Damage Diagnosis of Complex Connection Structures of Aircraft Fuselage Stringers with Guided Wave-Based Method

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ABSTRACT

For civil aircraft, structural forms of its components like fuselage and wing are very complicated. Usually, these structural components are manufactured separately and then riveted together. These connection parts, such as stringer joints and skin lap joints, are prone to be cracked and failure. In addition, most structures are inaccessible, making manual maintenance difficult. Therefore, it is of great significance to reliably monitor the fatigue crack damage of complex connection structures. Guided wave (GW) based structural health monitoring (SHM) has attracted wide attention in the aerospace field since it has the characteristics of being sensitive to small damages, and capable of monitoring large areas. However, the complex configuration, the limited space, and the interference of bolts and rivets make sensor deployment difficult. Moreover, during propagation in complex connection structures, guided waves will undergo reflection, transmission, and mode conversion, resulting in mode aliasing and wave packet deformation of response guided wave signals. The structural damage information contained in the signal will also be masked, which brings difficulties to crack monitoring in complex connection structures. Although there have been some related studies on crack monitoring of metal joint structures such as lap joints, there are still other parts in the complex joint structure of the actual fuselage, such as long stringers and belt plates. At present, especially for the multi-layer riveted butt joint structure with stringers, the research is still very limited. In this paper, the amplitude and mode of the guided wave signals of different types of channels between the components of the single strap butt joint structure with stringer are analyzed. By imposing simulated damage, the effect of the damage scattering signal on the damage identification ability after guided waves pass through multiple rivet holes or multi-layer structures of the complex structure is studied. The crack damage diagnosis method for the complex connection structure of aircraft fuselage stringer is studied and verified by the experimental results of real cracks. The diagnostic results demonstrate the effectiveness of the method.

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INTRODUCTION

The significance of aircraft structures in ensuring the overall performance and safety of civil aircraft cannot be overstated. For the civil aircraft structure, the aircraft fuselage structure is mainly composed of fuselage panels and fuselage bulkheads. These structures, including the fuselage, wing, and other components, undergo a manufacturing process where multiple structural elements are produced separately and subsequently connected and combined into a unified body by strip plates and rivets[1]. These crucial connection parts, such as stringer joints and skin lap joints, serve as vital links within the structure, making them vulnerable to potential damage and failure due to exposure to complex loads and harsh operating conditions.[2]

Complex connection structures in aircraft are frequently situated in hard-to-reach areas and often obscured by other components. The intricate geometry of these structures poses challenges for the application of certain detection methods. Additionally, a substantial number of intricate connection structures are riveted together, such that they cannot be disassembled for inspection and maintenance purposes. Consequently, manual inspection and maintenance of aircraft face significant difficulties and challenges in dealing with complex connection structures. Therefore, timely and reliable monitoring and diagnosis of fatigue crack damage in these complex connection structures assume paramount importance, whether it be during ground testing or continuous monitoring of individual aircraft in service.

In order to ensure the safety and reliability of aircraft structures, the aviation field has been exploring various technical means to better monitor and evaluate the health of aircraft structures. Structural Health Monitoring (SHM) technology emerges at a historic moment, thanks to the sensors integrated inside or on the surface of the structure, so there is no need to dismantle and move the structure during the structural health monitoring process[3]. This method can obtain information related to the health state of the structure online, reflecting the actual damage propagation process of the current structure. Among them, the structural health monitoring method based on guided waves has the characteristics of being sensitive to small damages, capable of monitoring large areas, and capable of both active damage monitoring and passive impact monitoring, and has attracted widespread attention in the aerospace field[4-6].

The configuration of the complex connection structure itself is extremely complex, and there are also a large number of bolts and rivets on the structure, which makes the boundary conditions for the propagation of guided waves in the complex connection structure complicated. At the same time, reflection, transmission, and mode conversion will occur when the guided wave meets the structural boundary during the propagation of the complex connection structure[7], resulting in the deformation of the response signal wave packet, and the structural damage information contained in the signal will also be masked. In addition, most of the complex connection structures are located in inaccessible areas, often hidden by other structures, and the available space is limited. These factors not only make the arrangement of structural health monitoring sensors difficult but also bring challenges to the crack damage diagnosis of complex connection structures.

Maio et al.[8] studied the propagation characteristics of lamb waves in metal plates with downward steps through laboratory experiments and discussed the influence of geometric discontinuity on the propagation of guided waves. For aircraft rivet lap joint structures, Wang et al.[9] extracted the lamb wave fatigue crack damage characteristics, and established a probability of detection (POD) model based on lamb wave damage detection. Alem et al.[10] used the instantaneous baseline technology to diagnose the damage of processing cracks for lap-jointed aluminum plates. Stolze et al.[11] identified and analyzed the damage characteristics of lamb wave scattering signals for multiple rivet butt-jointed aluminum plates. Chen et al.[12] proposed a framework for fatigue crack assessment based on guided wave-convolutional neural network (GW-CNN) integration and differential wavelet spectroscopy, where lapped structures were tested. Although there have been some related studies on crack monitoring of metal joint structures such as lap joints, there are still other parts in the complex joint structure of the actual fuselage, such as long stringers and belt plates. At present, especially for the multi-layer riveted butt joint structure with stringers, the research is still very limited.

In this paper, the piezoelectric guided wave crack damage diagnosis method for aircraft complex connection structures is studied. Taking the long stringer connection part of the aircraft fuselage frame section skin as the object, the amplitude and mode of the guided wave signals of different types of channels between the components of the long-truss butt joint structure are analyzed, and the damage identification ability of each channel is compared by imposing simulated damage, and the damage diagnosis for the single strap butt joint structure with stringer is studied. A verification test for machining crack damage diagnosis was carried out, and the result demonstrates the effectiveness of the method.

THE COMPLEX CONNECTION STRUCTURE OF AIRCRAFT FUSELAGE STRINGER

The single strap butt joint structure with stringers is the longitudinal connection structure of the fuselage skin, which is one of the key objects of crack damage monitoring in the structural health monitoring of civil aircraft. The longitudinal connection of the fuselage skin generally has two structural forms: skin lap joint and skin butt joint. Due to the differences in the number of rows of fasteners used along the longitudinal connection of the fuselage, the cross-sectional shape of the girders, the position of the girders, and the use of strip plates, etc., the structural forms of the longitudinal connection of the final fuselage skin are different. It is usually connected and strengthened by means of multiple rows of rivets and strip plates. There are many stress concentration locations in the structural area, and fatigue cracks of the structure are easy to initiate, so it is a key part that needs to be monitored for cracks.

Based on the above characteristics, a single strap butt joint structure with stringers is designed in this paper, as shown in Figure 1. The structure consists of skin (blue), strap plate (orange), stringer (yellow), stringer joints (green), frame clip (light blue), and is riveted together. The material refers to 2024 aluminum alloy, a commonly used aviation structural material, and selects a 1.5mm standard plate with a thickness similar to the actual fuselage skin for processing and manufacturing of structural parts. Considering the processing of subsequent structural crack damage, the limitation of the size of fixtures and processing equipment, the size of the skin is selected as 200mm×200mm, the size of the strap plate is 100mm×200mm, and the size after the skin is butted is 602mm×200mm. The distance between adjacent rivets is 16mm.

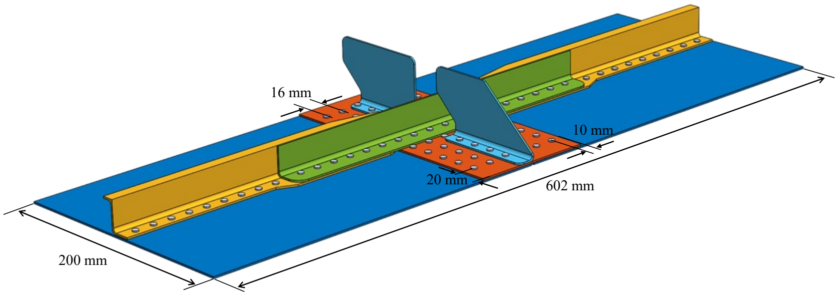


Figure 1. Single strap butt joint structure with stringers.

The strap palte is used to connect the two skins, and this part can be regarded as a single strap palte. Stringers are riveted on the skin, and the stringers of the two parts are connected by stringer joints. The shear clip is used to connect the frame to the strap plate.

EFFECT ON PROPAGATION CHARACTERISTICS OF GUIDED WAVES

The experimental study on the propagation characteristics of guided wave signals in the single strap butt joint structure with stringers was carried out. The structural health monitoring system developed by our team was used to excite and collcte elastic wave signals, and the elastic wave signal data of the structure under healthy and different damaged states were obtained for research. The experimental system is shown in Figure 2. The sensor layout and simulated damage setup are also shown in Figure 3. The simulated damage is applied by an additional mass.

Figure 2. Test system for Experiment on guided wave propagation characteristics.

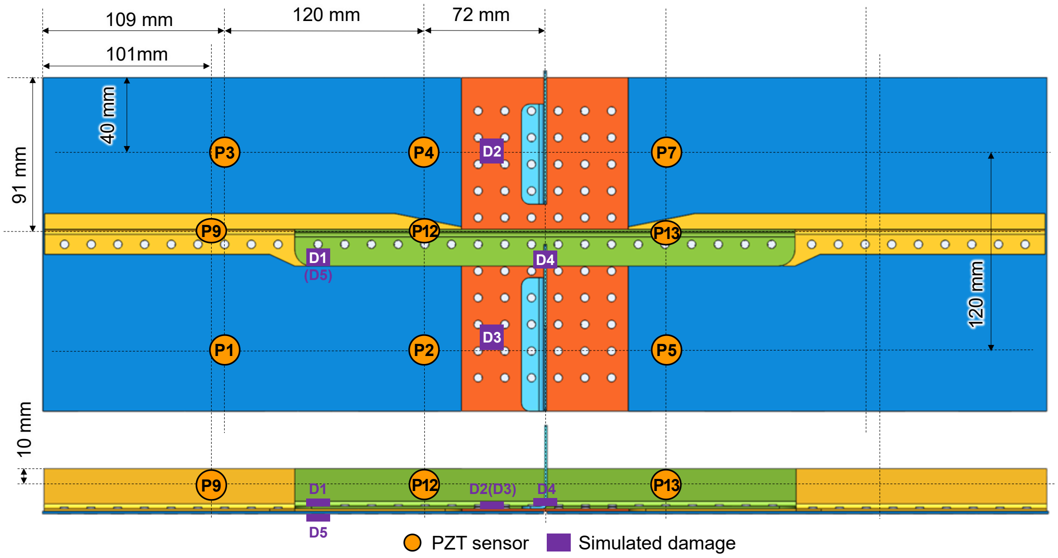
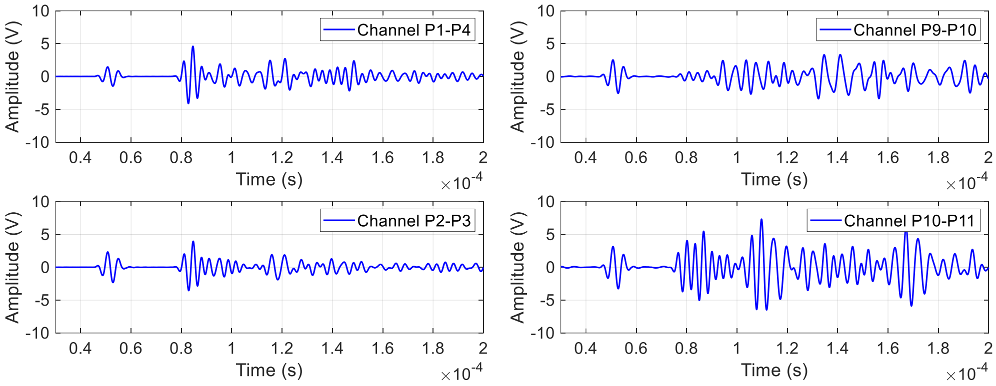


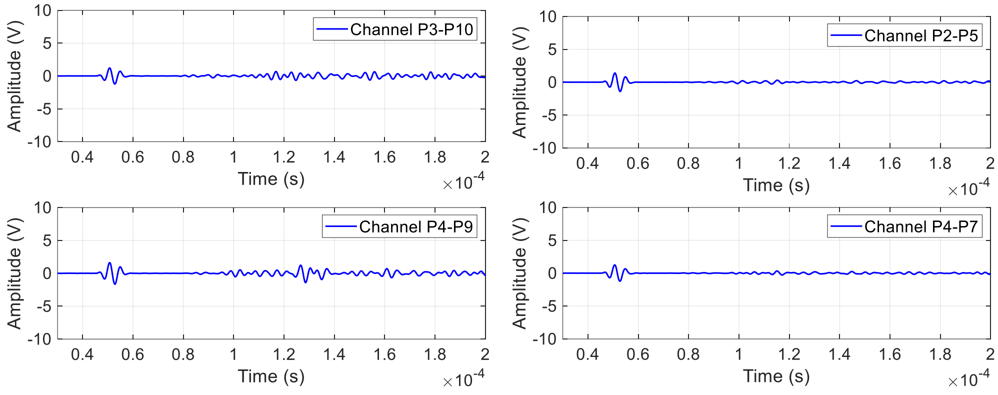
Figure 3. Sensor arrangement scheme and simulated damage setup.

The guided wave signal of the typical channel at 230 kHz is shown in Figure 4. The exciting PZT and sensing PZT of channel P1-P4 and channel P2-P3 are on the skin, and the exciting PZT and sensing PZT of channel P9-P10 and channel P10-P11 are on the stringer and stringer joint. The guided wave signals of these channels receive less boundary influence and less signal attenuation during propagation. The S0 mode of each channel at 230 kHz is relatively clear.

The exciting PZT of channel P3-P10 and channel P4-P9 is on the skin, and the sensing PZT is on the stringer or stringer joint. The exciting PZT and the sensing PZT channel P2-P5 and channel P4-P7 are distributed on the two different skins. The guided wave signals of these channels are limited by contact conditions during propagation. The signal attenuation is serious and the amplitude is small, so the change caused by damage is relatively small. The guided wave signal mode is converted, and the direct wave packet is difficult to distinguish.



(a) Type I channels (b) Type II channels



(c) Type III channels (d) Type IV channels

Figure 4. Guided wave signals of typical channels.

The simulated damage was set by tape for each typical channel. Comparing the amplitude changes of guided wave signals in the health state and damage state of each channel, the results are shown in Figure 5. The result of channel P2-P5 shows that the influence of structural damage on the signal with smaller amplitude is less obvious.

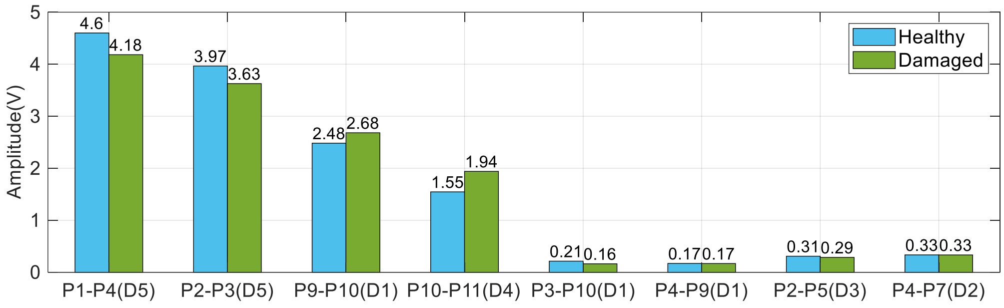


Figure 5. Typical channel signal amplitudes in healthy and damaged states.

Based on the research, the following conclusions are drawn. There is a layer of stringer or strip between the stringer joint and the skin, so the channel on the stringer or stringer joint has a poor effect on the simulated damage identification on the skin. Similarly, the channel on the skin has a poor effect on the simulated damage identification on the stringer joint. Therefore, when the piezoelectric sensor is arranged, the crack on the skin can be monitored by setting the channel on the skin, and the crack on the stringer joint needs to set the sensor channel on the stringer joint.

According to the investigation results of the crack initiation position and direction[13], it can be found that: the real crack damage is mostly initiated in the rivet hole where the stress is concentrated; the real crack damage propagation direction is perpendicular to the direction of the stress loading; the crack at the position of the multi-layer structure will not penetrate the multi-layer, exists only in one layer; the real crack damage crack width is smaller. In view of the above characteristics, this paper uses a finer drill to machine a crack.

Damage is located on the stringer joints, as shown in Figure 6(a). The final length of the crack is 14mm, of which the upper side is 3mm and the lower side is 11mm. The upper side reaches the web of the stringer joint, and the lower side reaches the boundary of the stringer joint. The crack is processed 1mm each time. Experiments were carried out on three specimens, which were recorded as DJ-11, DJ-12 and DJ-13. The diagnosis results of the selected channel to the machining cracks are shown in Figure 6(b). The results show that the selected piezoelectric sensor layout and specific channel can realize the damage diagnosis of the cracks in the typical position of the butt joint structure with stringers.

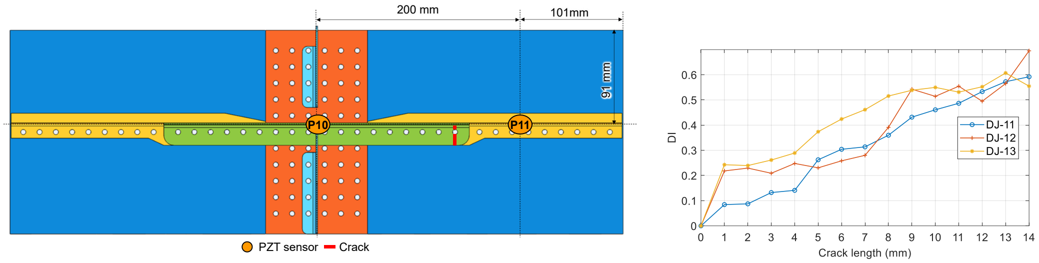


Figure 5. (a) Arrangement scheme 3 of PZT sensor and crack setting. (2) Damage index varies with crack length.

CONCLUSION

In this paper, the piezoelectric guided wave crack damage diagnosis research is carried out for the complex connection structure. Taking the single strap butt joint structure with stringers as the object, the signal amplitude, phase change, and the wave mode transformation of the guided wave when propagating in the stringer connection structure area are analyzed. The study also examines the influence of guided wave damage scattering signals on the damage identification ability after passing through multiple rivet holes or multi-layer structures in a complex structure. As a result, a crack damage diagnosis method is proposed for the complex connection structure of aircraft fuselage girders. The guided wave crack damage diagnosis method is verified by real crack test results, which demonstrate the validity of the method.

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