

High Accuracy Non-Contact Monitoring for Hole-Edge Crack of Aircraft Attachment Lug Based on Guided Wave Network

LIMING SHI, LEI QIU and SHENFANG YUAN

ABSTRACT

The attachment structure is the key component to ensure the structural integrity and bearing capacity in aircraft structure, and its service environment is often complex and harsh. As the main attachment structure between fuselage and wing, the aircraft attachment lug is much possible to initiates hole-edge crack at any direction and propagates, which leads to a decrease in structural integrity and then fracture failure. Owing to the advantages of non-contact monitoring, the hole-edge crack monitoring based on guided wave-structural health monitoring (GW-SHM) method has always been a topic of concern in recent years. However, research on aircraft attachment lugs still needs to be further developed. Due to the existence of large bolt hole and complex propagation characteristics of GW in aircraft attachment lug, it is difficult to accurately monitor hole-edge crack damage, especially small cracks. Aiming at this problem, a high accuracy monitoring method based on guided wave network is proposed in this paper. The damage features in GW network are quantified accurately by damage index (DI) method, and a reliable alarm mechanism is constructed. The crack localization imaging method is optimized for the bolt hole form to enhance the monitoring accuracy. The proposed method is verified by a monitoring experiment of small hole-edge crack in aircraft attachment lug. The results demonstrate that this method can achieve correct damage alarm and accurate damage location, which provides a research idea for the accurate monitoring of hole-edge crack damage.

Keywords: hole-edge crack monitoring, guided wave network, crack damage alarm, crack localization imaging

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1 INTRODUCTION

The attachment structure is the critical component that ensures structural integrity and load-bearing capacity in aircraft structure [1]. In attachment structures, attachment lug is often adopted in irregular connecting parts, such as wings to fuselage. However, the attachment lug is often located in narrow areas, and its service environment is often complex and harsh. It is much possible to initiate small hole-edge crack at any direction and propagates, which leads to a decrease in structural integrity and then fracture failure [2]. In addition, it is difficult to early detect small crack in attachment lug due to the cover of the bolts and screws. Consequently, the hole-edge crack monitoring of attachment lug is the focus of many researchers [3].

Structural health monitoring (SHM) technology plays an important role in crack damage monitoring, and therefore receives increasing attention. A typical SHM technology is based on guided wave (GW), and the piezoelectric sensors (PZTs) can be arranged outside the stress concentration area to avoid the sensor failure, such as bolt hole. So the GW-SHM method can achieve non-contact monitoring for hole-edge crack damage, and has the advantages of high sensitivity to small damage, low monitoring cost, etc., thus it has gained growing attention [4-5].

Regarding the hole-edge crack monitoring in attachment lug, Yuan et al. proposed a GW-hidden Markov model for hole-edge crack propagation evaluation [6]. The classification of hole-edge crack length states was achieved, but the resolution of crack monitoring was only 2mm. Soni et al established the GW-finite element model to achieve classification diagnosis of crack length based on extracted the spectral feature information from GW signal [7]. However, the classification resolution of crack length only reaches 2mm as well. Some previous studies have shown that the damage features extracted from GW signals based on a small number of channels are not sensitive enough to small crack damage [8-9], and the evaluation error of crack length exceeds 3mm. Therefore, the accuracy of crack monitoring in the attachment lug still needs to be improved. Teng et al. conducted GW monitoring research on the hole-edge crack localization based on improved imaging method [10], reducing the localization error to less than 4 mm. Additionally, this study indicated that boundary reflection can interfere with localization result.

In summary, accurately monitoring small cracks remains a challenge, and the presence of bolt holes in the attachment lug enhances boundary reflection, increasing the difficulty of accurately locating crack. Therefore, to improve the monitoring accuracy of small hole-edge crack, it is necessary to improve the monitoring method in combination with the structure form, and extract multi-channel feature information in GW network.

Aiming at accurate monitoring for small hole-edge crack in the attachment lug, a high accuracy monitoring method based on guided wave network is proposed. Firstly, the damage indexes (DIs) of all channels are extracted from GW network, and the damage alarm mechanism-based DI is established. The crack localization imaging method is improved for the bolt hole form in the attachment lug. Then, an experiment system for monitoring small crack is built. Finally, the experiment for monitoring 1mm small crack is carried out. The experiment results show that this method can achieve damage monitoring for 1mm small cracks. The damage alarm results are accurate, and there is no false alarm in the health state. And it realizes high accuracy localization for

1mm small crack damage at different positions, with a maximum localization error of only 3.18mm, which verifies the effectiveness and accuracy of the proposed method.

2 METHOD

2.1 Crack Alarm-Based DI

The principle of GW-SHM is shown in Figure 1. The piezoelectric sensor (PZT) is adopted to acquire the GW signal and the damage feature is extract by signal processing method, and then the monitoring information of the structure state can be obtained.

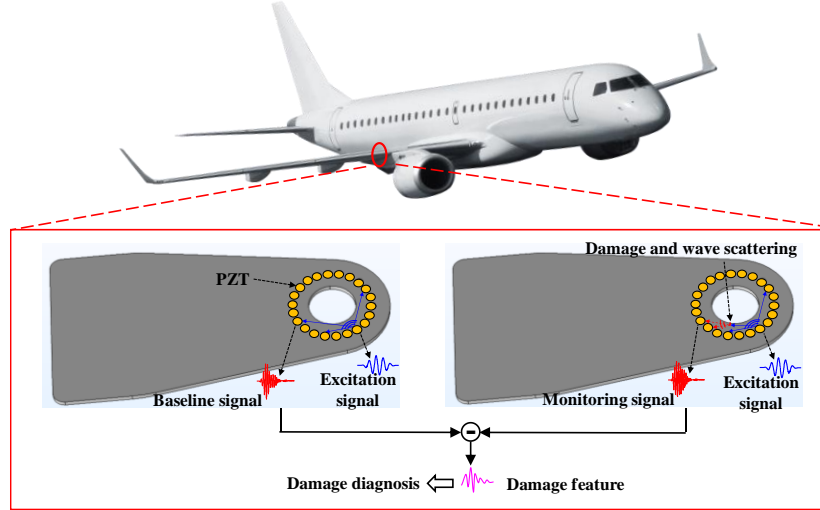


Figure 1. SHM principle based on GW

Due to the crack damage, the GW signal affected by the crack, including signal amplitude and phase. The damage index (DI) is used to associate the damage state with the characteristics in the GW monitoring signal [11]. It is used to quantitatively analyze the response of GW to damage. The root mean square error is adopted as DI, as shown in equation (1):

$$RMSE = \sqrt{\frac{\int_{t_1}^{t_2} [B(t) - M(t)]^2 dt}{\int_{t_1}^{t_2} B^2(t) dt}} \quad (1)$$

Where $B(t)$ and $M(t)$ are the baseline and monitoring signals, t_1 and t_2 are the start and stop time corresponding to the selected GW signal. In the actual monitoring, multiple PZTs are usually adopted to build an excitation-sensing monitoring network, and then the monitoring results are improved [12]. If the number of PZTs is n , any one PZT serves as an emitting sensor, the $n-1$ PZTs can receive GW signal. So, the whole GW network can be described as following:

$$N = n * (n - 1) \quad (2)$$

Where N is the channel number in the GW network. The DI of each channel in the GW network is extracted to obtain the mean of DIs, as shown in equation (3):

$$MDI = \frac{\sum_{j=1}^N DI_j}{N} \quad (3)$$

Where MDI is the average value of DIs. The damage alarming mechanism based on the average DI is proposed, and the damage alarm threshold is obtained, as shown in equation (4):

$$DAT = k * MDI \quad (4)$$

Where DAT is the damage alarm threshold, k is confidence coefficient, usually set 4. If the DI value of individual channel exceeds the alarm threshold DAT , this channel will trigger the damage alarm.

2.2 Crack Localization-Based DAS

The GW difference signal of each channel is extracted, and the arrival time of the difference signal is calculated, as shown in equation (5):

$$t(x, y) = t_{start} + \frac{\sqrt{(x-x_{ex})^2 + (y-y_{ex})^2} + \sqrt{(x-x_{se})^2 + (y-y_{se})^2}}{v_g} \quad (5)$$

Where t is the arrival time of difference signal, x_{ex} and y_{ex} are position coordinates of the excitation PZT, and x_{se} and y_{se} are position coordinates of the sensing PZT. The t_{start} is the excitation time of the GW signal, and v_g is the group velocity of GW propagation. The delay-and-sum (DAS) method is adopted, as shown in equation (6):

$$I_g(x, y) = \alpha * \sum_{i=1}^N E(t_i(x, y)) \quad (6)$$

Where I_g is the pixel value, α is the pixel weight, E is the difference signal through wavelet transform. According to the position of the through-hole, α can be described as following:

$$\alpha = \begin{cases} 1 & x^2 + y^2 > r_h^2 \\ 0 & \text{others} \end{cases} \quad (7)$$

Where r_h is the radius of hole. The min-max normalization method is adopted, as shown in equation (8):

$$I_{g_{nor}}(i, j) = \frac{I_g(i, j) - \min(I_g(x, y))}{\max(I_g(x, y)) - \min(I_g(x, y))} \quad (8)$$

Taking into account the range of the pixel focus area, the centroid position is used as the positioning coordinate, as shown in equation (9):

$$\begin{cases} x_f = \frac{\sum_{i=1}^a x_i}{a} \\ y_f = \frac{\sum_{i=1}^a y_i}{a} \end{cases} \quad I_{g_{nor}}(x_i, y_i) \geq \beta \quad (9)$$

Where x_f and y_f are coordinates of the damage localization, β is the range coefficient of the pixel focus area, usually set 0.7. In the previous study, the center point of the damage area is taken as the damage coordinate [13], and the localization error is shown as follows:

$$\xi = \sqrt{(x_f - x_c)^2 + (y_f - y_c)^2} \quad (10)$$

Where x_c and y_c are the real coordinate positions of the crack center.

3 EXPERIMENT AND VALIDATION

3.1 Experimental Setup

The attachment lug is made of aluminum alloy 2024-T4. The width of the structure is 180mm, the length is 343.5mm, and the thickness is 5mm. There is a bolt hole with a diameter of 48mm. The experimental system is built, including an integrated structural health monitoring system, a digital microscope, a computer, as shown in Figure 2.

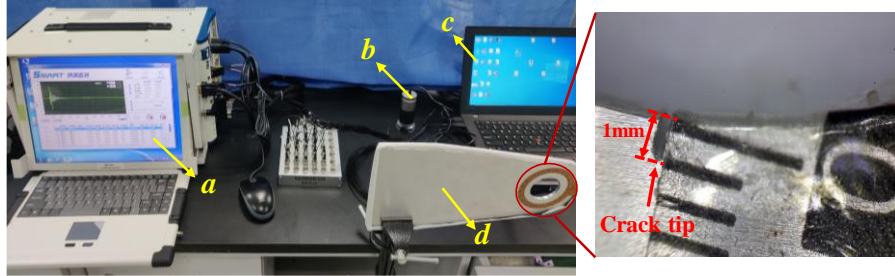
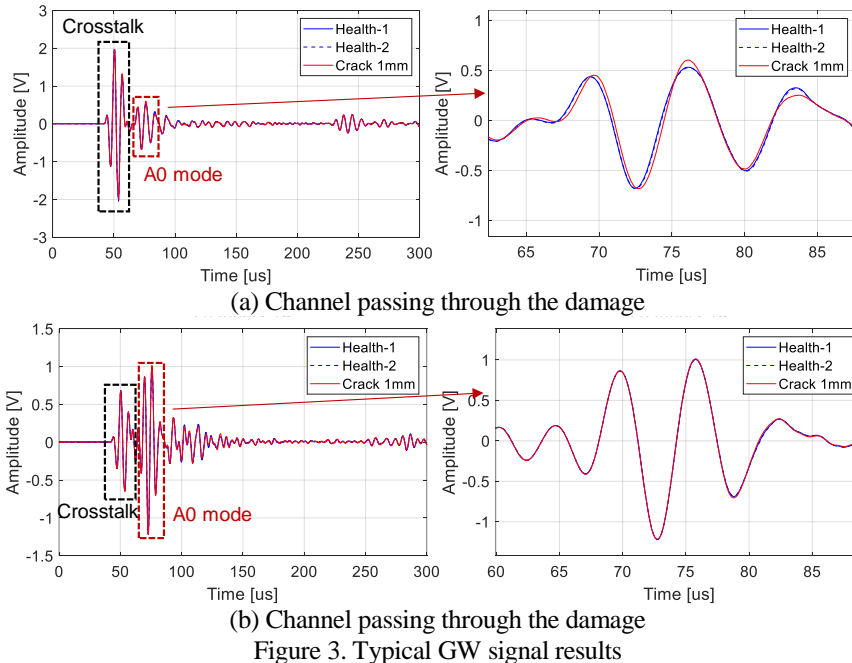


Figure 2. Crack monitoring experimental system. (a. Integrated SHM system, b. Digital microscope, c. Computer, d. Attachment lug with circular PZT array)

In the experiment, the excitation signal is adopted as the 3-cycle Hanning-windowed sine burst. Its central frequency is 150 kHz, and the amplitude is set to ± 70 V. The sampling rate is set to 10MHz. The small crack damage is cut at the bolt hole by the emery wire saw. The crack damage is observed through the digital microscope, and the crack length is 1mm.

3.2 Typical GW signal

The GW signal of typical channels are shown in Figure 3. including channel passing through the damage and channel away from damage. The GW signal of these two channels are compared. It can be seen from Figure 3 that due to the crack initiation, the GW of channel passing through the damage significantly changes in phase, with 2 data points offset. While the GW of channel away from damage have almost no change.



3.3 Small Crack Damage Monitoring Result

3.3.1 Damage alarm result

Based on the analysis of the above typical signals. The DIs of each channel in the GW network under the health state and 1mm crack damage state are calculated, as shown in Figure 4.

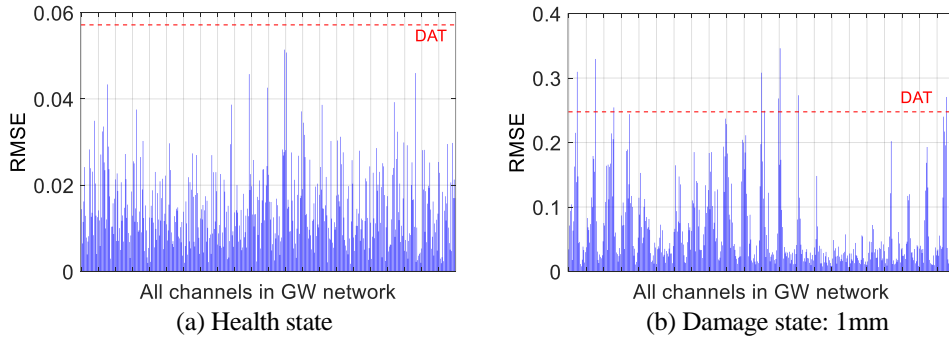


Figure 4. Alarming results for 1mm small crack damage

As shown in Figure 4, there are no false alarms in the health state, and the proposed alarm method can achieve accurate alarm for 1mm crack. In addition, the channels that trigger the alarm are all passing through the crack damage. It indicates that the extracted damage feature is effective, and the validity and accuracy of the DI method are verified.

3.3.2 Damage localization result

In this section, 1mm crack damage is made at four different positions to verify the localization method. The imaging results are shown in Figure 5.

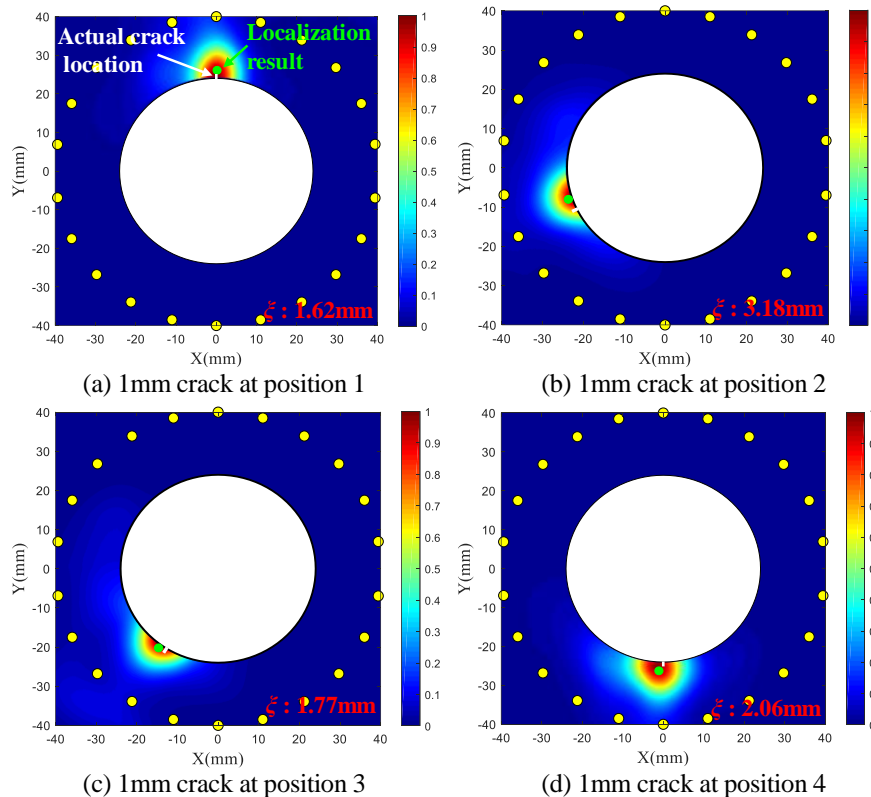


Figure 5. Localization results for 1mm small crack damage at different positions

As shown in Figure 5, the imaging pixels are obtained by the DAS algorithm and form the pixel focus area. The pixel focus area is relatively consistent with the actual crack position. It realizes high accuracy localization for 1mm small crack damage, with a maximum localization error of only 3.18mm. The experimental results have verified the effectiveness and accuracy of the monitoring method.

4 CONCLUSION

Aiming at accurate monitoring for small hole-edge crack in the attachment lug, a high accuracy monitoring method based on guided wave network is proposed. The monitoring method establishes a crack alarm mechanism based on the DI. And the probability distribution in the DAS algorithm is optimized for the large-sized bolt hole.

The experiment results show that this method can achieve damage monitoring for 1mm small cracks. The damage alarming results are accurate, and there is no false alarm in the health state. And it realizes high accuracy localization for 1mm small crack damage at different positions, with a maximum localization error of only 3.18mm, which verifies the effectiveness and accuracy of the proposed method.

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