DAMAGE MONITORING OF METAL STRUCTURES BASED ON ACOUSTIC TECHNOLOGY

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ABSTRACT

Metal materials are widely used in aircraft, crane and other major equipment. Under the combined effects of medium, temperature and cyclic load, metal structures are prone to corrosion cracking and cracks, which can cause structural failures and even lead to major safety accidents. This paper carries out research on structural damage monitoring based on acoustic technology. For the crack initiation, expansion and other active defects, the optical fiber technology and acoustic emission technology are integrated and innovative, and an acoustic emission monitoring system based on optical fiber transmission is developed to achieve long-distance transmission of local damage signals. In view of the damage of the metal plate and shell structure, ultrasonic Lamb wave monitoring technology based on the reconstruction algorithm for probabilistic inspection of damage is studied. The difference between the damage signal and the reference signal is used to identify and reconstruct the damage, to realize the monitoring and evaluation to the damage. Experimental results show that acoustic emission monitoring technology based on optical fiber transmission can identify the initiation and propagation of damage, and ultrasonic Lamb wave monitoring technology can identify and reconstruct the damage of metal plate shell structure more accurately. These two acoustic monitoring technologies can provide technical support for engineering applications of metal structure damage monitoring.

1. Introduction

Metal materials are widely used in major equipment such as aircraft and large crane. The long-term repeated action of stress or strain in the service process of the metal structure is prone to fatigue damage. The expression is the change of the microstructure of the metal material firstly, then the initiation of the microcrack, and finally the crack propagates until the visible crack is generated. In addition, it causes metal structural failure, which can lead to equipment damage and serious accidents such as casualties. In order to ensure the safe operation of metal structures, it is necessary to conduct early monitoring, location and evaluation of metal structure damage.

Acoustic emission is a phenomenon in which a material or component is deformed and fracture by an external force, or internal stress exceeds the yield limit and material enters an irreversible plastic deformation stage, releasing strain energy in the form of a transient elastic wave. Acoustic emission detection technology is sensitive to active defects and can detect the activity of defects under the applied load. Ultrasonic Lamb wave technology is an ultrasonic guided wave propagating in the plate structure. It has the advantages of fast detection speed, large detection range and strong defect identification ability. It has unparalleled advantages for damage monitoring of plate structure\textsuperscript{[1,2]}.

In this paper, an acoustic emission monitoring system based on fiber transmission is developed for active defects such as metal structure crack initiation and expansion, and the long-distance
transmission of structural damage signals is realized. Aiming at the damage of metal plate structure, the research of ultrasonic Lamb wave monitoring technology based on reconstruction algorithm for probabilistic inspection of damage is carried out to realize the localization and evaluation of macro defects. Combined with above two methods, the integrated real-time online monitoring of metal structure damage from initiation to formation of macro defects is realized.

2. Acoustic monitoring technology

2.1 Acoustic emission technology

Acoustic Emission (AE), also known as stress wave emission, is a phenomenon in which material is deformed or broken by external force or internal force, and stress-strain energy is released in the form of elastic waves. Most materials have acoustic emission when deformed and broken. Acoustic emission is the mechanical wave emission caused by local dynamic rearrangement of energy inside the material.

The principle of acoustic emission monitoring is shown in Figure 1. The elastic wave emitted from the acoustic emission source eventually propagate to the surface of the material, causing surface displacements that can be detected by acoustic emission sensors which convert the mechanical vibration of the material into electrical signals. These electrical signals are amplified, processed and recorded. People analyze and infer based on these acoustic emission signals to understand the mechanism by which the material produces acoustic emissions.

![Figure 1. principle of acoustic emission monitoring](image)

2.2 Ultrasonic Lamb wave technology and signal processing method

2.2.1 Ultrasonic Lamb wave technology

Ultrasonic Lamb wave technology is an ultrasonic guided wave propagating in a plate structure. In an infinitely uniform isotropic elastic structure medium, there are only two kinds of waves—transverse wave and longitudinal wave—both of which propagate at their respective characteristic velocities without waveform coupling. When the sound wave is excited at a certain point of the board, the waveform is converted due to the sound wave propagating to the upper and lower interfaces of the board. After a period of propagation in the board, the wave packet is generated due to the superposition, and it is called Lamb wave mode. When Lamb wave propagate through the plate, there are different modes, and the superimposed result of each mode is Lamb wave. In essence, Lamb wave is an elastic wave in which a transverse wave and a longitudinal wave are coupled to each other in a structure having two parallel surfaces.

When the Lamb wave propagates in the plate, the particles in the plate vibrate, and the vibration mode which changes with various parameters (frequency, plate thickness, etc.) is very complicated. According to the point vibration phase relationship between the two surface of the thin plate, Lamb wave mode can be divided into two types: symmetric wave and antisymmetric wave. Figure 2 shows the vibration of the plate under the condition of symmetric wave and antisymmetric wave. The symmetric wave is divided into multiple modes such as S0, S1, ..., Sn, and the antisymmetric wave is divided into multiple modes such as A0, A1, ..., Am.

![Figure 2-1. symmetric wave](image)
2.2.2 Ultrasonic Lamb wave signal processing method

In this paper, the reconstruction algorithm for probabilistic inspection of damage based on correlation coefficient is used to analyze and diagnose the damage. If there is damage on the propagation path, detection signal will be different when there are damage and no damage. In this paper, the damage information can be got by calculating the correlation coefficient of detection signals between damage and no damage on the sensing path. Calculated as follows:

\[
DI = 1 - \frac{\int_t^T \left[ H(t) - u_H \right] \left[ D(t) - u_D \right] dt}{\int_t^T (H(t) - u_H)^2 dt \int_t^T (D(t) - u_D)^2 dt}
\]  

(1)

H(t) is the health signal. D(t) is the monitoring signal. \( u_H \) is the average value of the health signal. \( u_D \) is the average value of the monitoring signal. \( t_1 \) is the starting time of the main wave packet. \( t_2 \) is the cut-off time of the main wave packet. DI is 0 means that the monitoring signal and the health signal are completely consistent, and it means that there is no damage on the sensing path. On the contrary, the larger the DI value, the larger difference between these two signals, and it means the greater damage on the sensing path[5,6].

The reconstruction algorithm for probabilistic inspection of damage is to map the damage index DI of the detection path to all discrete points of the monitoring range through the spatial distribution function. The DI of the detection path and spatial weighted value of each discrete point is calculated. The sum of the spatial weighted value multiply by DI can generate the imaging result of the entire measured range. The spatial distribution function of the damage index DI is as follows:

\[
m_{ij}(x, y) = \begin{cases} 
1 - \frac{R_{ij}(x, y)}{\beta} & R_{ij}(x, y) < \beta \\
0 & R_{ij}(x, y) \geq \beta
\end{cases}
\]  

(2)

\( \beta \) is a shape factor that controls the size of the ellipse in the measured range, which is the area affected by the DI of the excitation-sensing direct path, and is less than 1. \( R_{ij}(x, y) \) is that the sum of the distance between a discrete point \( R_{ij}(x, y) \) and the excitation sensor \((x_{ik}, y_{ik})\), and the distance between a discrete point \( R_{ij}(x, y) \) and the monitoring sensor \((x_{jk}, y_{jk})\), and the ratio of the sum and the distance between the excitation sensor and the monitoring sensor, and then minus 1. The expression is:

\[
R(x_k, y_k, x_{ik}, y_{ik}, x_{jk}, y_{jk}) = \frac{\sqrt{(x_k - x_{ik})^2 + (y_k - y_{ik})^2} + \sqrt{(x_k - x_{jk})^2 + (y_k - y_{jk})^2} - 1}{\sqrt{(x_{ik} - x_{jk})^2 + (y_{ik} - y_{jk})^2}}
\]  

(3)

The probability of damage at point \((x, y)\) in the monitored area of the N sensing paths is:

\[
P(x, y) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} DI_{ij} m_{ij}(x, y)
\]  

(4)
For example, when \( R=0 \), the pixel point \((x, y)\) is on the direct path of the excitation-sensing, at that time, \( I_y = 0 \). When \( R = \beta \), the pixel point \((x, y)\) is on the boundary of the area affected by the excitation-sensing path, at that time, \( I_y = 0 \).

3. Acoustic monitoring system

3.1 Acoustic emission monitoring system based on optical fiber transmission

Acoustic emission technology can monitor the initiation and expansion of cracks, but it also has its application limitations. It is affected by the inherent physical characteristics of transmission cables. And the transmission distance of acoustic emission signals is short and the anti-interference ability is weak. This technology is generally used for detection and cannot be used in Long-term monitoring of large metal structures (tanks, cranes, etc.) under operating conditions. In this paper, the optical fiber technology and acoustic emission technology are integrated and innovated. The acoustic emission monitoring system based on optical fiber transmission is designed and developed. It mainly consists of acoustic emission sensor array, acoustic emission preprocessing subsystem, optical fiber transmission subsystem and acoustic emission monitoring software subsystem. The composition is as shown in Figure 3-1. The system is shown in Figure 3-2. The system overcomes the shortcomings of the traditional acoustic emission system, and realizes the long-distance transmission of the acoustic emission signal. The designed system has the characteristics of strong anti-interference ability and long signal transmission distance, and provides a technical means for metal structure damage monitoring.

![Figure 3-1. Schematic](image1)

![Figure 3-2. System prototype](image2)

Figure 3. Acoustic emission monitoring system based on optical fiber transmission

3.2 Ultrasonic Lamb Wave Monitoring System

This paper selects the structural health monitoring system developed by Acellent Technologies, Inc, as shown in Figure 4. It includes piezoelectric flexible sensing array, multi-way switch, excitation/acquisition module and system software. The piezoelectric flexible sensing array realizes acquisition of ultrasonic guided wave signals on plate structure. Multi-way switch realizes fast switching between multiple high-voltage excitation signals and low-voltage receiving signals. The excitation/acquisition module includes central processing unit, excitation signal generating unit, linear power amplifying unit and acquisition signal processing Units, are used to generate and amplify sinusoidal modulated signals, amplify the acquired signals, and convert analog to digital. The basic functions of the system software include the structure definition to be measured, signal excitation/acquisition parameter settings, scan path definition, data acquisition and visualization, feature parameter extraction and historical data query.
4. Experimental research

4.1 Acoustic emission monitoring experiment

In order to verify the performance of the developed acoustic emission monitoring system based on optical fiber transmission, a large-scale component loading monitoring experiment was carried out. The large-scale component was tested by the developed system and the traditional acoustic emission detection system. The feasibility of the developed system in large-scale metal structure damage monitoring was verified.

The loading test device adopted the loading test bench produced by Beijing R&F Tongda Technology Co., Ltd. The main performance indexes were as follows: vertical maximum static test force was 10 tons, vertical maximum dynamic test force was less than 10 tons, effective stroke was 200 mm, working frequency was 0–2Hz. The loading device was shown in Figure 5. Large components were made of Q235 material, as shown in Figure 5.

In the experiment, the loading device was used to load the large component. The weld crack propagation process was tested by the acoustic emission monitoring system based on optical fiber transmission and the traditional acoustic emission detection system simultaneously. The developed monitoring system used two-channel sensors for monitoring. The sensor arrangement was shown in Figure 6-1, and the sensor of the traditional acoustic emission system was placed opposite the right-hand sensor of the developed system. Figure 6-2 showed the state in which the weld crack after loading, wherein the white marked portion was the weld crack before loading.

When the loading of the component was stopped, the monitoring was completed. The two systems recorded the acoustic emission signals of the weld crack propagation during the component loading.
process. The monitoring waveform of the developed acoustic emission monitoring system was shown in Fig. 7. The detection waveform of the conventional acoustic emission system was shown in Fig. 8.

Figure 7-1. Waveform  Figure 7-2. Amplitude vs. time scatter plot

Figure 7-3. Hit accumulated vs. time graph

Figure 7. Monitoring waveforms of developed system

Figure 8. Detecting waveforms of traditional acoustic emission system

It can be seen from the comparison of the detection waveforms that the monitoring results of the acoustic emission monitoring system based on optical fiber transmission are basically consistent with those of the conventional acoustic emission system. During the loading process, the amplitude greater than the threshold appeared more, the hit increased significantly. It is consistent with the crack propagation trend. It can be seen that the acoustic emission monitoring system based on optical fiber transmission can reflect the crack propagation of the metal structure, and can effectively extend the monitoring distance, has strong anti-interference ability, and can realize long-distance structural damage monitoring.

4.2 Ultrasonic Lamb wave monitoring experiment

Structural damage monitoring experiment were carried out on aluminum plates of length × width × thickness is 1000 × 1000 × 1 (unit: mm). Eight piezoelectric sensors were evenly arranged on the circumference of the center of the aluminum plate with a radius of 30 mm, as shown in Figure 9. At the middle of the center of the aluminum plate and the sensor 2, a 304 stainless steel cylinder which used to simulate damage having a diameter of 12 mm and a height of 45 mm was attached using a glue. A sensor was excited, and the remaining sensors were used as monitoring sensors to receive signals. It means that an excitation signal was applied to the i-th sensor (1 ≤ i ≤ 7), and the j, j+1,...(i ≤ j ≤ 8) sensor received the monitoring signal. The excitation signal which applied to the sensor was a 5-peak narrow-band pulse signal with a center frequency of 130 kHz and an amplitude peak-to-peak value of 10 V. First, the signal with the simulated damage was collected, and then the cylinder that simulates the damage was removed, and the signal without damage was collected.
The acquired signal was processed by correlation-based reconstruction algorithm for probabilistic inspection of damage. The processing result was shown in Figure 9. The right color band represented 0-1 from bottom to top. The color was closer to brownish red means that the probability value was close to 1. And it indicated that the probability of occurrence of damage was greater. The part marked by the white circle was the true position of the damage. It could be seen that the location of the damage imaging could cover and be greater than the location of the actual damage.

![Figure 9-1. Sensor layout](image1)
![Figure 9-2. Probability image](image2)

**Figure 9. Ultrasonic Lamb wave monitoring diagram of aluminum plate**

5. Conclusions

In view of the engineering requirements of metal structure damage monitoring, research on structural damage monitoring technology based on acoustic technology was carried out. The main conclusions are as follows:

(1) The developed acoustic emission monitoring system based on optical fiber transmission and the traditional acoustic emission system have the same detection results, and the former has the advantages of long transmission distance and strong anti-interference ability. The monitoring results can accurately reflect the initiation and expansion of cracks.

(2) The ultrasonic Lamb wave monitoring system and the reconstruction algorithm for probabilistic inspection of damage based on correlation analysis are used to monitor the damage of the aluminum plate. The imaging results are basically consistent with the actual position of the defect. The method has the advantages of fast monitoring speed, large monitoring range and strong defect identification capability.

(3) Combining the acoustic emission monitoring technology based on optical fiber transmission and the ultrasonic Lamb wave monitoring technology, real-time monitoring of metal structure damage initiation, expansion can be realized. This combined monitoring method is of great significance for ensuring the safe operation of metal structures, and has a broad engineering application prospects.

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References


