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Inspection of notch depths in thin structures using transmission coefficients of laser-generated Lamb waves

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ABSTRACT

The non-contact feature of the Laser/EMAT ultrasonic (LEU) technique is attractive for its NDT applications. However, it is challenging to apply it in thin structures because of the difficulties in the signal interpretations. In this work, the LEU technique is used to inspect the notch depths in thin steel plates. A Continuous Wavelet Transform (CWT)-based algorithm is developed to calculate the transmission coefficients of laser-generated Lamb waves. The effect of varying notch depths on Lamb waves' transmission coefficients is investigated both numerically and experimentally. The transmission coefficients of laser-generated Lamb waves calculated using CWT have been used successfully to predict the notch depths in thin structures.

1. Introduction

There has been a growing interest in the use of the Laser/EMAT ultrasonic (LEU) technique for non-destructive testing (NDT), especially for metal materials. Its applications include weld quality inspection [1], surface and internal defect testing [2–5], thickness estimation [6], testing of bonding and characterization of materials [7]. Its non-contact feature during operation makes it very attractive for on-line inspections [8]. Most of the previous work focused on its applications in thick structures [9–11], where bulk waves and Rayleigh waves are excited by the pulsed laser, and the acquired signals are analyzed based on time of flight (ToF). It is challenging to apply the LEU technique in thin structures because of the difficulties in interpreting the acquired signals. The reason is that the laser-generated ultrasounds in thin structures are broadband Lamb waves [12], which are very complicated. The generated Lamb waves propagate throughout the thickness of the structure. Thus no internal wave path can be traced, and the TOF analysis method does not work anymore [13].

However, it is very desirable to extend the application of the LEU technique to thin structures, such as for on-line weld inspection in automobile industry and delamination testing of multilayer structures. This requires identifying alternative indicators that are sensitive to the structure of interest in the acquired signals. Wu and Ume [14] proposed using superimposed laser sources and regression analysis to determine weld penetration depths in thin structures based on the reflection coefficients of laser-generated Lamb waves. However, the reflection coefficients were calculated based on 2-D Fourier Transform of B-scan signals. B-scan procedure makes the proposed method time-inefficient to implement.

Since a notch is a structural feature very important in NDT, this work investigates the possibility of using the LEU technique to inspect notches of varying depths in thin structures. Because of its importance, the interaction of Lamb waves with notch structures has been studied very extensively. However, previous studies mainly focused on the fundamental Lamb modes generated using the traditional ultrasonic transducers [15,16]. A Continuous Wavelet Transform (CWT)-based method is used to determine the transmission coefficients of laser-generated Lamb waves in thin structures, in a fast and accurate manner. The relationship between the transmission coefficients and the notch depths are studied both numerically and experimentally.

In this paper, first, the LEU signals acquired in a defect-free thin sample are characterized first to identify prominent Lamb waves. Next, a finite element (FE) model is developed and used to study how varying notch depths affected the transmission of individual Lamb waves identified previously. Later, experiments are conducted to measure the transmission coefficients of laser-generated Lamb waves using a CWT-based algorithm. Finally, the numerical and experimental results are compared.

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2. Inspection system

Fig. 1 shows the LEU inspection system used in this work, which consists of an Nd:YAG pulsed laser, a custom designed EMAT, a sample stage driven by a stepper motor, a high-speed acquisition card, and a control unit. The laser power is set to be 115 mJ/pulse, and the ultrasonic generation is in the ablative regime. The laser beam is focused to a radius of 0.5 mm on the sample. The EMAT has a bandwidth of [0.5 MHz, 2.0 MHz]. The sampling frequency is set to be 12.5 MHz. The EMAT is steadied to the samples by its built-in magnet. The system can inspect multiple locations along a line by moving the sample stage. The inspection system is automated and controlled by a GUI on a PC.

3. Characterization of laser generated lamb waves

First, a defect-free 2.5 mm thick steel plate was used to characterize the LEU signals in thin structures. Fig. 2 shows the experimental procedure. The laser was fired repeatedly at the same point while the EMAT picked up signals from 251 equally-spaced locations with a 0.4 mm pitch. Fig. 3(a) shows the compilation of the 251 signals based on their acquisition distances from the laser. The color in the figure represents the signal amplitude. 2-D Fourier Transform (FT) [17] was used to convert the signals to the frequency–wavenumber domain, as shown in Fig. 3(b). Fig. 3(c) shows the theoretical dispersive curves of a 2.5 mm thick steel plate. The comparison between Fig. 3(b) and (c) identifies the Lamb wave modes in the laser-generated ultrasounds. The prominent modes observed are A0, S0, A1 and S1. The other modes are either too weak or beyond the EMAT bandwidth. The amplitude of each mode is not uniform across its frequencies. Therefore, the LEU signals in thin structures contain multiple Lamb wave modes and broadband frequencies, which are very complicated. Future study will only focus on the identified prominent Lamb wave modes in the acquired signals.

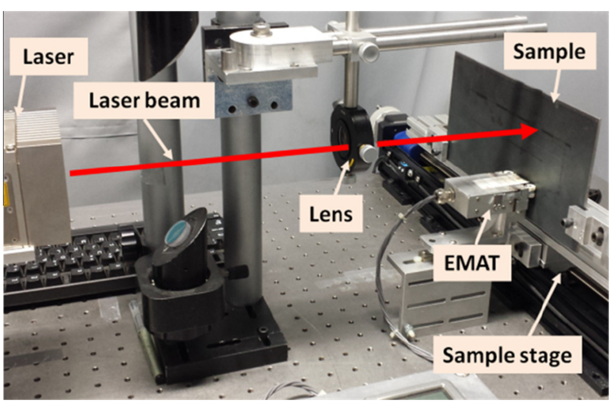

Fig. 1. Inspection setup.

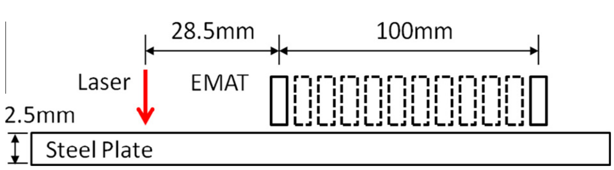

Fig. 2. Experimental procedure to characterize LEU signals.

4. Finite element study

Finite element analysis is first used to investigate how the varying depths will affect the transmissions of various Lamb waves across notches. The simulation of laser generation of Lamb waves is complicated and time consuming and therefore not suitable for parametric study of varying notch depths. Instead, a simple 2-D model is developed to quickly simulate propagation of any single-mode and narrow-band (SMNB) Lamb wave in thin plates, and study how it transmits across varying notch depths. Even though the laser-generated Lamb waves contain broadband frequencies and multiple modes, the simulation of SMNB Lamb waves is suitable for this work since the goal of this work is to investigate how the transmission coefficients of individual Lamb waves will be affected by the varying notch depths. Fig. 4 shows the FEA model, which is a plane strain analysis using the PLANE182 element in ANSYS. The simulation was divided into two load steps. In load step 1, the theoretical displacement field of a Lamb wave of interest was applied as the displacement loading to the red zone in Fig. 4. The displacement field was shaped both temporally and spatially with Hanning windows to avoid the abrupt changes at loading boundaries. The window functions are defined below:

$$W_{time} = 0.5 \times \left(1 - cos\frac{2\pi t}{D}\right) \tag{1}$$

$$W_{space} = 0.5 \times \left(1 + cos\frac{2\pi x}{L}\right) \tag{2}$$

where D is the duration of the displacement loading, and L is the length of the loading area. In load step 2, the displacement loading was removed to let the excited waves propagate freely in the plate.

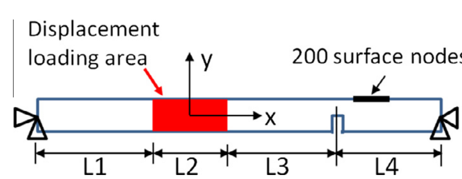

Fig. 4. Finite element model.

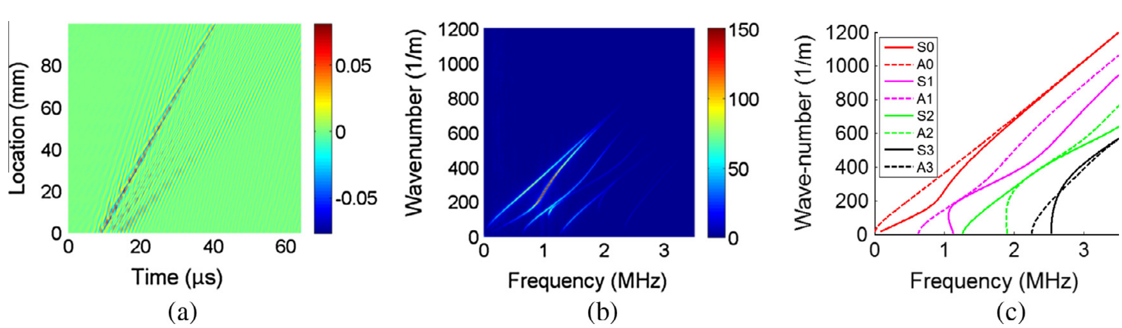

Fig. 3. (a) Time–space representation of signals; (b) frequency–wavenumber domain representation of signals; (c) theoretical dispersive curves of 2.5 mm steel plate.