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Surface integrity determination of aluminum plates using laser-generated Lamb waves

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Abstract

Laser based ultrasonics is an important method in non-destructive testing for material characterization and process control. This paper describes the generation and characterization of Lamb waves in a thin aluminum plate-using laser based ultrasonics. Nd: YAG laser is used for ultrasonic generation and He-Ne Laser Heterodyne Interferometer is used for detection. Laser generation of Lamb waves leads to simultaneous generation of various frequency component as well as multiple Lamb wave modes. The surface integrity of a thin aluminium plate is studied.

Keywords: Lamb waves, Laser Generation, surface integrity

Introduction

Lamb waves are the kind of elastic waves that travel in planar structures parallel to surface boundaries and arise from a coupling between shear and longitudinal waves reflected at the top and bottom of plate surface (Viktorov, 1967). Lamb waves are dispersive in nature as their propagation properties depend on frequency of vibration and thickness of plate (Rose, 1999). Theoretical treatments of the excitation of Lamb and other guided waves have been reported extensively in the literature (Achenbach, 1973; Miklowitz, 1978; Weaver & Pao, 1982; Spicer *et al.*, 1990). In ultrasonic non-destructive evaluation (NDE), properties of elastic waves are used to detect the material in-homogeneities and determine the material characteristics (Krautkramer & Krautkramer, 1990). Experimental confirmation of Lamb waves at megacycle frequency is given by Worlton (1957). Monchalin (1986) gives an elaborate review on the techniques for the detection of ultrasound by interferometry. Legendre *et al.* (2001) presents wavelet-based method to perform the analysis of NDE ultrasonic signal. Reports are available on: laser generated Lamb waves in plates (Cheng, 1996), discussion on the laser generated Lamb waves plates (Jhang *et al.*, 2006; Mannan *et al.*, 2006; Vajradehi *et al.*, 2006) and the study of the spectral behavior of laser-generated Lamb waves using wavelet transforms (Pramila *et al.,* 2007; 2009).

Ultrasounds provide a perfect tool to investigate the integrity of opaque structures (such as aluminum or steel) in comparison with optical methods. For plate like structures the most adequate ultrasounds to be used are Lamb waves. They propagate in thin layers, of the order of an ultrasonic wavelength thick. As surface guided waves they propagate parallel to the boundary surfaces, having smaller spreading effects than bulk waves. Because they produce stress fields throughout the bulk of the plate, they can provide information of its entire thickness through large distances. Ye Lu et al. (2006) carried out surface integrity studies using PZT generation of Lamb waves.

The present work deals with the surface integrity studies using laser generated Lamb waves. The study brings out the simplicity and ease of the laser methods for surface integrity studies.

Theoretical formulation

Lamb waves describe two types of normal modes also called plate modes that can exist in a plate with free boundaries. In a Lamb wave the displacement of the particles occurs both in the direction of wave propagation and perpendicular to the plane of plate. This wave has two groups of modes that can independently satisfy the wave equation: symmetric and anti-symmetric. The symmetric modes are also referred to as longitudinal modes because the average displacement over the plate thickness is in the longitudinal direction. The motion of anti-symmetric modes is in the transverse direction and as a result they are also known as Flexural modes. The two different modes of Lamb waves are shown schematically in Fig.1.
The equations for the symmetric and anti-symmetric modes are given as:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{\left(q^2-k^2\right)^2}, \quad \text{for symmetric modes} \qquad (1)$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{\left(q^2-k^2\right)^2}{4k^2pq}, \quad \text{for anti-symmetric modes} \qquad (2)$$

Where, $p^2 = \frac{w^2}{c_L^2} - k^2$ and $q^2 = \frac{w^2}{c_T^2} - k^2$

h is half plate thickness, w is circular frequency of vibration, c_L, c_T are longitudinal and shear wave velocities for the medium and k is wave number. Lamb wave is the group of waves that get reflected from upper and lower surface of plate and recombined in a packet at

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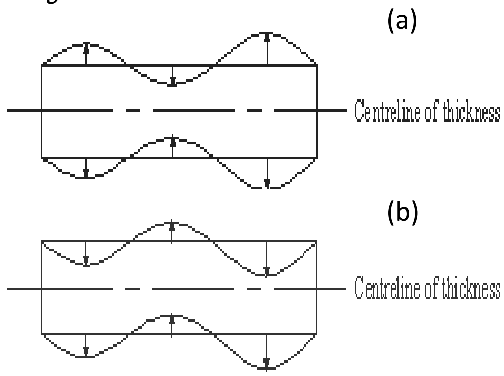
later length. The set of above two equations are called Rayleigh-Lamb frequency equations (Rose, 1999).

Experimental details

The instrumentation used in this experimental investigation is shown schematically in Fig. 2. The setup consists of an Nd: YAG pulsed laser to generate ultrasonic Lamb waves and an optical heterodyne type laser interferometer to detect the Lamb waves displacements in the aluminum plates. A series of pulses from a Nd: YAG laser were used to excite elastic waves in an aluminum plate. The set-up utilizes a Yokogawa DL1740 (four channels, one GSa/sec, 500 MHz) Digital Storage Oscilloscope (DSO). The signals are amplified and digitized using the oscilloscope. The scanning is done manually using two single axis micrometer controlled XYZ translator mounted on the optical test bench.

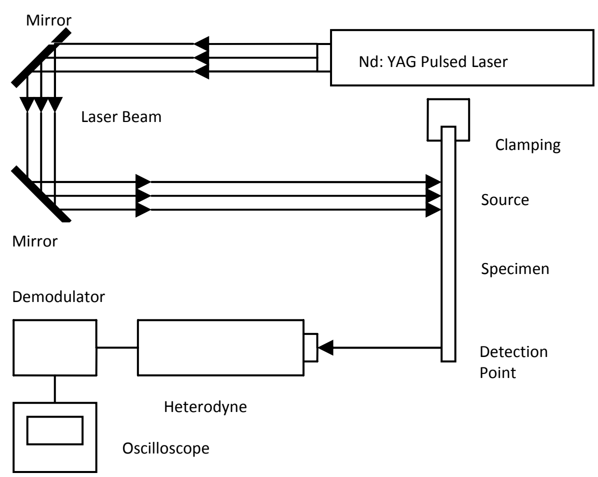
Fig.1. Lamb wave modes



(a) Symmetric mode (S);
(b) anti-asymmetric mode (A)

Fig.3 (a) shows the schematic of an aluminum plate of 2 mm thickness (without scratches on the surface) is used as a specimen to generate Lamb waves. On the other hand Fig.3 (b) represents the schematic of a thin aluminum plate with scratches on the one end of surface on which the laser pulse is impinged. Typically a pulsed Nd: YAG laser is used with pulse energy of the order of 200mJ and pulse width of the order of 20ns. A precise calibration of heterodyne interferometer is done prior to the experiment. The signals are recorded in DSO. Wavelet transforms of these signals are carried out. The arrival times of different frequency components are extracted from the Wavelet transforms.

Fig.2. Schematic of experimental set-up for laser based ultrasonic system



Results and discussion

A. Wavelet transform

Jean Morlet first proposed the concept of wavelets in its present theoretical form. A wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelet transform is a useful tool for the interpretation and the analysis of ultrasonic data in the Non-Destructive Evaluation (NDE). Main applications of the wavelet transform are signal analysis in the time-frequency domain, data compression and signal processing. Using wavelet analysis, signals can be characterized in both time and frequency domain simultaneously. The transform image is plotted as scale vs. sample number vs. intensity. Wavelet transform of signal obtained for thin aluminum plate shows three windows (Fig.4). The first window shows the original signal whose wavelet is to be taken. The second window shows the three-dimensional plot in which X-axis corresponds to sample number, Y-axis corresponds to frequency according to scale, and Z-axis corresponds to intensity. In this two-dimensional plot of the wavelet transform, the variation in intensity taken in the Z-axis is depicted with help of various colour schemes. The colour scheme in the present figure is such that one can see a gradual change of colour from black to white in its varying shades of grays. The blackish area corresponds to minimum intensity while the whitish area indicates the presence of a strong signal. The third window gives temporal distribution of the signal at a particular frequency corresponding to a given scale. By choosing different coefficient lines, one can study the behaviour of different frequency components present in a given signal. As the recorded signals contain various frequency components, the wavelet transform of signal is used to obtain arrival times for different frequency components.

B. Signal analysis

An aluminum plate of 2 mm thickness is used as a specimen to generate Lamb waves. As Lamb waves are dispersive in nature, the velocities of different spectral components of the Lamb wave signal are different. Lamb wave signal with source detector distance of 200 mm is shown in Fig.4. The temporal behaviour of individual spectral components can be studied with the help of coefficient lines. In the wavelet coefficient line corresponding to 178 KHz, one can see three well separated wave packets. From the arrival time of the first wave packet the velocity of this frequency component is calculated to be 3448 m/s. Keeping this velocity constant, the distance traveled by the second and third wave packets are calculated to be 300mm and 542mm respectively. The 300mm distance corresponds to the distance from the source to the fixed back edge of the plate and then from the back edge to the point of detection while the 542mm distance corresponds to the separation between the source and the front edge of the plate and then back to the point of detection. Hence, one can rightly conclude that the second and third wave packets correspond to the signals reflected from the back and front edges of the plate respectively.

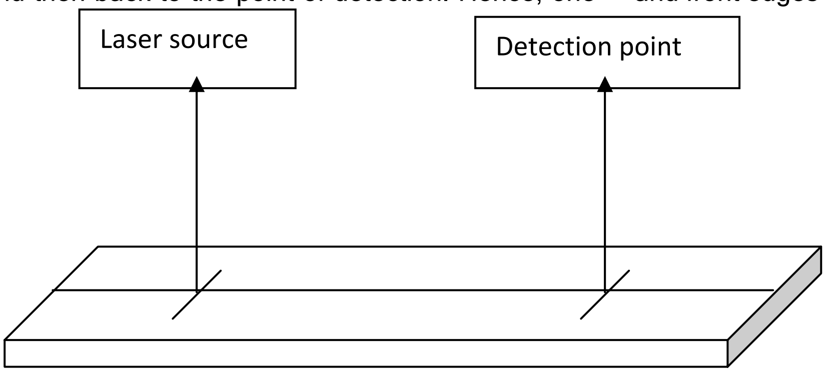


Fig.3 (a). Schematic of a smooth Aluminium plate

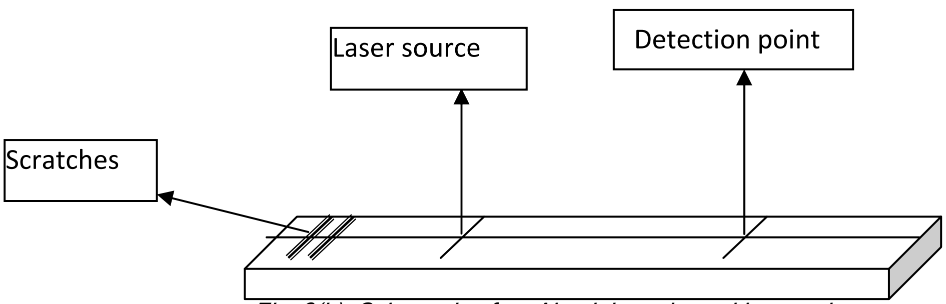
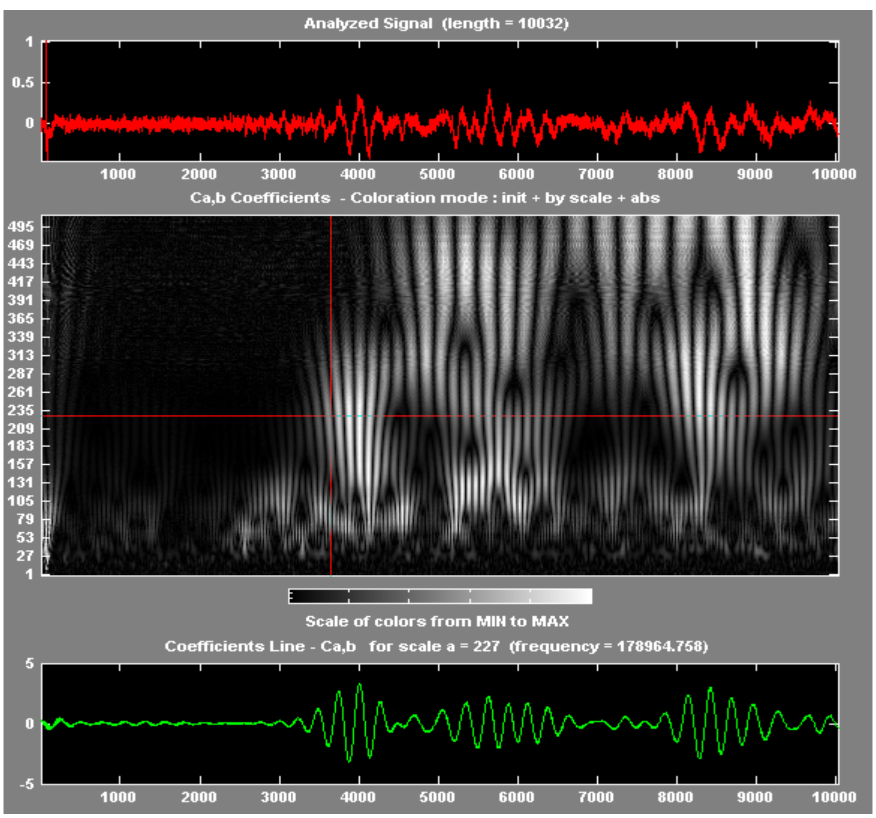


Fig. 3(b). Schematic of an Aluminium plate with scratches

Laser generated Lamb wave signal generated in a thin aluminum plate with scratches on one side of the surface, with source-detector distance of 180mm is shown in Fig.5 along with its wavelet transform. A band of frequencies lying in the range 81-466 KHz are seen to be present in the signal with the help of coefficient lines. The temporal behaviour of the frequency components is studied with the help of individual coefficient lines.

The coefficient line corresponding to the signal frequency (145 KHz) lying in the central region is shown in Fig.5. In the wavelet coefficient line corresponding to 145 KHz, from the arrival time of the first wave packet, the velocity is calculated to be 3157 m/s. Keeping this velocity constant, the expected distance traveled by the two consecutive wave packets due to back and front edge reflections are calculated to be 292mm and 408mm respectively. It is clearly seen from coefficient line while the third wave packet corresponding to the back reflection of the signal from the front edge is well defined, the second wave packet is somewhat distorted and attenuated. As the second wave packet corresponds the signal reflected from the back edge of the plate, one can conclude that signal distortion takes place due to overlapping of the partially reflected signals from the ridges present in the scratched surface at this end. In comparison to smooth Aluminium plate (Fig 4), due to its surface smoothness, there is no signal distortion present and signals are fully reflected. Thus, by the study of the temporal behavior of individual spectral components of laser generated Lamb wave signals recorded in various plate orientations, one can establish whether a particular plate has uniform smoothness or not.

Fig.4. Wavelet transform of signal and coefficient line corresponding to 178 KHz



Conclusions

The results of the analysis of the Lamb wave signals, generated in thin aluminum plates with and without scratches on one end of the surface, using wavelet transforms is presented. With the help of a comparative study of coefficient lines corresponding to

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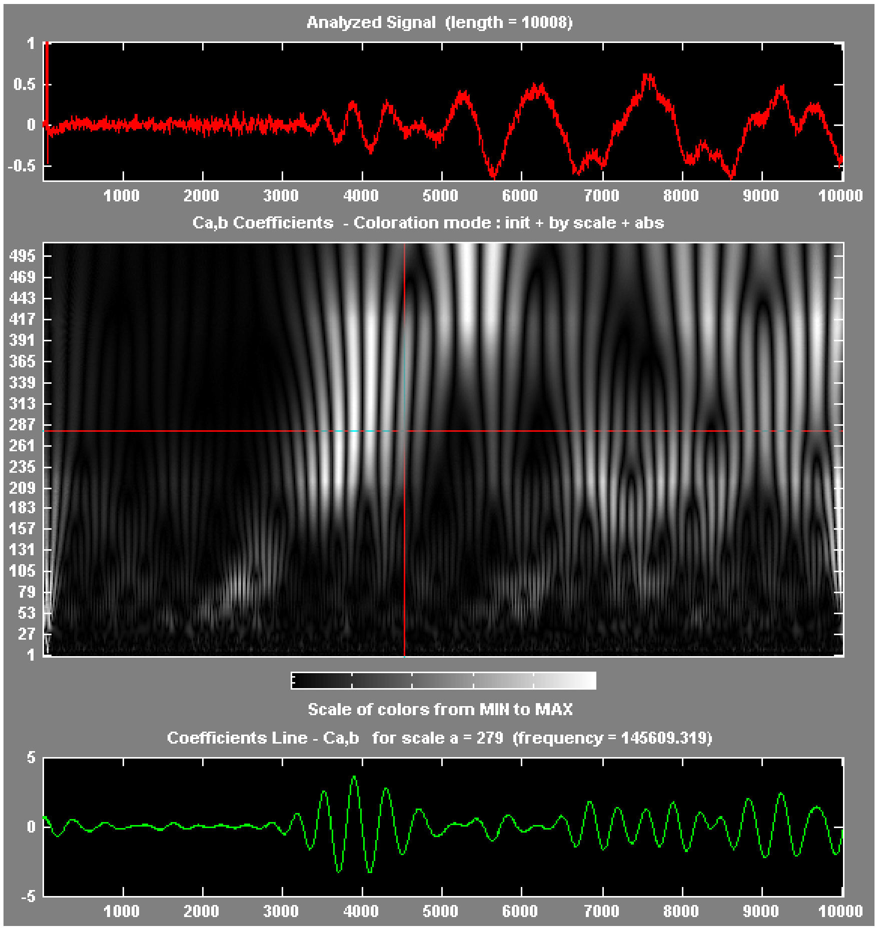
different frequencies , it is shown that study of laser based lamb waves coupled with coefficient lines of wavelet transforms presents a simple but effective tool for carrying out studies to determine the surface integrity of the plate under study.

Fig.5. Wavelet transform of signal and coefficient line corresponding to 145 KHz



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