Nondestructive Evaluation of Stress using Ultrasonic Leaky Lamb Waves

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1. Introduction

The principle of ultrasonic stress detection relies on the fact that changes in the stress state of a solid cause variations in ultrasonic wave velocity in that solid [1]. By measuring the ultrasonic wave velocities in a stressed structure, it is possible to obtain the stress field information. Generally, the magnitude change of ultrasonic wave velocity due to the stress fields is extremely small. The interference spectrum of leaky Lamb wave (LLW) of a plate immersed in fluid provides an alternative to measure the small velocity changes with simple equipment [2], compared with existing ultrasonic techniques where the ultrasonic flight time is measured with extremely high precision equipment to calculate the velocity of ultrasonic waves. The key parameters used in LLW technique are the plate thickness, density, and longitudinal and transverse wave velocities, which cannot be decoupled in a straightforward way for the general LLW case [3]. Under high frequency assumption, the Modal Frequency Spacing (MFS) method provides a straightforward way to decouple the Lamb wave equation parameters leading to a simple relationship between the transverse wave velocity and the modal frequency spacing of two adjacent Lamb wave modes [2]. However, the MFS method has not previously been used to measure stress fields in metals.

2. Theoretical Background of Leaky Lamb Waves

Consider an isotropic infinite plate immersed in an acoustic coupling fluid, such as water. Leaky Lamb waves are excited by an obliquely incident longitudinal wave, as shown in Fig. 1.

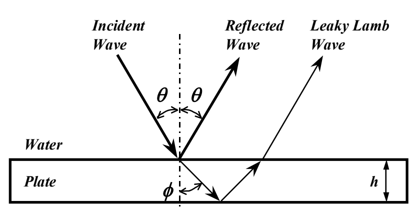


Fig. 1: Schematic of leaky Lamb wave.

For plate thickness h, incident angle θ, acoustic wave velocity V_0 of water, and transverse wave velocity V_T, the MFS method gives [2]:

$$V_T = \frac{1}{\sqrt{\frac{1}{4h^2(\Delta f)^2} + \frac{\sin^2\theta}{V_0^2}}} \tag{1}$$

if

$$\left|\pi f h\sqrt{\sin\theta/V_0^2 - 1/V_L^2}\right| >> 1 \quad \text{and} \quad \frac{V_0}{V_L} < \sin\theta < \frac{V_0}{V_T}$$

where V_L is the longitudinal wave velocity, $\Delta f = f_S - f_A$ is the modal frequency spacing, and f_S and f_A are modal frequencies of symmetric and antisymmetric modes in the amplitude spectrum of LLW, respectively.

3. Experimental Hardware

The system used for obtaining LLW data consists of two transducers, transmitter and receiver, mounted on a motorized guiding arc and submerged in a water tank that fixes the transducers in a pitch-catch arrangement at a specific angle to the surface normal of the test specimen. Two metal tensile specimens of aluminum 7075-T6 and mild steel are used. The thickness and wave velocities of the samples at zero stress are summarized in Table 1. These samples were tested using a frequency of 5 MHz at incident angles of 16º, 18º, 20º, and 22º. A Vishay P-3500 strain indicator with an SB-10 balance unit and Measurements Group WK-00-030WT-120 strain gauge are used to measure the axial strain in microstrain (μm/m, or με) in the test specimen, which is loaded by a hydraulic loading frame that is actuated by a double-acting pump. A PC simultaneously captures the ultrasonic waveform via a Tektronix TDS-2024 oscilloscope and the gauged strain in the specimen.

Table 1: Properties of Tensile Specimens.

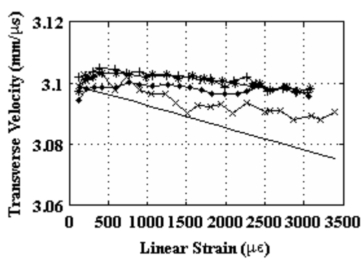
Material	Thick-ness (mm)	Young's Modulus (GPa)	Long. Velocity (mm/μs)	Trans. Velocity (mm/μs)
Aluminum	4.8	71.7	6.35	3.10
Mild Steel	4.5	200	5.90	3.25

4. Experimental Results and Discussion

The steel and aluminum specimens were lightly pre-loaded to eliminate any free play in the testing rig and ensure that the specimen position remained unchanged. The specimens were pulled incrementally up to approximately 50% of its yield stress and the corresponding acoustic velocity was determined by measuring the MFS as per Eq. (1).

4.1 Aluminum Specimen

The variation of transverse wave velocity vs applied linear strain in the aluminum specimen is shown in Fig. 2. Very few data of aluminum 7075-T6 are available in the literature. Stobbe measured the relation of transverse wave velocity vs strain using aluminum 7075-T651 and calculated the averaged slope of the velocity-strain relationship as -7.23 mm/μs/με [4]. The difference between the 7075-T6 and 7075-T651 is that the former is not stress relieved while the latter is stress relieved. As a comparison, we plotted a reference line in Fig. 2 using Stobbe's slope but starts from the transverse wave velocity of V_T = 3.10 mm/μs, which is common for aluminum 7075-T6. Our measured mean velocity at zero strain is about 3.11 mm/μs. In addition, the measured results exhibit very good consistency. The change in velocity is also fairly consistent with expected values, varying linearly at –1.98 mm/μs in the range of 0 - 3000 με, lower than the reference because of Stobbe's use of stress-relieved T651 aluminum.



× θ=16° + θ=18° * θ=20° ● θ=22° — Reference
Fig. 2: Velocity variation vs strain in aluminum.

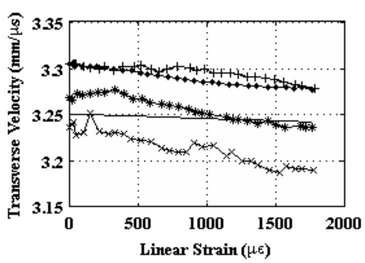


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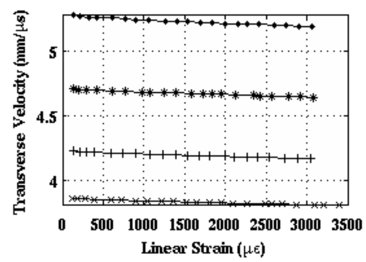
Fig. 3: Velocity variation with strain in mild steel.

4.2 Steel Specimen

The results of the steel specimen are shown in Fig. 3. There is typically more noise and less signal power received from steel specimen compared with its aluminum counterpart, largely due to the higher acoustic impedance of steel than aluminum [3]. For reference, a measurement of velocity vs strain in rail steel made by Egle and Bray, who give a slope for the velocity-strain relationship of –4.87 mm/μs/με [5], is plotted as reference in Fig. 3 with a velocity of 3.25 mm/μs at zero strain. The mean velocity in the mild steel specimen is 3.32 mm/μs at zero strain and a slope approximately –19.9 mm/μs/με is observed over the range of 0 - 2000 με. Overall, the change in wave velocity with stress is linear, and the slope if greater to that of the reference, due to the differences in wave velocity between rail and mild steel used in testing.

4.3 Comparison of LLW and Existing Methods

Fig. 4 shows wave velocities for the same aluminum specimen obtained by correlation of waveform peaks in the time domain. The slope of the velocity-strain relationship is comparable to the results obtained by using MFS, validating the MFS theory. However the absolute wave velocity is unreliable, due to the difficulty of obtaining accurate ultrasonic geometry measurements.



× θ=16° + θ=18° * θ=20° ● θ=22° — Reference
Fig. 4: Velocity variation vs strain in aluminum.

5. Conclusions

We have demonstrated the novelty of non-destructive evaluation of stress in a finite plate using ultrasonic leaky Lamb waves and MFS method. Under specific conditions, modal decoupling leads to simple relationships between h, Δf, V_0, V_T and θ. Our experimental results are comparable to existing acoustoelastic work, although the materials differ slightly. In addition, it has been shown that LLW method are more sensitive and can provide more accurate results than the existing methods that measure flight time using the same equipment.

References

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