Corrosion Depth Monitoring of Hole-Edge Based on Lamb wave

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\textbf{Abstract:} This study proposed a novel method using Lamb wave to detect corrosion depth at the hole-edge of plate-like structure. An experimental procedure with a hexagon layout using 6 piezoelectric sensors (PZTs) was applied. The A0 mode of the Lamb wave was selected to detect depth-loss damage, and the amplitude of A0 mode gradually decreases with the increasing of corrosion depth. The simulation results are consistent with the real damage pictures, which confirms the effectiveness of the proposed method. The results show that A0 mode of Lamb wave can be used to identify corrosion depth damage at the hole-edge of plate-like structure.

1. Introduction

With the development of astronautic industries and the increase of aircraft's service year, there are more than 14000 aging aircrafts in the world, and corrosion is one of the most important damage problems faced by the aging aircrafts [1]. Besides, for those aircrafts which often need to work under severe conditions such as humidity, high salt, acid rain and high temperature, the corrosion is more serious. [2]. And corrosion depth is an important factor, which can be used to determine maintenance methods of damaged aircrafts, and to determine whether the corrosion of structures meets the damage tolerance requirements [3].

Lamb wave is a kind of ultrasonic guided wave. When conducting in the thin plate, it will exist in multiple modes, for example, the symmetrical modes are S0, S1, S2, etc., and the antisymmetric modes are A0, A1, A2, etc. At different frequencies, there will be two or more Lamb wave modes [4]. So the major advantages of Lamb wave tomography include multi-mode, low cost, long distance of propagation and good sensitivity to inaccessible and complex components. In recent years, Lamb wave tomography has aroused wide concern. Jenot [5] monitored and estimated the corrosion thickness of steel plate by measuring the group velocity of Lamb wave S0 mode. Rao et al. [6] intended to reconstruct the thickness map of plate-like structure which has artificial defects with different sizes and depths, and discussed the reconstruction accuracy of the full waveform inversion (FWI) algorithm by using simulations and experiments results.
Besides, it is shown that PZTs are an effective tool with the advantages of high accuracy and high speed of response signal. Yu et al. [7] used PZTs for corrosion damage monitoring in plate-like aluminum structures. And all kinds of algorithm and sensor layout are also applied to corrosion damage monitoring. For instance, Thomas et al. [8] designed a circular array of PZTs layout to detect material loss in thin metal sheet. Wang et al. [9] proposed a method using a cross-hole sensor layout, and iterative algebraic reconstruction technique (ART) method was used for hole-edge corrosion damage in aluminum structures. And Wang et al. [10] applied the probability imaging algorithm for corrosion area expansion monitoring at the hole-edge of aluminum plate.

In this study, a method based on Lamb wave active sensing for corrosion damage identification is proposed. A hexagon sensor layout is designed according to the size of specimen. And a real corrosion with different depths at the hole-edge of aluminum alloy plate is made artificially. The propagation characteristics of Lamb wave A0 mode at certain frequency are explored and observed. The simulation imaging results and real corrosion pictures are quantitatively compared and analyzed. In the end, a method for corrosion depth monitoring is drawn.

2. Material and Methods

2.1. Test design
The specimen is aluminum 2024-T3 with the size of 400mm×200mm×2mm, and a hole with a diameter of 10 mm is at the center point of the plate. The material properties of the specimen are shown in Table 1.

| Type            | Parameters        | 1 | 2 | 3 | 4 |
|-----------------|------------------|---|---|---|---|
| Poisson's Ratio | 0.33             |   |   |   |   |
| Density         | 2.78 g/cc        |   |   |   |   |
| Young’s modulus | 73.1 GPa         |   |   |   |   |
| Fatigue Strength| 130 MPa          |   |   |   |   |

Figure 1. The diagram of specimen and the sensor layout

The layout of the PZTs is designed according to the size of specimen as shown in Figure 1. 6 PZTs which are both used as transmitter and receptor are bonded to the surface of the plate. 30 effective sensor paths of different length are obtained in this layout.

2.2. Experiment equipment
ScanGenie-II integrated structural health monitoring scanning system produced by Acellent Technologies is used to excite and acquire Lamb wave signal. The system can realize large-area, long-
distance and multi-point health monitoring. The experiment device includes specimen, piezoelectric sensors, connecting box, signal generator, ScanGenie-II piezoelectric monitoring device and digital acquisition software, as shown in Figure 2. The main technical parameters of the equipment are shown in Table 2.

![Experiment Device Image](image)

**Figure 2.** The experiment device [10].

| Type | Parameters |
|------|------------|
| 1    | Device number | ScanGenie-II |
| 2    | Integrated Power Amplifier | ±60V |
| 3    | Frequency | 50kHz~200kHz |
| 4    | Step | 10kHz |
| 5    | Sampling rates | 24MS/s |
| 6    | sampling length | 10000 points |

### 2.3. Signal design

In this study, SMART Suitcase sensor produced by Acellent company is used to record the signal. A smoothed 5-count Henning-windowed sine tone burst is used as excitation signal, and the excitation signal of 90 kHz is shown in Figure 3. The expression of excitation signal is as follows (1).

\[
u(t) = A \left[ H(t) - H\left(t - \frac{N}{f_c}\right) \right] \times \left(1 - \cos 2\pi f_c t \right) \sin 2\pi f_c t \quad (1)\]

where A is the signal amplitude, H(t) is the Heaviside step function, N is the number of crests, and \(f_c\) is the central frequency of the signal. The sampling rate is 24 MS/s, and the sampling length is 10000 points.
2.4. Experiment process
After experiment design, the corrosion depth damage is made artificially with diameter of 20mm. 2024-T3 aluminum alloy plate is not acid resistant. Therefore, Hydrofluoric (HF) acid solution provided by Hengxing Reagents is mixed with water in a ratio of 1:2, the chemical compositions of HF are shown in Table 3. The mixed solution is used to produce corrosion in different depth at the edge of the central hole.

| Content            | Impurity content (%) |
|--------------------|----------------------|
| 1 HF               | ≥40%                 |
| 2 Fe               | ≤0.0001              |
| 3 Cl               | ≤0.001               |
| 4 PO₄              | ≤0.0002              |
| 5 Heavy metal (Pb) | ≤0.0005              |
| 6 Fluorosilicate (SiF₆) | ≤0.04   |
| 7 Others           | ≤0.004               |

To protect the hole, the plastic piece is pasted on the back side of the middle hole with glass glue in advance, and then glass glue is also filled in the hole. To prevent the PVC pipe from moving and the corrosion liquid from leaking to destroy the specimen, fix PVC pipe with glass glue at the corrosion position to form an etching solution groove, as shown in Figure 4.
After the glass glue is solidified and stable, mixed corrosion solution is injected into the PVC pipe using a medical syringe to corrode the aluminum plate. During the corrosion procedure, HF reacts with aluminum plate to produce small bubbles. When there are no bubbles in the PVC pipe, the corrosion procedure is finished. In the end, remove the PVC pipe, glass glue and plastic piece. Different corrosion depth is made by controlling the amount of corrosion solution and corrosion time. Use different amount of corrosion solution in each experiment and repeat above operation, five corrosion experiments are carried out in turn. The specific amount of corrosion solution, corrosion time and parameters of five-corrosion depth are shown in the Table 4.

| Corrosion State | Amount of corrosion solution (ml) | Corrosion time (h) | Corrosion depth (mm) |
|-----------------|----------------------------------|--------------------|----------------------|
| No Corrosion    | 0                                | 0                  | 0                    |
| 1st Corrosion   | 20                               | 8                  | 0.60                 |
| 2nd Corrosion   | 20                               | 8                  | 1.20                 |
| 3rd Corrosion   | 10                               | 4                  | 1.38                 |
| 4th Corrosion   | 8                                | 4                  | 1.58                 |
| 5th Corrosion   | 8                                | 2                  | 1.68                 |

3. Results and Discussion
The dispersion curves of phase velocity and group velocity of Lamb wave on the 2mm thick 2024-T3 aluminum plate are shown in Figure 5. When the product of frequency and thickness is less than 0.7 MHz, there are only S0 mode and A0 mode. And the group velocity of A0 mode changes more significantly than that of S0 mode. This represents that the A0 mode is more sensitive to the thickness change of the structure at the same frequency, which is better for corrosion depth identification. Therefore, A0 mode at the low frequency is chosen for the next analysis.

![Figure 5 Dispersion curve of the Lamb wave in 2mm thick aluminum plate](image-url)

Six kinds of sensor paths are as follows: 72mm, 80mm, 120mm, 134mm, 144mm and 160mm. The distance of 72mm and 80mm path is too short to let S0 mode and A0 mode be separated completely, so the complete shape of A0 mode wave packet can’t be observed. Although the distance of 120mm and 134mm path is appropriate, these two types of paths do not pass through the corrosion damage directly. The damage can not directly affect the signal, which is not conducive to observe the variation of signal parameters. On the contrary, 144mm and 160mm paths both cross the damage straightly, and their distance is long enough to separate the wave packet. Next, the 144mm path is represented by path 2-5,
and the 160mm path is represented by path 3-6. The time domain distributions of Lamb wave signals propagating along one path are shown in Figure 6. On two paths, the S0 mode arrives earlier than the A0 mode. However, S0 mode is overlapped by the crosstalk ahead. On the contrary, the wave packet of A0 mode is independent and complete. It confirms again that A0 mode is better than S0 mode in this experiment. At path 3-6 and 90kHz, the phase difference of A0 mode between healthy signal and damage signal is too big, and the signal amplitude has no specific variation, while the amplitude regularity of signal in path 2-5 is obvious, so path 2-5 will be selected for further analysis.

Amplify the A0 mode wave packet on path 2-5, as shown in Figure 7. When A0 mode encounters damage, the continuity of signal transmission is interrupted at the damage, and the energy is attenuated after scattering and reflection. With the corrosion depth increasing, A0 mode meets larger damage, so the signal attenuates more energy. The amplitude of A0 mode gradually decreases compared with the previous corrosion.
At the initial stage of corrosion damage, the amplitude of A0 mode is larger than that of health state. That's because the specimen with a thickness of only 2 mm is selected in this experiment, and the attenuation of signal energy in thin plate is less than that in thick plate. Therefore, when corrosion damage occurs, the amplitude of A0 mode increases. Besides, the expansion of corrosion area will increase the proportion of thickness thinning area in the monitoring area. But in this experiment, the corrosion area is fixed, so the influence of the corrosion area expansion on signal amplitude is the same in five experiments. But when signal meets larger damage, it will cause more signal energy attenuation. So with the increase of corrosion depth, the signal attenuation is increasing and the amplitude of A0 mode gradually decreases, even lower than the health state. Different damage will have different effects on Lamb wave signal, and different modes of Lamb wave also show various phenomena. For corrosion depth in this experiment, the amplitude of A0 mode shows specific regularity, so this kind of damage can be qualitatively identified by Lamb wave A0 mode.

In order to verify the effectiveness of Lamb wave for damage identification, the simulation results are compared with real corrosion depth damage as shown in figure 8. The red part in the circle represents the corrosion depth area. The rest, such as the blue part, represents the undamaged area. As shown in figure 8 (a) to (e), the red part in the circle deepens gradually with the increasing of the corrosion depth. The simulation results are consistent with the real damage pictures. The result proves the effectiveness of this method. Lamb wave A0 mode can be used for corrosion depth identification at the hole-edge of plate-like structure.
Figure 8. Comparison of five times real damage and simulation diagram from (a) to (e)

4. Conclusions
In this study, Lamb wave A0 mode is used to detect the damage of corrosion depth increase at the hole-edge of the aluminum plate. Active sensing method with improved sensors layout and integrated experiment equipment are applied. And HF acid solution is used to make different corrosion depths artificially. With the increasing of corrosion depth at the hole-edge, the amplitude of Lamb wave A0 mode is decreasing gradually, which is an obvious feature for the corrosion depth identification. Five simulation results are compared with real damage pictures, and the results demonstrate the effectiveness of this method. Lamb wave A0 mode can be applied to damage identification.

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