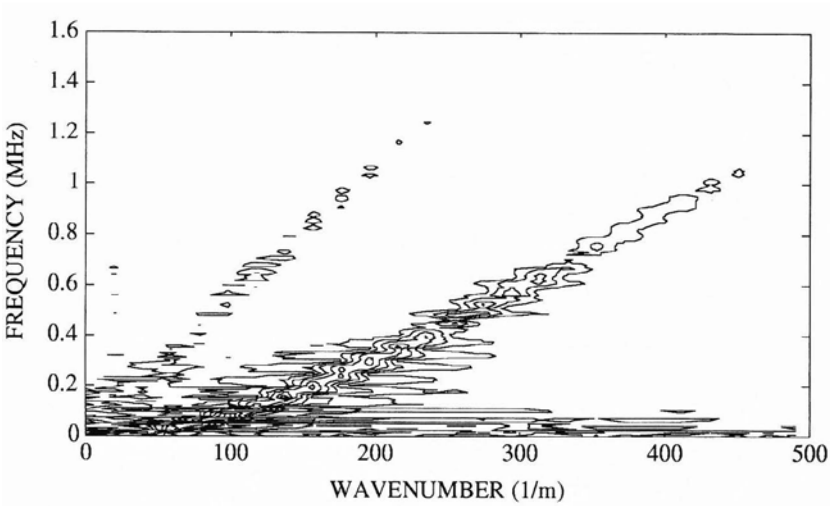

Fig. 4a Contours of magnitude of 2-D FFT for laser generated Lamb waves in 1.016 mm thick aluminum plate.

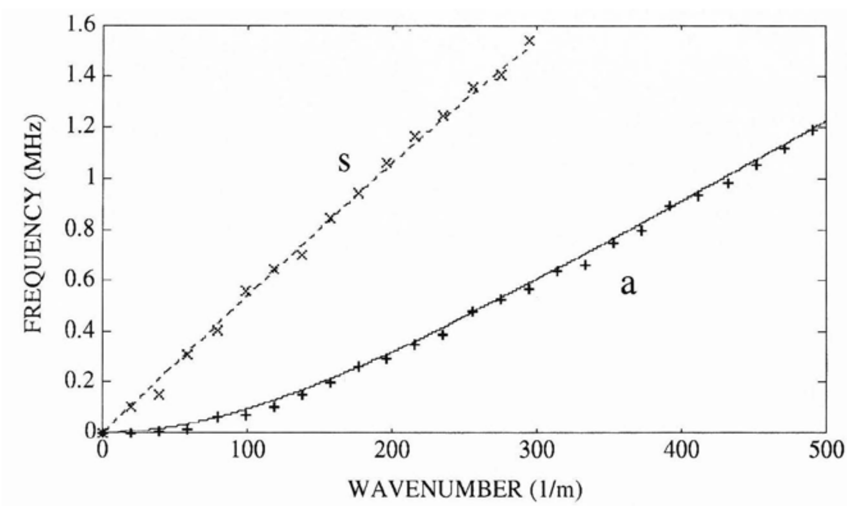

Fig. 4b Maxima from contour plot and theoretical dispersion curves for lowest order antisymmetric (a) and symmetric (s) modes.

ACKNOWLEDGEMENTS

This work was supported in part by the National Science Foundation. The authors are very grateful to Prof. Laurence Jacobs and the Engineering Science and Mechanics program of the School of Civil Engineering at Georgia Institute of Technology for allowing them the use of their laboratory.

REFERENCES

1. Scruby, C.B., *et al.*, *Laser Generation of Ultrasound in Metals,* in *Research Techniques in Nondestructive Testing,* R.S. Sharpe, Editor. 1982, Academic Press: London, UK. p. 281-327.

2. Royer, D. and E. Dieulesaint, *Analysis of thermal generation of Rayleigh waves.* J. Appl. Phys., 1984. 56(9): p. 2507-2511.

3. Wagner, J.W., *et al.*, *Modulated Laser Array Sources for Generation of Narrowband and Directed Ultrasound.* Journal of Nondestructive Evaluation, 1990. 9(4): p. 263-270.

4. Vogel, J.A., A.J.A. Bruinsma, and A.J. Berkhout. *Beamsteering of Laser Generated Ultrasound.* in *Ultrasonics International '87.* 1987. London, UK: Butterworths, London. p. 141-152.

5. Berthelot, Y.H. and J. Jarzynski, *Directional Laser Generation and Detection of Ultrasound with Arrays of Optical Fibers.* Journal of Nondestructive Evaluation, 1990. 9(4): p. 271-277.

6. Cielo, P., F. Nadeau, and M. Lamontagne, *Laser generation of convergent acoustic waves for materials inspection.* Ultrasonics, 1985. 23(March): p. 55-62.

7. Alleyne, D. and P. Cawley, *A two-dimensional Fourier transform method for the measurement of propagating multimode signals.* J. Acoust. Soc. Am., 1991. 89(3): p. 1159-1168.

8. Hutchins, D.A., K. Lundgren, and S.B. Palmer, *A laser study of transient Lamb waves in thin materials.* J. Acoust. Soc. Am., 1989. 85(4): p. 1441-1448.

9. Pierce, A.D. *Wave Interpretation of Random Vibration of Elastic Shells with Ribs.* in *13th International Congress on Acoustics.* 1989. Belgrade, Yugoslavia: Sava Centar. p. 351-354.