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Research on Nondestructive Testing of Plate Components Based on Lamb Wave

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Abstract: With the development of engineering technology, people have higher and higher requirements for plate components. Small defects in the structure may also lead to engineering construction, so non-destructive testing technology arises at the historic moment. Ultrasonic guided wave is widely used in non-destructive testing because of its unique advantages. Lamb wave is widely used in nondestructive testing of plate components because of its fast propagation speed and strong penetration ability. This paper gives the steps of the damage imaging process of Lamb wave, and introduces its excitation and reception, signal analysis, damage identification methods, existing problems and future trends.

1. Introduction

Plate components are a common material in the fields of civil engineering, aerospace and so on. With the increasing demand for plate components in engineering applications, its damage detection has gradually become the focus in recent years. Cracks and scratches will inevitably occur in the production of plate components, when it is used in various projects, complex processing procedures may destroy its safety state [1]. In the course of use, due to the influence of environmental and human factors, these defects may gradually expand over time to have an impact on the safety of the structure. In order to avoid accidents, the safety status of components should be known in time. Under the premise of ensuring structural safety, non-destructive testing technology arises at the historic moment. Traditional nondestructive testing techniques include acoustic emission, infrared, X-ray and so on, but these instruments are huge and complex to operate, so they are not suitable for structural safety testing anywhere.

Ultrasonic guided wave nondestructive testing has the advantages of strong testing ability, simple equipment and less pollution to the environment, so it has been widely used in non-destructive testing. Lamb wave is a composite ultrasonic guided wave formed by the coupling of shear wave and longitudinal wave, which has the characteristics of strong penetration, wide propagation range and fast propagation speed, which can greatly shorten the testing time and improve the testing efficiency. It is more suitable for large-scale non-destructive testing of thin-walled structures [2]. At present, a signal exciter is installed on the surface of the structure to stimulate the guided wave. when there is damage in the structure, there is reflection and refraction between the guided wave and the damage, resulting in damage scattered waves [3]. According to the propagation characteristics of the guided wave and the signal receiver, the damage information with damage characteristics can be obtained, and then the damage situation of the structure can be obtained by using the damage identification method. Xia Xiaosong et al. [4] realized the non-benchmark detection of composites by using the time reversal method combined with the improved damage imaging method. Zhang Haiyan et al. [5] used distributed sensor networks combined with time reversal method to successfully detect defects in aluminum plates and image them. Ing et al. [6] used time reversal technique to compensate the dispersion effect of Lamb wave, and successfully focused Lamb wave to detect the defects in the plate. Li Tingting et al. [7] use the algorithm to skillfully apply the dispersion and mode conversion characteristics of Lamb waves to defect detection and imaging.

Starting with the propagation characteristics of Lamb wave, this paper gives the steps of the damage imaging process of Lamb wave, and introduces its excitation and reception, signal analysis, damage identification methods, existing problems and future trends.

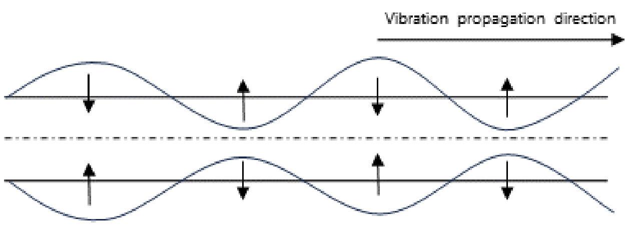
2. The basic principle of Lamb wave damage detection.

2.1 Propagation of Lamb waves in the plate

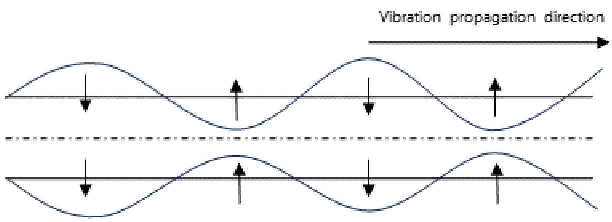
Assumes that the plate structure is a uniform, isotropic elastic medium, and its motion and displacement equation can be expressed by Navier-Stokes equation without external force:

$$(\lambda+\mu)\nabla\nabla\bullet\tilde{u}+\mu\nabla^2\tilde{u}=\rho\frac{\partial^2\tilde{u}}{\partial t^2} \tag{1}$$

Where $\tilde{u}$ is the displacement vector; and λ and μ is the Lame constant; t is the time; ρ is the density. The dispersion equation of Lamb wave is obtained by substituting the stress free boundary equation. According to the vibration direction of the neutral plane, it can be divided into symmetrical type (Symmetric Modes, S mode) and antisymmetric type (Antisymmetric Modes, A mode).As shown in Fig.1:



(a) symmetrical mode



(b) Antisymmetric mode

Figure 1: Propagation mode of lamb wave in thin plate.

The corresponding frequency equations can be expressed as [8]:

Symmetric mode:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2-k^2)^2} \tag{2}$$

(0.1)

Antisymmetric mode:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2-k^2)^2}{4k^2pq} \tag{3}$$

Where $p=\sqrt{\frac{\omega^2}{c_L^2}-k^2}$; $q=\sqrt{\frac{\omega^2}{c_T^2}-k^2}$; $c_L=\sqrt{\frac{\lambda+2\mu}{\rho}}$; $c_T=\sqrt{\frac{\mu}{\rho}}$.

h is half the thickness. The propagation velocity and attenuation characteristics of these modes are closely related to frequency, plate thickness, material properties and other factors. The propagation characteristics of Lamb wave determine its detection effect in different thickness and materials.

2.2 Signal excitation and reception

In order to realize the identification and location of damage, ultrasonic guided wave must be excited firstly. The common signal excitation methods include piezoelectric sensor (PZT), electromagnetic acoustic sensor (EMAT), Doppler scanner (SLDV) and so on. This paper mainly introduces the piezoelectric sensor, which is widely used because of its light weight and small size. Piezoelectric sensors are usually attached to the surface of the structure or installed in the interior of the structure, through the piezoelectric effect to achieve the excitation and reception of Lamb waves.

Fig. 2 is a schematic diagram of the excitation-reception of the sensor based on the one-send-one-receive mode. Under the inverse piezoelectric effect, the sensor of the excitation signal will convert the electrical signal into mechanical energy, and then transfer the mechanical energy to the surface of the structure to produce Lamb waves. When the Lamb wave encounters the damage in the structure, the phenomena such as reflection and scattering will occur to change the Lamb wave signal. Then the Lamb wave transmits the signal to the sensor that receives the signal, and the receiving sensor converts the transmitted mechanical energy into electrical signals under the action of positive voltage. This method can receive the structural information between the two sensors, and understand the damage location of the structure by comparing the arrival time, amplitude and phase of the current signal and the signal with complete structure.

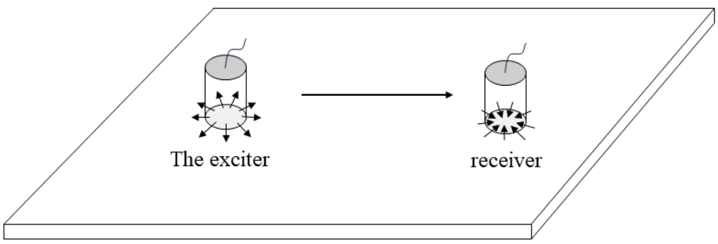


Figure 2: Schematic diagram of sensor based on one-send-one-receive mode.

2.3 Signal analysis and processing

When the signal receiver receives the Lamb wave with damage information, the received signal is more complex because of its own dispersion, multi-mode characteristics and environmental influence. Therefore, it is necessary to simplify the processing of the received signal to get the required damage information. The signal processing of guided wave includes time domain analysis, frequency domain analysis and time-frequency domain analysis.

2.3.1 Time domain analysis

Time domain analysis is to use the collected signals to get the most intuitive information, such as phase, amplitude, attenuation, etc., which is usually suitable for signals with simple waveform and high signal-to-noise ratio. The commonly used time domain analysis methods include time reversal method, Hilbert transform, correlation analysis and so on.

(1) time reversal method

In the time reversal method, the received signal wave packet is loaded and excited by the sensor after the head-to-tail position intermodulation, and whether the sensing path is damaged or not is judged according to the comparison with the signal before flipping.

(2) Hilbert transform

If the guided wave time domain signal is $f(t)$, then the Hilbert transform of $f(t)$ is changed to:

$$H(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{f(\varepsilon)}{t-\varepsilon}d\varepsilon \tag{4}$$

After transformation, the phase will shift, and the analysis will become more simplified.

(3) correlation analysis

The signal of the structure is divided into health signal and damage signal, and the correlation between them and the signal to be tested is expressed by correlation.

If the health signal and the signal to be tested are x_i and y_i respectively, the correlation coefficient between them can be expressed as:

$$r_{xy}=\frac{\sum_{i=1}^{N}\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)}{\sqrt{\sum_{i=1}^{N}\left(x_i-\bar{x}\right)^2}\sqrt{\sum_{i=1}^{N}\left(y_i-\bar{y}\right)^2}} \tag{5}$$

$\bar{x}=\frac{1}{N}\sum_{i=1}^{N}x_i$; $\bar{y}=\frac{1}{N}\sum_{i=1}^{N}y_i$. The more similar the two are, the higher the correlation is.

2.3.2 Frequency domain analysis

Frequency domain analysis is to transfer the signal from time domain to frequency domain so as to master more signal characteristics. It is suitable for the characteristic changes of waveforms which cannot be obtained directly from time domain signals, including Fourier transform (FT), two-dimensional Fourier transform (2DFT), discrete Fourier transform (DFT) and so on. The actual broadband signal needs to be processed by filter, but it can easily lead to the loss of damage characteristic signal. The waveforms of amplitude under different frequency signals can be extracted from stationary and linear signals by Fourier transform[9].

The guided wave number at different frequencies can be obtained by two-dimensional Fourier transform, which is defined as follows.

$$H(k,\omega)=\iint u(x,t)e^{-(kx-\omega t)}dxd\omega \tag{6}$$

Where k is the wavenumber and $u(x,t)$ is the guided wave acquisition signal, the two-dimensional Fourier transform can be used to describe the Lamb wave signal or even identify multiple waveform patterns in the same frequency band, which makes the analysis more simple.

2.3.3 Time-frequency domain analysis

Time-frequency domain analysis is a combination of the former two, which reflects both time domain information and frequency domain information, which can effectively avoid the loss of signal characteristic information of Lamb wave. The commonly used time-frequency domain analysis methods include short-time Fourier transform (STFT), wavelet transform and so on. The application conditions of the above methods are different, and appropriate methods should be adopted for analysis according to the specific situation.

2.4 The method of damage identification

The method of damage identification is to establish the relationship between the damage and the signal characteristics of the Lamb wave received by the receiver, and infer the size and location of the damage according to the characteristic information. The commonly used damage imaging methods include probabilistic imaging, phased array imaging, tomography and so on[10]. Phased array imaging is based on the principle of damage reflection, arranging multiple sensor elements into a special array, and then controlling and adjusting the guided wave phase excited by different sensors to achieve ultrasonic guided wave focus and damage detection of the structure. The basic principle of tomography is that the sensor array collects the parameters such as energy attenuation, flight time and mode conversion in the signal, establishes the model equation, and solves these equations to realize the damage assessment and the construction of damage image. The probabilistic imaging algorithm compares the signal in the healthy state of the structure with the damage signal of the structure, and then obtains the damage information of the structure, without analyzing the propagation characteristics of the wave and the performance of the selected material, which greatly reduces the intermediate error. The probabilistic imaging method divides the detection area into a grid of uniform size, and the damage existence probability of different points can be obtained by superimposing the damage index of different sensing paths. The obtained results are presented intuitively on the image, and the higher probability point on the image is the area where the damage is most likely to exist.

For any detection path, the damage index can be expressed as

$$DI=\frac{\int_{t_1}^{t_2}[S_c(t)-S_b(t)]^2dt}{\int_{t_1}^{t_2}[S_b(t)]^2dt} \tag{7}$$

Where $S_b(t)$ represents the reference signal, $S_c(t)$ represents the actual response signal, and t_1 and t_2 represent the start and end time of the direct wave signal, respectively. After the DI values of each path are obtained, combined with the spatial probability distribution function, the damage location of the structure can be obtained.

3. The problems of Lamb wave in nondestructive testing

Because of its high sensitivity to defects, Lamb wave can detect tiny cracks, voids and other defects, and has the advantages of long propagation distance, small attenuation and strong penetration, so it is often used in large-scale non-destructive testing. The nondestructive testing method based on Lamb wave combines the technology of various disciplines and fields. Domestic and foreign scholars have made a lot of research and achievements on guided wave propagation mechanism, signal processing and so on. However, there are still many problems to be solved.

1) It is difficult to separate the modes of Lamb waves.

Lamb waves can produce a variety of modes at different frequencies, including symmetric modes and antisymmetric modes. The superposition of different modes will lead to complex waveforms, which are difficult to separate and identify. Especially in the high frequency band, the dispersion effect of different modes is more significant, which makes the signal processing more complex. The dispersion characteristic of Lamb wave makes the wave velocity related to frequency, and waves with different frequencies will have different degrees of delay in the process of propagation. This dispersion effect not only increases the difficulty of signal processing, but also may lead to the reduction of detection accuracy.

2) The influence of material and structure

Actual detection objectis often the heterostructure composed of many kinds of materials. The reflection, refraction and scattering phenomena of different material interface make the propagation path of Lamb wave complex, which increases the difficulty of signal interpretation. The difference of wave impedance of heterogeneous materials may also lead to signal attenuation and noise increase. The structure of complex geometry will cause multiple reflections and refractions of Lamb waves in the process of propagation, resulting in multi-path propagation. This multipath effect makes the received signal contain multiple overlapping echoes, which increases the difficulty of signal processing.

3) Testing environment and conditions

External interference such as electromagnetic noise and mechanical vibration in the detection environment will pollute the Lamb wave signal and affect the accuracy of the test results. Especially in the industrial field, the environmental noise is usually difficult to eliminate completely, so it is necessary to use complex signal processing algorithms for filtering. The change of temperature will affect the elastic modulus and density of the material, thus changing the propagation velocity and dispersion characteristics of Lamb wave. In the environment of high temperature or low temperature, the detection result of Lamb wave may have a large deviation, which needs temperature compensation.

4) Signal processing and data analysis

Lamb wave signal processing involves analysis in time domain and frequency domain, and complex mathematical tools such as Fourier transform and wavelet transform are usually needed. The selection of signal processing algorithm and parameter setting have a direct impact on the detection results, which need to be optimized according to the specific application. A large number of test data need to be analyzed and explained effectively. Data analysis is not only to identify the location and size of defects, but also to assess the nature and severity of defects. Artificial intelligence and machine learning technology show good application prospects in this field, but the training and verification of their models require a lot of labeled data and high requirements for computing resources.

Solution:

(1) Modal separation technology: develop a more efficient modal separation algorithm to improve the accuracy of signal processing.

(2) Dispersion compensation method: the compensation method of dispersion effect is studied to reduce its influence on the detection results.

(3) Multi-material and complex structure detection: explore the detection methods suitable for heterogeneous materials and complex geometric structures to improve the adaptability and accuracy of detection.

(4) Environmental compensation technology: research and develop the compensation technology of environmental noise and temperature change to improve the stability of detection.

(5) Intelligent signal processing and data analysis: using artificial intelligence and machine learning technology to improve the automation and intelligence level of signal processing and data analysis.

4. Research status and development trend

At present, Lamb wave nondestructive testing technology has made remarkable progress in theoretical research and engineering applications. Through numerical simulation and experimental research, the researchers deeply discussed the propagation mechanism and mode selection of Lamb wave. Advanced signal processing techniques, such as time-frequency analysis, wavelet transform and machine learning algorithm, further improve the accuracy and reliability of Lamb wave nondestructive testing. The future development trends mainly include:

(1) Intelligent testing system: with the combination of sensor network and artificial intelligence technology, an intelligent Lamb wave nondestructive testing system is developed to realize automatic and real-time defect detection and evaluation.

(2) Multi-material testing: expand the application of Lamb wave nondestructive testing technology in composite materials and heterogeneous materials, and improve the testing ability of complex structures. With the continuous emergence of new materials, the propagation characteristics of Lamb waves in new materials are studied, and non-destructive testing techniques for new materials are developed.

(3) Portable equipment: develop portable and easy-to-operate testing equipment to enhance the convenience and efficiency of on-site testing.

(4) High resolution imaging: by optimizing the detection algorithm and hardware equipment, the defect imaging with higher resolution can be achieved and the visualization of the test results can be improved.

(5) Multimodal fusion: Lamb wave is combined with other nondestructive testing techniques (such as ultrasound, infrared thermal imaging, etc.) to improve the accuracy and reliability of testing.

5. Conclusion

As an efficient and sensitive testing method, Lamb wave nondestructive testing technology has shown its unique advantages in many fields. With the deepening of theoretical research and the continuous innovation of technical means, Lamb wave nondestructive testing technology will play an important role in more complex structures and new materials. Future research should continue to pay attention to the intelligence of testing system, multi-material adaptability and the development of high-resolution imaging technology, so as to promote the wide application and popularization of Lamb wave nondestructive testing technology.

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