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Laser Ultrasound for the Non Contact Characterisation of the Mechanical Properties of Materials

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Abstract
We present our perspectives on using laser ultrasound, coupled with optical detection, to characterise the properties of plate like structures. The laser source launches a wideband signal in spatial and temporal domains exciting a Lamb wave spectrum over several octaves. Optical detection picks out the modal dispersion curves and inverting these mathematically presents values for thickness, density, modulus and Poisson ratio with confidence levels of a few per cent. Our investigations have compared approaches to dispersion curve measurement involving both 2-D and short time FFT to examine different areas of the specimen. We have compared high peak power impulse excitation with synthetic pulse generation using frequency scanned (or Pseudo Random Binary Sequence pulsed) low power sources based on semiconductor lasers or fibre amplifier based systems. A thorough analysis of the numerical inversion process has demonstrated that, with careful optimisation, the data obtained from the sample may be confidently inverted. Our demonstrations to date have been on large scale (mm thick by cm longitudinal dimensions) samples and studies of the application of the concepts to micro-systems are currently under way.
Keywords: Laser ultrasound, Lamb wave propagation, material properties measurement

1. Introduction

The evaluation of the structural properties of materials is an essential input both to the design of structures based upon these materials, and the assessment of the processes through which the materials themselves are fabricated. At the macroscopic scale there are many process-dependent parameters which influence properties, such as shear and bulk modulus, thermal conductivity, Poisson ratio etc. For micro and nano scale structural components, process-dependent factors in both the surface and the bulk become very much more influential so that insight into the structural influence of these parameters is critical. Measurement of materials properties using ultrasonic techniques is well established [1-3], and longitudinal and shear velocity measurement in homogeneous and isotropic materials (along with density), allow the estimation of Young's modulus and Poison ratio. High resolution schemes have been described [4] that exploit the high temporal and spatial bandwidths attainable from pulsed laser sources [5] where the ultrasonic frequencies extend to the GHz regime. Of particular interest at these high frequencies are the possibilities of thin film characterisation (thickness, substrate bonding etc), and microstructural properties. In thin plate-like structures where the acoustic wavelengths are comparable to the thickness, the dominant acoustic transmission mechanism (along the thickness of the plate), is that of Rayleigh-

Lamb propagation [2]. Here the influence of boundary conditions (the upper and lower surfaces of the layer) imposes coupling conditions between the compressional and shear waves in the material, giving rise to the familiar characteristic dispersive propagation characteristics exemplified in figure 1. It has been demonstrated that such Rayleigh-Lamb frequency dispersion curves are sensitive to changes in materials parameters [1], and figure 1 also indicates the effects of 5% changes of Young's modulus and Poisson's ratio.

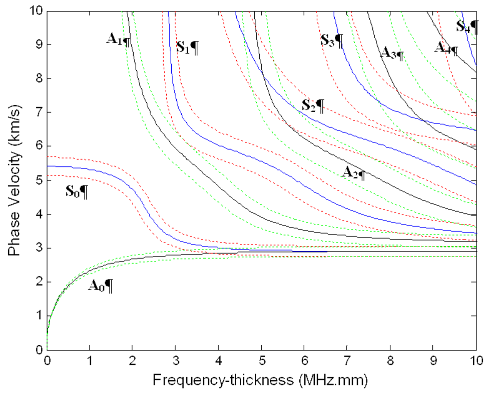


Figure 1(a) Lamb wave dispersion curves in aluminium (solid lines) and 10% variation in E (dotted lines)

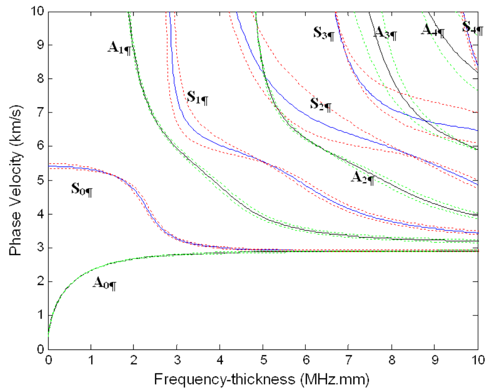


Figure 1(b) Lamb wave dispersion curves in aluminium (solid lines) and 10% variation in ν (dotted lines)

2. Lamb wave dispersion measurements and materials measurements

2.1 Experimental Dispersion Measurements

Dispersion curves as illustrated in figure 1 are readily calculated from forward numerical solution of the characteristic equations using tools such as Disperse [6]. However the inverse problem of estimating the material properties from the changes in the dispersion curves is a more challenging problem and in general requires some non-linear optimisation to provide fitting between a forward model and experimentally measured dispersion relations. The dispersion curves may be experimentally measured using either multiple frequency narrowband sources and receivers [1] or more conveniently by employing an impulse source. Such a source provides a broad spectrum of temporal and spatial frequency component excitation and may be used to monitor the dispersion relations using either short time fourier transform methods STFT and re-assignment STFT techniques (for enhanced resolution) [7], or 2D FFT techniques [8]. When using a laser to provide the impulse source, it is relatively straightforward to achieve both the required impulse in time [5], and the impulse in space (diffraction limited focussed spot). Combined with a laser based detection scheme (that also provides high temporal and spatial resolutions), it is then possible to measure the resulting displacements at different positions in the plate and thus derive the corresponding dispersion relations [9]. Figure 2 shows the typical results of such an experiment which was conducted on an aluminium sample approximately 1mm thick over a propagation distance of a few centimetres.

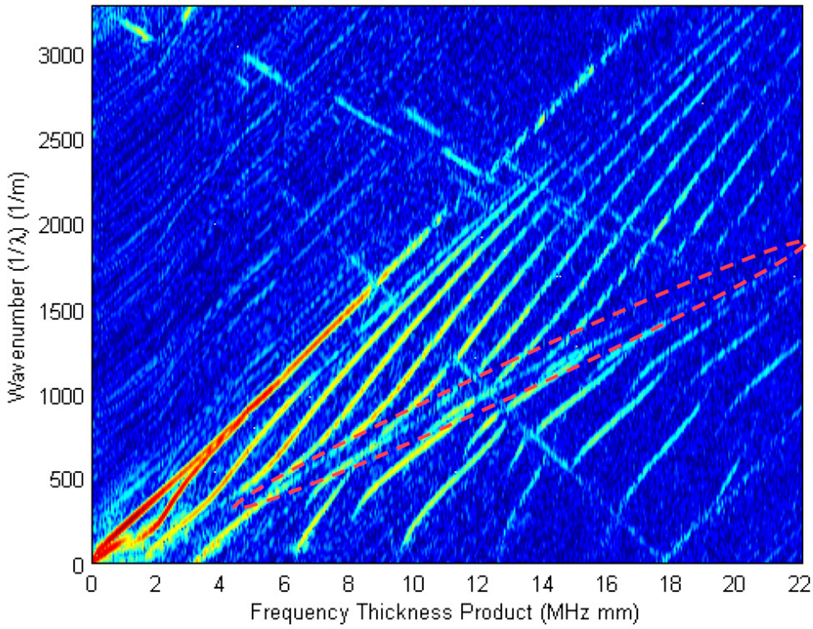


Figure 2. Experimentally measured Lamb wave dispersion in cast aluminium plate sample 1.84 mm thick, 2D FFT technique

2.2 Considerations for Inversion

Having experimentally measured the dispersion curves in a material sample, a significant challenge is in the efficient and accurate inversion of the dispersion characteristics to extract the material parameters. The task is to find values of E and ν that minimise the error function defined by the sum of square differences between experimental (c_i) and theoretical (c) phase velocity values at relevant points of the dispersion curves:

$$\sum_{i=1}^{N} A_i \; [c(f_i, c_i, \rho, E, \upsilon) - c_i]^2 \qquad (1)$$

Where A_i is a weighting factor.

Phase velocity space is used to frame the optimisation problem due to the linearity of the materials properties with this parameter (over the regions considered [10]). The conversion between the [ω-k] space of the experimentally determined dispersion curves and [ω-c] phase velocity space, involves a non-linear transformation which means that the equally spaced grid of points in wavenumber space is transformed to a non-uniformly spaced grid in phase velocity. The significance of this lies in the relative error in available phase velocity measurements ($\Delta c/c$) illustrated in figure 3 where it is clear that the highest errors in phase velocity are associated with the asymptotes of the curves, and also the low frequency –thickness product areas of the fundamental modes S_0 and A_0. Measurements in these areas will produce corresponding larger uncertainties in the elastic properties estimates and should therefore have decreased weighting in the error function of eqn (1) associated with them. This is accomplished through application of the weighting factor ($l\, f_i/c_i$) .

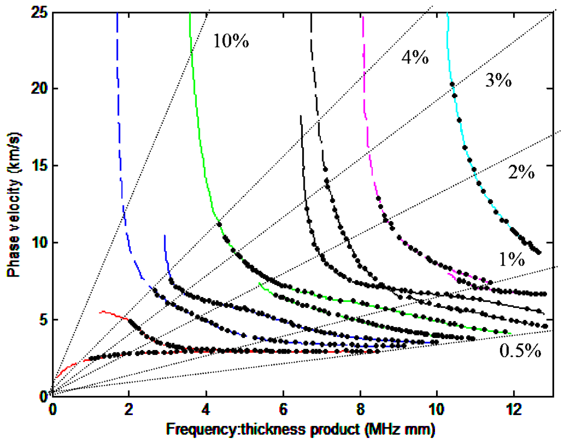


Figure 3. Relative phase velocity error contours and experimentally measured points (aluminium sample)

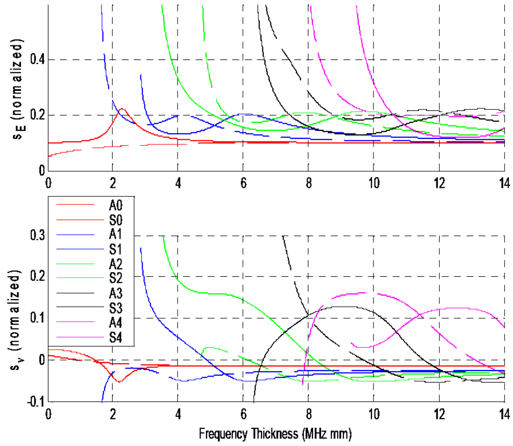
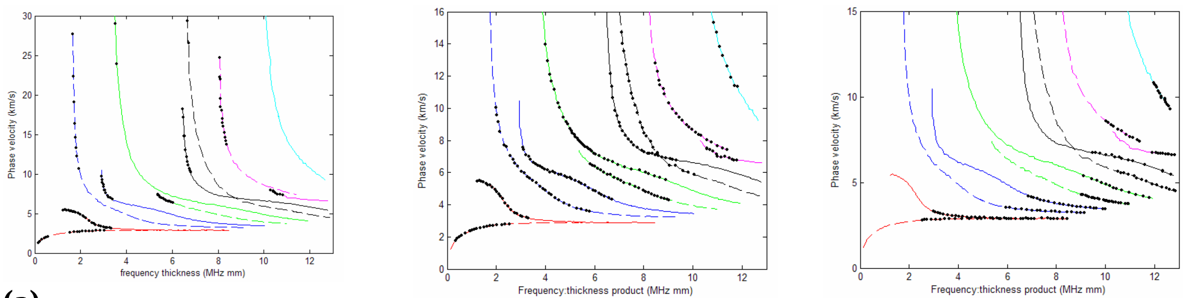


Figure 4. Sensitivity curves for small changes in E and ν , isotropic material, E=64.8 GPa, ν=0.3333.

Different modes have widely varying sensitivities to the mechanical properties (figure 4) and therefore careful consideration must also be made to the sensitivity functions s_E and s_ν which correspond to the differences in phase velocities associated with small changes in E and ν normalised to the phase velocity. Note that s_E values are always positive (provided regions of negative group velocity near asymptotes are avoided [10]) whilst s_ν values may take either sign. We therefore modify the weighting function A_i by a factor ($s_E + |s_\nu|$) to obtain:

$$A_i = \frac{\left(s_E + |s_\upsilon|\right)}{c_i / \left(f_i \cdot l\right)} \tag{2}$$

In performing the optimisation, a number of strategies were considered. To compare performance a downhill simplex (DHS), combined gradient and line search for non-linear least squares (LSP) were considered. Figure 5 shows 3 separate regions of experimentally obtained phase velocity data (a), (b), and (c) corresponding to data in the vertical asymptotic region, central region and horizontal asymptote respectively.



(a) **(b)** **(c)**

Figure 5. Experimentally obtained points from 3 regions of dispersion curves, (a) vertical asymptote, (b) central region, (c) horizontal asymptote.

This data was presented to both the DHS and LSP algorithms to obtain the experimental materials values in table 1. Results from regions (b) and (c) were considerably closer to real values than from region (a) where the experimental error was higher. Both algorithms converged to the same final values, with the quasi-newton LSP generally faster.

Table 1. Obtained property values as function of algorithm and experimental point region (Target values E=70.7584, ν=0.3375)

	Region (a)			Region (b)			Region (c)		
	E (GPa)	ν	t (s)	E (GPa)	ν	t (s)	E (GPa)	ν	t (s)
DHS	73.0443	0.3418	135	71.7341	0.3488	146	70.5618	0.3528	107
LSP	73.0443	0.3418	155	71.7341	0.3488	36.5	70.5618	0.3528	20

2.3 Laser Source Considerations

A significant problem arises from conventional laser ultrasonic sources in that the peak power density associated with short often Q-switched laser pulses can easily exceed the ablation and thermal damage threshold of the materials; a problem much exacerbated in thin films. An alternative technique to these short, high power pulses lies in using modulated continuous wave (CW) sources such that the peak power is kept below the material damage threshold. Although the generation efficiency is now much reduced, this is compensated for to some extent by the fact that the average source power can be raised. Techniques developed in photo-acoustic generation [11] have been extended to the laser-ultrasonic approach. CW excitation typically employs a narrowband modulation combined with sensitive lock-in detection, and has been used to measure dispersion relation in thin films up to around 200 MHz [12] at successive narrowband frequency excitation. An alternative approach lies in utilising a broadband approach using the digital modulation schemes commonly employed in spread-spectrum communications systems. Use of pseudo-random binary sequences (PRBS) and correlation detection [13] has demonstrated successful Lamb wave generation in thin plates at relatively low frequencies (a few MHz) limited by the constraints of the direct current modulation scheme employed. Both m sequence and Golay code modulation schemes have been employed with the Golay codes better suited to the uni-polar nature of optical signals. Figure 6 illustrates a typical Lamb wave signal detected in this fashion from a 0.15mm thick steel sample. Since operation was at low frequency-thickness products (<1MHz.mm) the A_0 mode displays dispersion characteristic of this region.

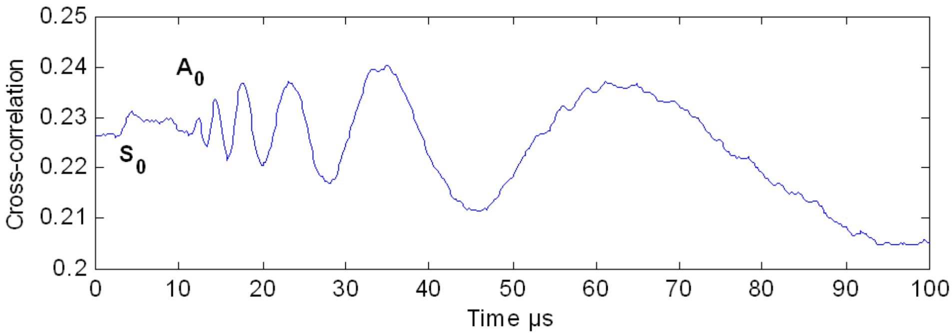


Figure 6. Lamb wave signal generated in thin steel sample using PRBS modulation of CW laser diode

3. Conclusions

This paper has discussed ongoing work at The University of Strathclyde into optical non-contacting techniques for measurement of materials properties, with particular application to thin films. We have used conventional high peak power laser sources to generate broadband Lamb waves in plates, measured the phase velocity dispersion spectrum, and then used different optimisation strategies to estimate the corresponding material parameters. *E* and *v* were measured to 1.5% and 3% accuracy respectively. We have also investigated the use of modulated CW laser sources, to increase average power, but decrease peak power delivery. Using m-sequence and Golay code modulation we demonstrated Lamb wave propagation in thin steel samples (0.15mm thickness). Currently we are extending this work to use low power modulation, followed by optical amplification [12] where we anticipate a significant increase in available bandwidth.

Acknowledgements

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