

# Research on Ultrasonic Guided Wave Damage Detection Methods for Metal Plate Structures based on Piezoelectric Sensors

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## Abstract

Ultrasonic damage detection technology based on Lamb waves holds significant application value in the field of structural health monitoring for plate-like structures. However, due to the multimodal propagation characteristics of Lamb waves, their detection signals often exhibit complex features, which poses challenges for the effective extraction of damage information. To address this issue, this paper proposes a damage detection method for metal plate structures based on the construction of single-mode baseline signals using a mobile sensor setup. The innovation of the method lies in the adoption of a mobile sensor array composed of an excitation sensor and a receiving sensor, which constructs temporary baseline signals by measuring the signal responses of structurally healthy areas in real time. Based on these baseline signals, the system can accurately identify differences in structural response signals across different regions of the same structure. By calculating the difference between the current detection signal and the baseline signal, the damage scattering signal can be extracted. This study provides a new technical approach for the non-destructive testing of plate structures and shows promising potential for engineering applications.

## Keywords

Lamb Waves; Baseline Signal Construction; Single-Mode; Mobile Sensor.

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## 1. Introduction

As fundamental components in modern engineering systems, plate-like structures have a direct impact on the overall reliability of engineering systems. In the aerospace sector, critical components such as aircraft skins and wing panels are often designed in plate-like forms. Similarly, in transportation industries, high-speed train bodies and ship decks rely on the mechanical performance of plate-like structures. In the construction field, steel structural slabs and curtain wall support systems also widely adopt plate-like structural forms. During their service life, these structures are subjected to complex alternating loads, extreme environmental erosion, and other multifaceted factors, inevitably leading to various types of damage such as fatigue cracks, corrosion-induced thinning, and delamination[1-6].

Traditional manual inspection methods suffer from inherent limitations such as inefficiency and subjectivity, particularly in the inspection of large structures or concealed areas. Statistics show that approximately 35% of structural damage in aircraft maintenance is discovered incidentally during periodic overhauls rather than through proactive detection. This passive damage discovery model often means that structures have operated with damage for extended periods, posing significant safety risks. Therefore, there is an urgent need in the engineering field to develop efficient and accurate non-destructive testing (NDT) technologies. Among these, Lamb wave-based detection technology has gained widespread attention due to its rapid propagation speed, long detection range, and excellent sensitivity to various types of structural damage [7-9]. During detection, Lamb waves generated by excitation sensors propagate through the structure and scatter when encountering damaged areas. The

signals received by the sensors include both direct waves and damage-scattered waves, with the latter carrying critical damage information. However, the practical application of this technology faces two major challenges: first, Lamb waves exhibit multimodal propagation characteristics in plate structures, with different modes displaying distinct propagation features at varying frequencies, making the acquired signals highly complex; second, damage-scattered signals often overlap with direct signals in the time domain, further complicating signal analysis, particularly when the damage is located close to the sensor path, making it difficult to extract the damage-scattered signal for analysis.

The Baseline-based Method, which relies on the collection of original structural signals, has become the most widely adopted technical approach in this field due to its maturity and reliability. This method is grounded in rigorous comparative analysis theory, with its core idea centered on establishing a signal baseline database of the structure in its undamaged state to provide a scientific reference and evaluation standard for subsequent damage identification. The implementation of the Baseline Method requires data collection during the initial undamaged state of the structure before it is put into service or after rigorous confirmation of its health status. This characteristic makes it particularly suitable for the long-term health monitoring of newly constructed critical infrastructure or key equipment [10-12].

To overcome the limitations of traditional methods, researchers in recent years have developed various baseline-free damage detection techniques, primarily including signal simplification and reconstruction methods. Among these, Lamb wave excitation and signal acquisition technologies based on mode selection have gained extensive research attention. Under low-frequency excitation conditions, only two fundamental propagation modes ( $S_0$  and  $A_0$  modes) exist in plate structures. By employing specially designed transducers and optimized arrangements, the extraction of single-mode signals can be achieved. Xu Kailiang et al. [13] proposed a single-mode dispersion compensation method to address dispersion issues under multimodal conditions, applied to Lamb wave mode separation for single-mode extraction. Kan Tingting et al. [14] introduced a defect localization and imaging algorithm based on dispersion compensation, achieving high-precision defect imaging. Giurgiutiu et al. [15] proposed a mode selection method based on piezoelectric actuator size optimization, achieving mode control by precisely matching actuator dimensions with excitation frequencies. Building on this principle, the Salas team [16] developed variable-length piezoelectric composite transducers capable of selectively enhancing specific modes at different frequencies. Su et al. [17] innovatively proposed a dual-mode piezoelectric actuator arrangement scheme, achieving specific mode enhancement and suppression by symmetrically arranging actuators on the upper and lower surfaces. Although mode selection techniques can effectively reduce signal overlap and enable the extraction of damage-scattered signals through time-domain windowing, these methods still face inherent limitations: when damage is located near the transducers, damage-scattered signals inevitably overlap with direct signals in the time domain, posing new challenges for signal analysis.

Additionally, significant progress has been made in baseline-free damage detection methods based on Lamb wave modal characteristics. Park and Kim [18] proposed a baseline-free method using dual piezoelectric transducer pairs for extracting single Lamb wave mode signals. Huang and Jia [19] achieved damage detection in composite plates and metal plates based on the principle of reciprocity. Sun [20] realized damage localization in composite structures by comparing signals acquired from similar excitation-sensing paths. Other studies have obtained damage information or identified damaged paths by calculating Lamb wave mode propagation signals. These baseline-free detection methods effectively address the difficulty of obtaining baseline signals but still face the following technical bottlenecks: first, they impose high requirements on transducer performance and consistency; second, unavoidable experimental errors (such as deviations in transducer placement) significantly affect detection accuracy. As a result, the applicability of these methods in practical engineering applications remains limited.

This paper proposes a damage detection method for metal plate structures based on the construction of single-mode Lamb wave baseline signals. The method employs a movable sensor array to excite

Lamb waves and collect signals, effectively reducing the influence of the actuator-sensor setup on signal response. By using the designed sensor array to collect healthy signals from different locations in the structure's test area, temporary baseline signals are constructed as structural response references. Based on the comparison between the currently acquired signal and the obtained structural response signal, path-specific damage-scattered signals are extracted. Finally, the effectiveness of the proposed damage detection method is validated through experiments conducted on aluminum plates.

## 2. Construction of Strictly Similar Paths Using a Movable Sensor Array

This study focuses on homogeneous isotropic media. Lamb waves, as a unique form of ultrasonic guided waves in plate structures, exhibit multiple symmetric and antisymmetric propagation modes. The excitation sensor is used to generate Lamb waves that propagate within the plate, while the surface-mounted receiving sensors capture the time-domain response signals. It is important to note that the signal response characteristics are primarily influenced by three factors: the performance of the excitation/receiving sensors, the propagation distance, and the guided wave propagation characteristics.

When considering the influence of the sensors, the signal response  $S(t)S(t)$  for a specific Lamb wave mode can be expressed as:

$$s(x, t) = A_a V_s f(r, t) \quad (1)$$

Where,  $A_a$  represents the amplitude of the Lamb wave mode excited by the excitation sensor,  $V_s$  denotes the output voltage amplitude of the sensor, and  $f(r, t)$  indicates the propagation signal at a propagation distance of  $r$ . The excitation amplitude  $A_a$  can be expressed as:

$$A_a = -\frac{1}{P} \int_{\Omega} \mathbf{u}(\Omega) \mathbf{F}(\Omega) d\Omega \quad (2)$$

Where,  $\mathbf{u}$  represents the surface displacement,  $\mathbf{F}$  denotes the load applied by the actuator on the plate,  $P$  is a frequency-dependent parameter, and  $\Omega$  indicates the effective area of the excitation sensor. The excitation sensor influences the amplitude of the Lamb wave it generates through both its effective area  $\Omega$  and the applied load  $\mathbf{F}$ . The output voltage amplitude  $V_s$  of the sensor can be expressed as:

$$V_s = C_s \int_{\Omega} \varepsilon(\Omega) d\Omega \quad (3)$$

where,  $C_s$  is a constant related to the sensor parameters (such as Young's modulus, dimensions, etc.), and  $\varepsilon$  represents the corresponding strain. The propagation signal  $f(r, t)$  can be characterized in terms of the signal response as:

$$f(r, t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) e^{i(\omega t - kr)} d\omega \quad (4)$$

where,  $r$  is the propagation distance,  $F(\omega)$  and  $\omega$  represent the frequency spectrum and center frequency of the excitation signal, respectively, and  $k$  is the wave number corresponding to the Lamb

wave mode. For symmetric and antisymmetric Lamb wave modes, the wave number  $k$  can be solved using the frequency equation:

$$\frac{\tan(k_s b / 2)}{\tan(k_l b / 2)} = - \left[ \frac{4k^2 k_l k_s}{(k_s^2 - k^2)^2} \right]^{\pm 1} \quad (5)$$

$$k_s^2 = \left(\frac{\omega}{c_s}\right)^2 - k^2 \quad k_l^2 = \left(\frac{\omega}{c_l}\right)^2 - k^2 \quad (6)$$

$$c_l = \sqrt{\frac{2\mu + \lambda}{\rho}} \quad c_s = \sqrt{\frac{\mu}{\rho}} \quad (7)$$

where,  $k$  is the wave number,  $\rho$  represents the plate density,  $\lambda$  and  $\mu$  are the Lamé constants,  $c_p$  and  $c_s$  denote the longitudinal and shear wave velocities, respectively, and the superscripts + and - correspond to the symmetric and antisymmetric modes, respectively.

According to the signal propagation model established in Equation (4), when the propagation distance is fixed, the signal response of a specific guided wave mode exhibits stable characteristics. Based on this property, paths with identical signal propagation distances and propagation characteristics are typically classified as similar paths in engineering practice. By analyzing the signal differences between similar paths, damaged paths can be effectively identified. It is important to emphasize that the detection accuracy of this method is primarily constrained by the following two factors: (1) the performance parameters of the actuator and sensor, and (2) the modulation effects on the signal response amplitude.

To address this issue, this study employs a movable sensor array to construct strictly similar paths. One sensor serves as the excitation sensor (used to generate Lamb waves), while the other acts as the receiving sensor (used for signal acquisition). This design ensures that the sensor parameters and propagation distance remain entirely consistent during each signal acquisition. Based on signal propagation model theory, the signals acquired by this movable sensor array should exhibit complete consistency.

### 3. Extraction of Damage-Scattered Signals

The acquired signals consist of both structural response signals and damage-scattered signal components. Therefore, the damage signals can be extracted by removing the structural response signals from the current acquired signals, expressed as:

$$S_d(t) = S_c(t) - S_s(t) \quad (8)$$

where,  $S_s(t)$  represents the damage-scattered signal,  $S_i(t)$  is the currently acquired signal, and  $S_s(t)$  is the structural response signal. To obtain the structural response signal, multiple sets of signals (labeled #1, #2, etc.) need to be collected from different regions of the structure using the same excitation-acquisition configuration shown in Figure 1. In healthy regions (such as paths #1, #2, #4, etc.), the Lamb wave propagation paths are unaffected by damage, so the acquired signals exhibit consistency. However, in localized damaged regions (such as path #3), the signals show significant differences. Therefore, the structural response signal can be obtained by selecting healthy signals and calculating their mean, which is mathematically expressed as:

$$S_s(t) = \frac{1}{M} \sum_{i=1}^M S_i(t) \tag{9}$$

where,  $S_s(t)$  represents the structural response signal,  $S_i(t)$  denotes the  $i$ -th group of healthy signals, and  $M$  indicates the total number of collected healthy signal groups. In practice, this structural response signal is a temporarily constructed baseline signal. Therefore, this method is a detection approach based on baseline signal construction, with its core principle relying on the constructed baseline signal for damage identification. While conceptually similar to traditional baseline signal methods, this approach innovatively addresses the critical challenge of baseline signal acquisition.

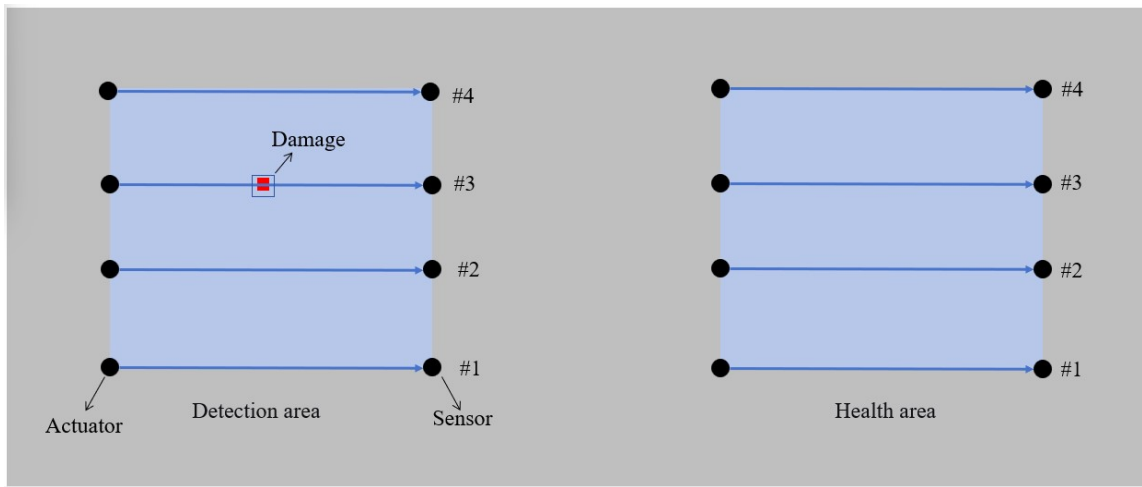


Figure 1. Area Scanning for Damage Detection Using a Mobile Sensor Array

#### 4. Damage Detection Experiment

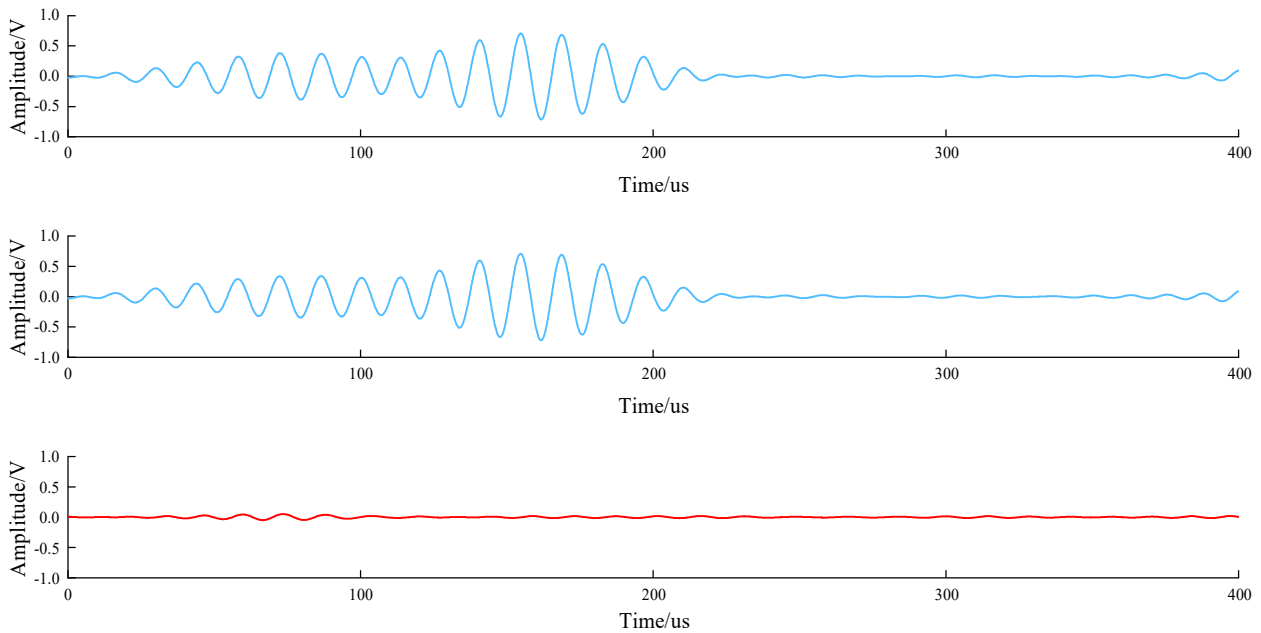
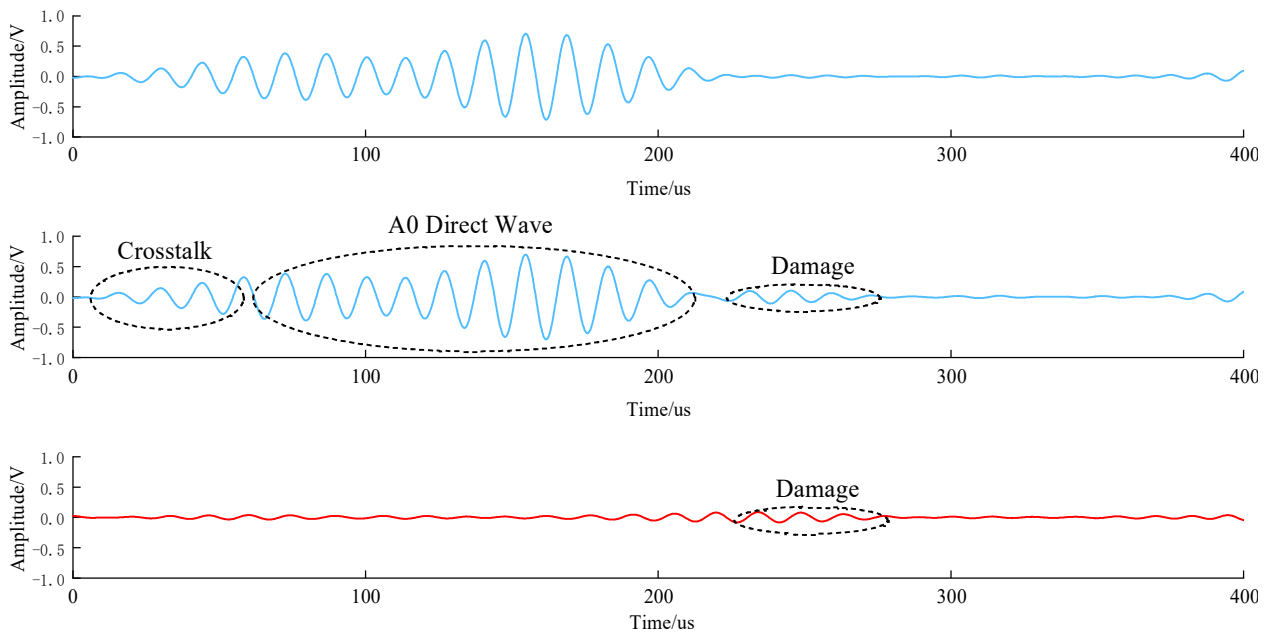


Figure 2. Comparison of Baseline Signals Between Detection Area and Health Area



**Figure 3.** Damage Extraction Map of the Inspection Area

To validate the method for extracting damage signals, an aluminum plate measuring  $2000 \times 1000 \times 4$  mm was used in the experiment. Two circular piezoelectric sensors with a diameter of 8 mm were attached to the surface of the aluminum plate to serve as the excitation sensor and the signal reception sensor, respectively, for generating and receiving Lamb wave signals. A small test block was employed to simulate damage. The spacing between the sensors was set at 200 mm. The A0 mode is dominated by out-of-plane displacement, while the S0 mode is dominated by in-plane displacement. The vibration direction of the sensors was aligned with the thickness direction of the plate, producing out-of-plane displacement. Consequently, only the A0 mode was captured in the signals collected during the experiment. A 10-cycle Hanning window-modulated sinusoidal signal was used, with a scanning frequency range of 50–200 kHz and a step size of 10 kHz. The signal sampling rate was set to 6 MHz. The movable sensor array was coupled to the structure using Vaseline, with the sensors and structure achieving coupling through atmospheric pressure. The use of Vaseline aimed to eliminate air at the contact surface, ensuring full contact between the transducers and the structure.

Figure 2 shows a comparison between the baseline signals from the healthy area and those from the inspection area. It can be observed that the differences between the baseline signals are minimal, allowing them to serve as temporary baseline signals in place of those from the inspection area. By applying these temporary baseline signals to detect damage in the inspection area, as illustrated in Figure 3, the damage signals can be fully extracted. Apart from minor deviations, the extracted damage signals exhibit good consistency with the actual damage information obtained from the experiments.

## 5. Conclusion

This paper proposes a damage detection method for metal plate structures based on the construction of single-mode baseline signals using a movable sensor array. By designing a movable transducer pair to excite Lamb waves and acquire signals, temporary structural response signals are constructed from healthy signals collected in different regions to serve as substitute baseline signals. Damage-scattered signals for each path are then extracted by calculating the difference between the currently acquired signals and the structural response signals. Experimental validation conducted on aluminum plates demonstrates that signals collected from different healthy regions exhibit good consistency, and distinct damage-scattered signals can be extracted from damaged paths. Compared to traditional methods, this study offers three key innovative advantages: first, it replaces the need for pre-existing

traditional baseline signals with experimentally measured structural response signals, effectively addressing the challenge of baseline acquisition; second, it eliminates the requirement for pre-obtained structural parameters such as material density, elastic modulus, and thickness; third, compared to traditional ultrasonic (non-guided wave) non-destructive testing techniques, this method significantly reduces data acquisition volume and enhances detection efficiency. These features make the proposed method highly valuable for practical engineering applications in damage detection.

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