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A Study on Lamb Wave Based Damage Identification and Detection on A Metallic Structure

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***Abstract*—Damage identification and detection on an engineering structure is an overwhelming need for several industrial applications. Lamb wave based damage identification and detection is an attractive choice for monitoring of the structural health monitoring (SHM) for structural safety and maintenances. Lamb waves are subset of ultrasonic waves family which disperse along the structure when it propagates. The interaction of Lamb wave with damage causes reflection, mode conversion and attenuation in the measured signal at the receiving end. The change in the received signal used to locate the size and position of the damage. In this work we have demonstrated damage detection using pitch catch configuration of Lamb wave propagation in 1-mm thick aluminum 2024-T3 plate. To simulate multimode guided waves interaction with damage we have used The WaveFormRevealer 3.0 software.**

***Keywords*—Lamb wave,PWAS, SHM, PWAS**

I. INTRODUCTION

Advanced Non-Destructive Techniques (NDT) are being used presently to detect damages and these methods are time consuming and expensive [1]. As inspections are planned at scheduled intervals, the damage could potentially exist on structure in the intervening period. Notwithstanding the fact that structures are designed based on damage tolerance philosophy for perceived threats, it is desirable to detect as it happens along with the location and size. In literature there are three methods exist to detect damage which are wave propagation based, vibration based and electromechanical impedance based method [2-4]. Lamb wave based ultrasonic method is a classic example for wave propagation based approach where propagation reflection and mode conversion of Lamb waves are measured, by which one can estimate position and the size of the damage. Typically, Lamb wave based method includes pitch catch and pulse echo techniques. In pulse echo method waves are generated through transmitting transducer and received at different location on the structure the severity of damage can be estimated based on attenuation and dispersion. In contrast to pitch catch, pulse echo method used same transducer for transmitting and receiving the wave, damage can be detected through reflection of wave and location can be detected through the time of flight distance travelled by the wave.

Damage monitoring using different sensing methods like Resistance Strain Gauges and Fiber Bragg Gratings [5], Fiber Optic Interferometer [6], Fiber Optic Doppler Sensor [7], Piezoelectric sensor [8] are proposed in literature.

Due to multimodal dispersion characteristics modelling of lamb wave is challenging problem. At certain plate thickness-frequency several mode exists and phase velocity varies with frequency [9]. To solve such problem using numerical methods such as finite element method (FEM) or boundary element method (BEM) usually adopted [10,11]. The transient analysis at high frequency requires small step size and mesh size which are time consuming and computational resource expensive. Analytical approach can give an alternative solution with less cost [12]. In this work, we have validated an analytical approach based on the 1D (straight crested) guided wave propagation analysis using MATLAB [13] and the WaveFormRevealer (WFR) graphical user interface (GUI) software develop by laboratory for active materials and smart structures (LMSS), University of South Carolina, USA [14]. The damage effect into the analytical model by considering wave transmission, reflection, mode conversion, and higher harmonics components described through damage interaction coefficients at the damage site are available either from literature or from FEM, BEM analysis performed separately in a separate computational module of the software.

II. LAMB WAVE PROPAGATION EQUATION

In a thin isotropic and homogeneous plate shown in the figure-1, wave equation under plane strain condition described as [13]

$$\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial z^2} = \frac{1}{c_l^2}\frac{\partial^2 \emptyset}{\partial t^2} \quad \ldots (1)$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = \frac{1}{c_t^2}\frac{\partial^2 \psi}{\partial t^2} \quad \ldots (2)$$

Equation 1 described governing longitudinal wave mode and equation 2 for governing transverse wave modes. c_l and c_t represents velocity of longitudinal and transverse waves respectively. Sinusoidal solutions to the wave equation were postulated, having x- and z-displacements of the form

$$\emptyset = A_x g_x(z) exp\big(i(\omega t - kx)\big) \quad \ldots (3)$$

$$\psi = A_z g_z(z) exp\big(i(\omega t - kx)\big) \quad \ldots (4)$$

This form represents sinusoidal waves propagating in the x direction with wavelength 2π/k and frequency ω/2π.

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Displacement is a function of x, z, t only; there is no displacement in the y direction and no variation of any physical quantities in the y direction. The physical boundary condition for the free surfaces of the plate is that the component of stress in the z direction at z = ± d/2 is zero. Applying these two conditions to the above-formalized solutions to the wave equation, a pair of characteristic equations can be found.

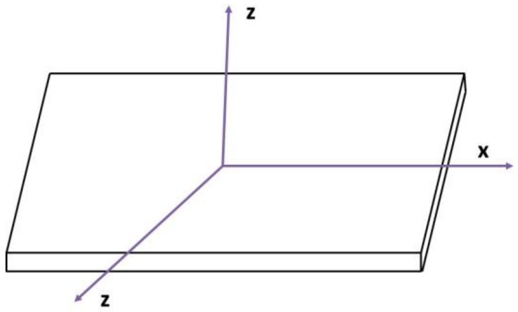

Figure 1: A thin plate of 2d thickness

$$\frac{tan(\beta d/2)}{tan(\alpha d/2)} = \frac{-4\alpha\beta k^2}{(k^2-\beta^2)^2} \quad \dots (5)$$

$$\frac{tan(\beta d/2)}{tan(\alpha d/2)} = \frac{-(k^2-\beta^2)^2}{4\alpha\beta k^2} \quad \dots (6)$$

Where $\alpha^2 = \frac{\omega^2}{c_l^2} - k^2, \beta^2 = \frac{\omega^2}{c_t^2} - k^2$

Numerical methods are used to find the phase velocity c_p= f λ ω/k, and the group velocity c_g = dω/dk, as functions of d/λ or fd.

The Lamb waves propagate in two types of modes; the symmetrical (S) and the anti-symmetrical (A) modes which is shown in figure-2.

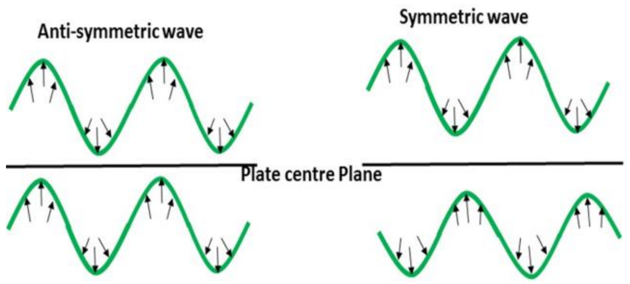

Figure 2: Anti-symmetric and symmetric lamb wave modes

In the S modes, the plate displacements are symmetrical with respect to its center plane while in the A mode, it is anti-symmetrical. There are infinite number of modes (S and A) existing in a plate. For a particular Lamb wave excitation, the available modes depend on the excitation frequencies and the thickness of the plate.

III. LAMB WAVE PROPAGATION IN PRISTINE PLATE

Figure 3 shows the pitch-catch active sensing method, where one transducer acts as the transmitter and sends out the guided waves, and another transducer acts as the receiver and pick up the sensing signal. In the pristine case (baseline), the interrogating waves are generated by the transmitter, propagate along the structure, and are picked up by the receiver. In the damaged case, the interrogating waves generated by the transmitter, propagate along the structure, interact with the damage, carry the damage information with them, and are finally picked up by the receiver. The subtraction between these two states reveals the damage scattering response, which may indicate the presence and severity of the damage.

This section describes how an electrical tone burst applied to a transmitter Piezoelectric wafer active sensors transducer (T-PWAS) propagates through a structural waveguide to the receiver Piezoelectric wafer active sensors transducer (R-PWAS) in pitch-catch mode.

Figure 3: Pitch catch configuration of Lamb wave propagation in pristine plate

The propagation takes place through ultrasonic guided Lamb waves which are generated at the T-PWAS through piezoelectric transduction and then captured and converted back into electric signal at the R-PWAS. Since several Lamb wave modes traveling with different wave speeds exist simultaneously, the electrical tone-burst applied on the T-PWAS will generate several wave packets. These wave packets will travel independently through the waveguide and will arrive at different times at the RPWAS where they are converted back into electric signals through piezoelectric transduction. Three test cases were conducted:

a. incident S_0 wave excitation
b. incident A_0 wave excitation
c. incident S_0 and A_0 wave excitation

The transmitter PWAS (T-PWAS) and receiver PWAS (R-PWAS) are placed 500 mm away from each other on a 1-mm thick aluminum 2024-T3 plate. A 5-count Hanning window modulated tone burst centered at 150 kHz is used as the excitation which is given by

$$x(t) = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi t}{T}\right)\right] \sin(2\pi f t), t\epsilon[0, T] \quad \dots (7)$$

Received signal by R-PWAS, the dispersion curves; the excitation spectrum overlap with the S_0 and A_0 tuning curves and the structure transfer shown in figure-4 for S_0 excitation A_0 excitation and (S_0+A_0) excitation.

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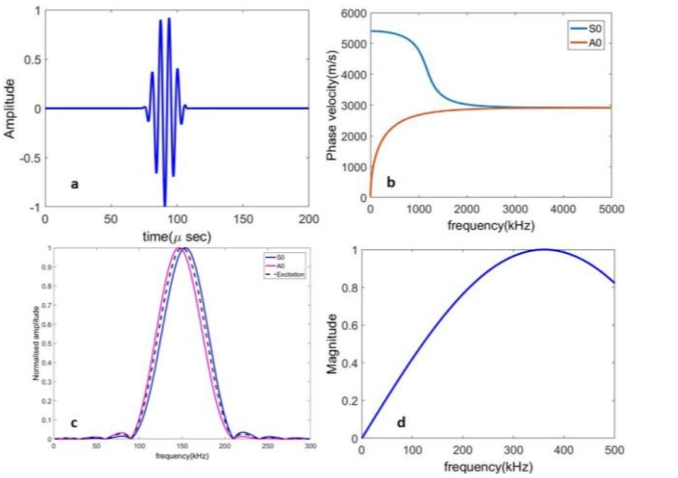

Figure 4.a: Various parameter for S_0 mode excitation: (a) Received signal by R-PWAS (b) The dispersion curves (c). The excitation spectrum overlap with the S_0 and A_0 tuning curves (d) structure transfer function

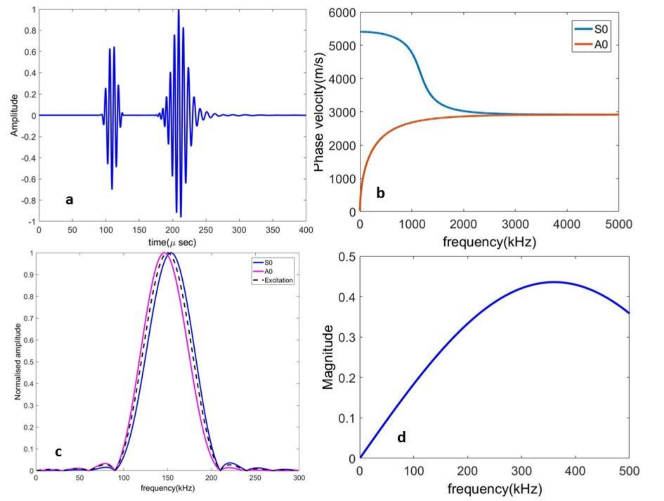

Figure 4.b: Various parameter for A_0 mode excitation: (a) Received signal by R-PWAS (b) The dispersion curves (c). The excitation spectrum overlap with the S_0 and A_0 tuning curves (d) structure transfer function

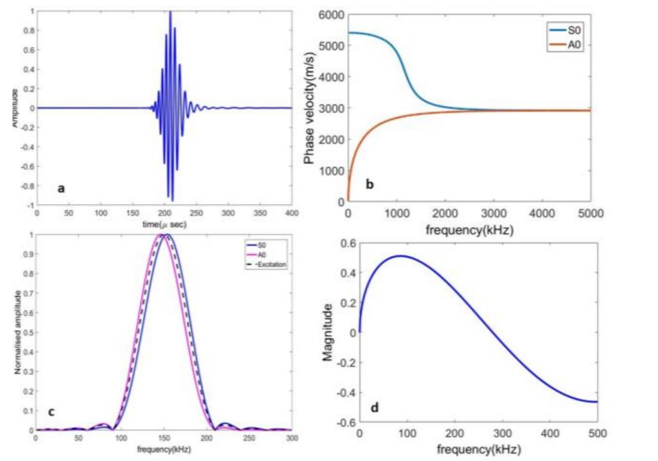

Figure 4.c: Various parameter for S_0+A_0 mode excitation: (a) Received signal by R-PWAS (b) The dispersion curves (c). The excitation spectrum overlap with the S_0 and A_0 tuning curves (d) structure transfer function

IV. LAMB WAVE PROPAGATION IN DAMAGED PLATE

The transmitter PWAS (T-PWAS) and receiver PWAS (R-PWAS) are placed 500 mm away from each other on a 1-mm thick aluminum 2024-T3 plate. The damage is placed 250 mm from the T-PWAS. A 5-count Hanning window modulated tone burst centered at 150 kHz is used as the excitation, the setup is shown in the figure 5.

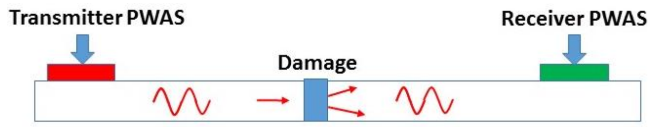

Figure 5: Pitch catch configuration of Lamb wave propagation in damaged plate which is 250 mm away from T-PWAS

Three test cases were conducted similar to pristine plate

a. incident S_0 wave excitation
b. incident A_0 wave excitation
c. incident S_0 and A_0 wave excitation

The wave signal at the damage location takes the damage information by considering transmission, reflection, mode conversion, and higher harmonics. Each of these addition phenomena is modeled by software as a new wave source at the damage location using damage interaction coefficients. Linear interaction between Lamb waves and damage interaction with S_0, A_0, S_0+A_0 mode shown in figure 6.

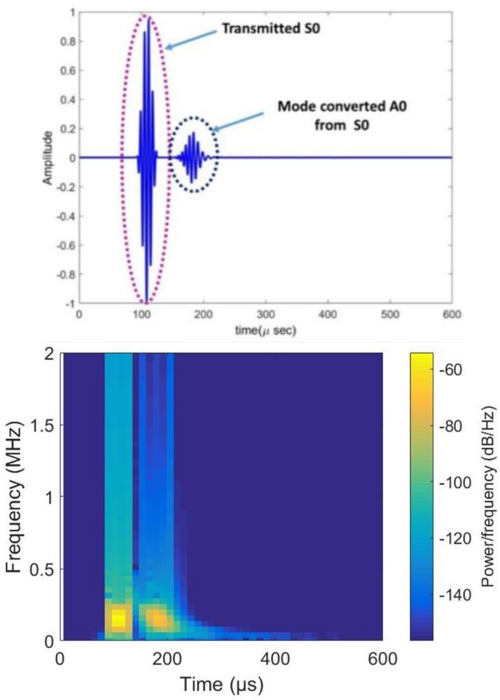

Figure 6.a: Interaction between Lamb waves and damage with S_0 mode, received signal by R-PWAS(top) and corresponding spectrogram(bottom)

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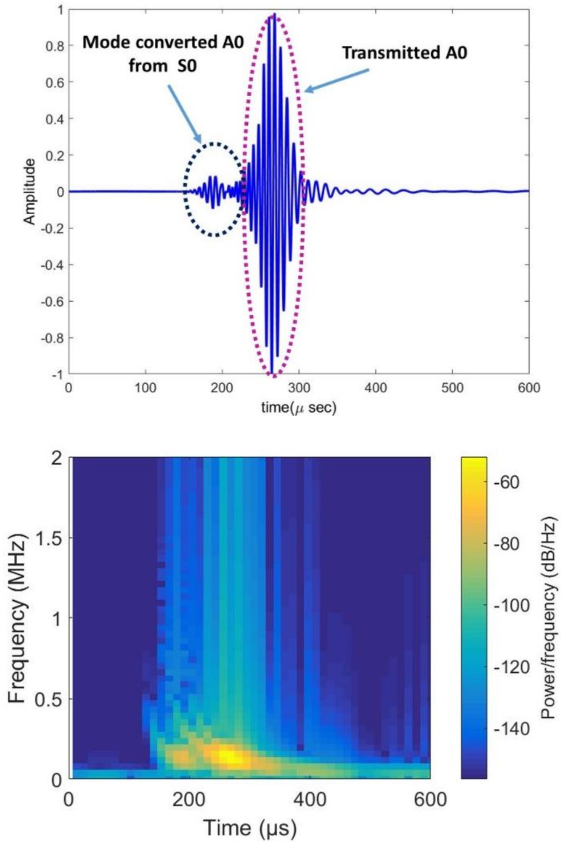

Figure 6.b: Interaction between Lamb waves and damage with A_0 mode, received signal by R-PWAS(top) and corresponding spectrogram(bottom)

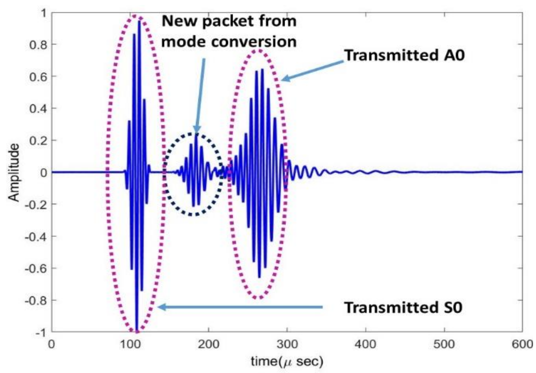

Figure 6.c.i: Interaction between Lamb waves and damage with S_0+A_0 mode, received signal by R-PWAS

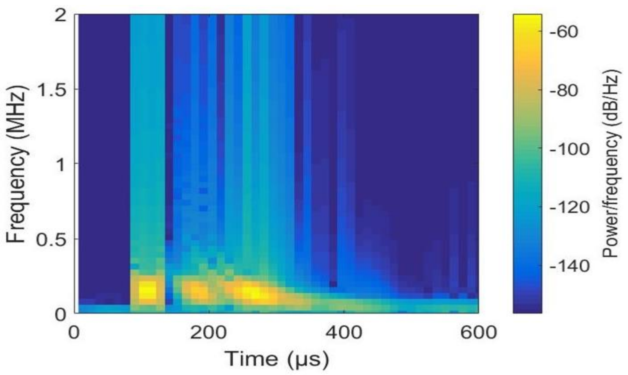

Figure 6.c.ii: Interaction between Lamb waves and damage with S_0+A_0 mode, received signal's spectrogram

Figure 6.a through Figure 6.c show that new wave packets appear due to the interaction between interrogation Lamb waves and damage. The incident S_0 wave will generate A_0 wave component from mode conversion at the damage; whereas the incident A_0 wave will generate S_0 wave component from mode conversion at the damage. However, from the time-frequency analysis, it could be observed that after linear interaction, the frequency spectrum of the waves still center around the excitation frequency 150 kHz. No higher harmonic frequency components are observed.

V. CONCLUSION

In this work Structural Health Monitoring using active sensing is presented. Lamb wave based wave propagation model using WFR software has explored. In plate like structure pitch catch based model used for healthy and damaged metallic plate. The receiver and transmitter are separated by 500 mm and damage is present at 250 mm from the transmitter. Received signal by the receiver, dispersion curve, frequency spectrum of A_0, S_0 and excited tone burst and plate transfer function has presented for healthy case. In damaged case received signal and mode converted signal and its spectrogram is presented. The damage presented in this work is linear so there is no higher harmonics exist in the spectrogram.

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