Simulation Method of Piezoelectric Guided Wave Propagation in Multi-layer Riveted Structures

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Abstract: Multi-layer riveted structures are widely applied to aircraft. During the service, cracks may appear within these structures due to stress concentration of the riveted holes. The guided wave monitoring has been proved to be an effective tool to deal with this problem. However, there is a lack of understanding of the wave propagation process across such kinds of structures. This study proposes a piezoelectric guided wave simulation method to reveal the propagation of guided waves in multi-layer riveted structures. Effects of pretension force, friction coefficient, and cracks that might influence wave characteristics are studied. The guided wave simulation data is compared with the experimental results and the results verify the simulation model. Then the guided wave propagation in a more complex long-beam butt joint structure is further simulated.

Key words: multi-layer riveted structures; piezoelectric guided wave simulation; guided wave monitoring; pretension force

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0 Introduction

In civil aviation, the fuselage and wings of a commercial aircraft are typically composed of numerous individual structural components, which are manufactured separately and then assembled through connections like riveting and bolting. The connecting parts of these components are critical regions susceptible to fatigue crack damages due to stress concentration at fastening holes under intricate service conditions. However, it is difficult to examine their structural states since they are usually non-disassembled and located in hard-to-reach regions. In recent years, the structure health monitoring (SHM) technology has been paid a lot of attention, which integrates sensors with the structure to monitor and assess the structural health status in real-time, for enhancing the safety, reliability, and reducing maintenance costs of aircraft[1-2].

Among SHM technologies, the guided wave-based method has been deemed as one of the promising techniques. Studies have been conducted on guided wave SHM technology for connecting parts. For example, Ihn et al.[3] observed the expansion of cracks in a riveted lap joint structure using a PZT sensor/actuator network, which consists of two aluminum plates fastened with rivets. Stolze et al.[4] used PZT sensor layers for damage monitoring in the riveted strap joint of two aluminum plates. The amplitude characteristic of the guided wave was used to denote crack presence at rivet holes. Chen et al.[5] proposed a fatigue crack evaluation framework based on guided wave convolutional neural network ensemble and differential wavelet spectrogram, which was tested on complex multi-layer structures. Asadi et al.[6] developed a baseline-free guided wave monitoring technique for detecting bolt hole cracks in plate structures with stiffeners. Lissenden et al.[7] used tomographic imaging algorithms to detect and

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locate cracks in an aluminum plate with five fastening holes. All these studies have shown the effectiveness of the guided wave (GW)-based SHM on crack damage monitoring in aircraft connecting structures.

The numerical simulation plays a crucial role in optimizing guided wave behavior and guiding experimental results. Among existing methods, the finite element method has become one of main simulation techniques because of its flexibility and practicality. For example, Nirbhay et al.[8] simulated the propagation of guided wave in three-dimensional plates and brass tubes for damage detection using finite element simulation. Qiu et al.[9] proposed a multi-physics field simulation method for the propagation of lamb wave on aluminum plates using piezoelectric transducers under load conditions, and studied the influence of load conditions on the phase and amplitude of guided wave. He et al.[10] constructed a baseline model on aluminum plates using finite element simulation data and calibrated the model using Bayesian updating methods, which can reduce the amount of experimental data required for actual components.

Luca et al.[11] conducted numerical studies on a composite plate and a curved panel to investigate the propagation mechanism of guided wave. Veit et al.[12] proposed a method for exciting higher-order ultrasonic guided wave modes using phased array probes at a constant phase velocity. Finite element simulations were performed on thin composite plates. Hervin et al.[13] studied the propagation and scattering of guided wave at elliptical delamination in quasi-isotropic composite laminates finite element simulations. Bhuiyan et al.[14] simulated the propagation of guide wave in multi-hole lap joint structures and their interaction with rivet hole cracks through finite element analysis. It can effectively simulate and analyze the scattering effects of rivet hole cracks on Lamb wave and SH wave. Meiand et al.[15] proposed a method for simulating the excitation and propagation of guided wave in damped composite plates. By combining finite element methods with analytical expressions, it can effectively simulate the propagation of guided wave in composite plates. It can be seen that most of the above studies focus on plate structures, or plate structures with holes, and there are fewer reports on the simulation of guided wave in multi-layer riveted structures. The main problem lies in the difficulties caused by the multi-layer boundaries, and the application of rivet pretension force. For multi-layer riveted structures, due to the overlap between layers, it is necessary to define contact in finite element analysis software to build the correct physical field connections between structures at different positions, shapes, and materials. Secondly, in the transient analysis of the simulation, the application of pretension force in riveted or bolted connections will produce impact vibrations in the time domain analysis, causing the signal excited by the piezoelectric sensor to be submerged.

Therefore, this paper studies and proposes a simulation method for the propagation of piezoelectric guided wave in multi-layer riveted structures, based on the commercial finite element simulation software of COMSOL Multiphysics, taking a stiffened plate as an example. In addition, the effects of pretension force, friction coefficient, and cracks on guided wave propagation are studied, and the piezoelectric guided wave propagation in more complex long-beam butt joint structures is further simulated.

The structure of this paper is as follows: Section 1 introduces the simulation method of piezoelectric guided wave propagation in multi-layer riveted structure proposed in this paper; Section 2 compares the guided wave simulation data with the guided wave experiment, verifies the simulation model, studies the effects of pretension force and other factors, and carries out simulation modeling of multi-layer stringer splice joint structure; Section 3 summarizes the paper.

1 Simulation Method for Propagation of Piezoelectric Wave in Multi-layer Riveted Structures

This paper proposes a simulation method for the propagation of piezoelectric guided wave in multi-layer riveted structures, which includes the basic process of finite element simulation for guided wave propagation, modeling of riveted structures, contact simulation, and the method for eliminating vibration caused by pretension force. The following is a detailed introduction.

1.1 Finite element simulation method for piezoelectric guided wave propagation

The finite element method for simulation modeling is divided into the following steps: geometric model construction, material properties, global and local parameter settings, physical field boundary condition settings, finite element meshing, and solver settings, as shown in Fig.1.

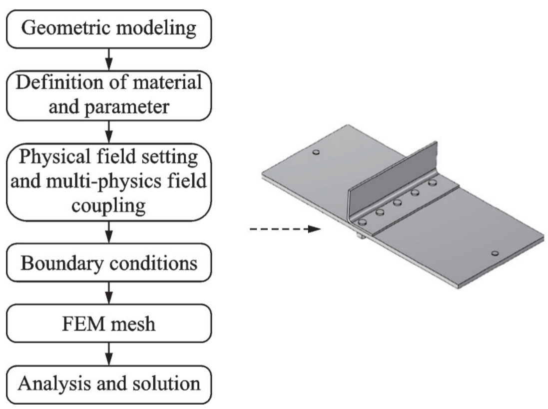

Fig.1 Finite element simulation process of piezoelectric guided wave propagation

Step 1 Geometric model construction: A 3D model is used in this paper, including the aluminum plate, the piezoelectric sensors, rivet and spar.

Step 2 Definition of global and local parameters and material: The global variable is set as excitation signal and the probe makes the voltage and the average voltage of the whole surface output. Material properties also need to be set, which contain the density, lame constant, Murnaghan constant, relative permittivity, piezoelectric constant, and compliance coefficient.

Step 3 Physical field setting and multi-physical field coupling: Physical field settings contain electrostatics and mechanics. The two physics are coupled by the multi-physics-piezoelectric effect.

Step 4 Boundary conditions: Boundary conditions in solid mechanics contain contact, constraint, and load. In addition, the default boundary conditions for the electrical physics field are charge conservation, 0 potential, and initial value. The custom boundary conditions required are potential and grounding.

Step 5 FEM mesh: The mesh type is free tetrahedral. Two mesh sizes are required to set, in which one is the largest mesh size and the other is the smallest mesh size. For the plate, the mesh size depends on GW wavelength. According to some research on GW simulation, the largest mesh length is recommended to be smaller than 1/6 of the wavelength. Meanwhile, the smallest mesh size is decided by the speed of wave packet and length of time step.

Step 6 Analysis and solution: For solving the multiphysics simulation model given above, one study step is adopted to construct the study of the simulation model. Time dependent is performed to simulate the process of GW excitation-propagation-response. The results of Step 1 can be found in the probe table.

1.2 Modeling of riveted structures

The mechanical model of the riveting essentially involves the residual stress from the plastic deformation and upsetting of the rivet clamping the connected parts. Force transmission relies on the bearing pressure between the rivet shank and the hole wall, as well as the interfacial friction between the rivet head and the connected parts. This paper simplifies the riveting model as the interfacial friction and clamping between the rivet head and the connected parts. The extrusion between the shank and the hole wall is not considered.

According to the simplified riveting model proposed in the article, the extrusion between the rivet bolt shank and the hole wall is not considered, and only the interface friction and clamping between the rivet head and the connected parts are taken into account. The form of adding contact pairs and pretension force is adopted to achieve the interface friction and clamping between the rivet head and the connected parts. The specific key parameters include the contact pair between the rivet and the upper surface of the stringer, and the contact pair between the rivet and the lower surface of the skin. The pretension force is applied in the section of the bolt. The setting of specific contact pairs and pretension force will be discussed in the following text.

1.3 Contact simulation

When using the assembly modeling, a physical relationship among the piezoelectric patch, aluminum plate, stringer and bolt needs to be established. To more closely approximate real conditions, the physical field transmission between parts is discontinuous when affected by an extremely small gap. If two boundaries are set as a contact pair, the two surfaces can move away from each other or come into close contact but cannot penetrate each other.

Therefore, the piezoelectric patch and the aluminum plate are set as a boundary pair. As shown in Fig.2, the bolt and the stringer, the aluminum plate and the stringer, and the nut and the aluminum plate are set as three contact pairs, respectively.

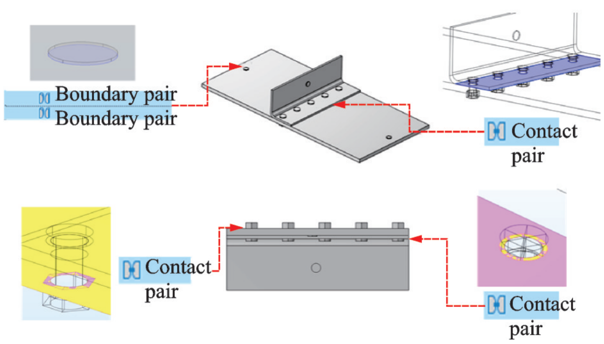

Fig.2 Boundary condition settings for piezoelectric guided wave propagation simulation model

When the bolt is inserted into the connected parts, the nut or internal thread causes the bolt to stretch and deform. This elastic deformation produces an axial force that squeezes the clamped parts together, forming a pretension force. Since the pretension force is the condition that brings the structure into contact, when the structure is in contact and under stress, there is a slight relative displacement. The magnitude of the friction is related to the coefficient of friction. When the stress wave excited by the piezoelectric actuator is transmitted to the bottom of the stringer, due to the pretension force of the bolt and the contact between the stringer and the aluminum plate, part of the stress wave is transmitted to the stringer structure.

1.4 Method for eliminating the impact of pretension force

The structural guided wave simulation requires the use of transient analysis. At this time, the pretension force of the mechanical connection will become an impact signal, applied to the structure in the form of an impact load. After the structure is impacted, the energy is released in the form of stress wave and propagates in the plate. Moreover, the strain amplitude of the stress wave caused by the pretension force is 4—5 orders of magnitude higher than the strain amplitude caused by the piezoelectric actuator. The strain fluctuations caused by the pretension force will "mask" the strain fluctuations caused by the actuator. To obtain more accurate piezoelectric guided wave simulation results, it is necessary to greatly reduce the vibration amplitude introduced by the application of pretension force before simulating guided wave propagation. To address this issue, this paper mainly adopts three measures: slow application of the pretension force, phased damping and delayed excitation, and filtering.

(1) Slow application of pretension force

The impact signal generated by the pretension force can be reduced by slowing down the spread of stress wave generated by the pretension force, shortening the influence of impact produced by the pretension force, and quickly reducing the sensor voltage signal brought by the load impact. This paper uses the following sigmoid function multiplied by the pretension force to control the speed of applying the pretension force

$$f(t)=\frac{1}{1+\mathrm{e}^{-10^6 t+10}} \tag{1}$$

where t represents the time, and f is a function of t in Fig.3.

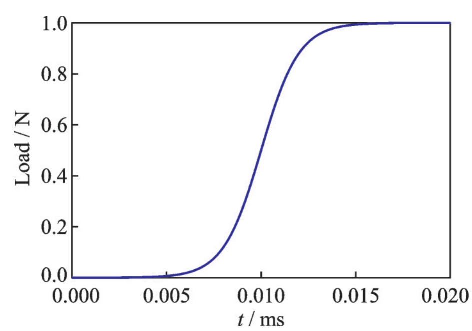

Fig.3 Slowly changing sigmoid function

(2) Structural damping and delayed excitation

Adding damping is also an effective way to accelerate the vibrational energy produced by impacts in the structure. Here, the added damping is the viscous damping of the aluminum material, which is a way to simulate the internal friction force of the material or structure. It simulates the energy dissipation of vibration generated by pretension force within the material, leading to the decay of system vibrations or motion. It is used here to absorb the vibrational energy brought by the pretension force.

Considering the subsequent generation of useful signals by the piezoelectric actuator, the added structural damping cannot always exist. Therefore, at the beginning of using the piezoelectric actuator to excite guided wave, the damping returns to 0. The piecewise function of the damping and its graph (Fig.4) are shown as

$$\begin{cases} \xi = 1\,000 & t \leqslant t_1 \\ \xi = 0 & t > t_1 \end{cases} \tag{2}$$

where ξ represents the structural damping. By observing different damping values in the model to observe the speed of signal decay, it is found that when the damping is taken as 1 000, the damping is significantly reduced, and if the damping is further increased, the signal decay effect is not obvious. According to the observation of simulation data, the guided wave signal generated by piezoelectric excitation stays at the order of magnitude of 10^{-5}, so t_1 is the moment when the mechanical vibration caused by pretension force is less than 10^{-5}.

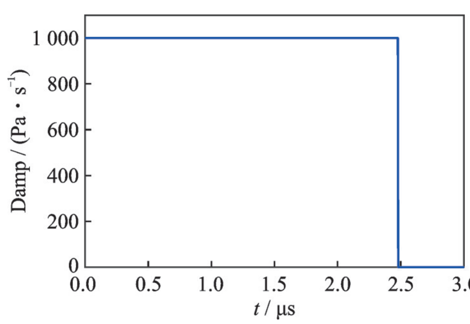

Fig.4 Piecewise-applied structural damping function

By applying the damping, the vibration in the structure is attenuated to a certain degree, at which point the guided wave signal is not interfered by the excitation. At the same time, an excitation is applied to the piezoelectric sensor. Here, a piecewise function is used to realize the delayed excitation. The diagram and expression of the piecewise function is shown as

$$\begin{cases} E = 0 \qquad T < t_1 \\ E = A \cdot [1 - \cos(2\pi f t / N)] \cdot \sin(2\pi f t) \cdot \\ \qquad [t < (N/f)] \qquad T \geqslant t_1 \end{cases} \tag{3}$$

where A is the amplitude of signal, f its frequency and N the peak number.

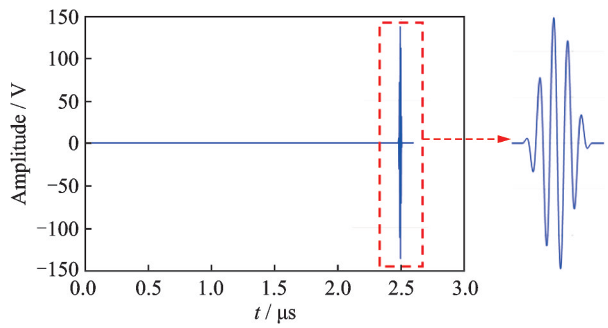

Fig.5 Delayed excitation signal of piezoelectric guided wave

(3) Filtering

In addition, considering that structural vibrations cannot be completely removed, and due to the existence of structural stress caused by simulated pretension force, there will also be certain low-frequency and DC components in the piezoelectric sensor. To obtain a cleaner simulation signal, this method will further filter the collected piezoelectric guided wave signals. This paper uses a finite impulse response (FIR) filter to filter the vibration signals caused by pretension force, allowing the piezoelectric sensor to collect as many signals carrying structural damage information as possible. The filter extracts the signal at the center frequency f_c. It is necessary to set the filter bandwidth higher than the sensor signal bandwidth, and the bandwidth of the sine-modulated signal is known through the excitation signal bandwidth M.

$$M = \frac{2}{N} f_c \tag{4}$$

Thus, the starting frequency of the filter f_l, is shown as

$$f_l = f_c - \frac{M}{2} \tag{5}$$

The cutoff frequency f_h can be shown as

$$f_h = f_c + \frac{M}{2} \tag{6}$$

In summary, the simulation method of piezoelectric guided wave propagation in multi-layer riveted structures proposed in this paper is as follows. First, the stress wave caused by pretension force decays under the damp. After a period of time, the sensor begins to excite, and the piezoelectric sensor begins to accept signals. When the stress and strain caused by pretension force decay to a certain extent, the signals received by the sensor are used to analyze the characteristics of guided wave.

2 Simulation and Experimental Comparison Verification

2.1 Guided wave simulation of muti-layer riveted structure

The following step is the guided wave simulation of the multi-layer riveted structure. The structure is imported into COMSOL Multiphysics, and solid mechanics and electrical physics fields are added. In the material property settings, the piezoelectric material is set to PZT-5A, and the remaining structural parameters are for 2024 aluminum alloy. By setting low reflection boundaries, the interference of reflected signals on the signals collected by the sensor can be reduced. The low boundary reflection condition setting is shown in Fig.6.

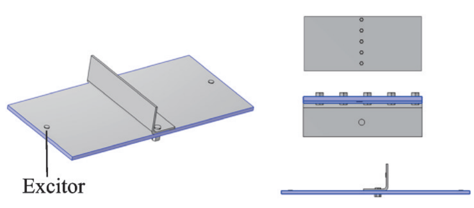

Fig.6 Multi-layer riveted structure with low-reflection boundary setup

In the simulation, the potential on the upper surface of the excitation piezoelectric patch is set to a sine-modulated five-peak wave, and the lower surface is set to ground (0 potential) to simulate the piezoelectric effect of the piezoelectric patch. The Poisson's ratio of 2024 aluminum alloy is 0.222, the elastic modulus is 3×10^5 MPa, the density is 3 000 kg/m^3, and the piezoelectric parameters are chosen from the default material properties that come with the COMSOL. Considering that the guided wave simulation is a dynamic simulation that depends on the time variable, the size of the finite element and the time step of the simulation calculation are closely related to the wavelength and frequency of the guided wave[16]. According to the minimum mesh size set to 0.1 mm, the established finite element model is shown in Fig.7.

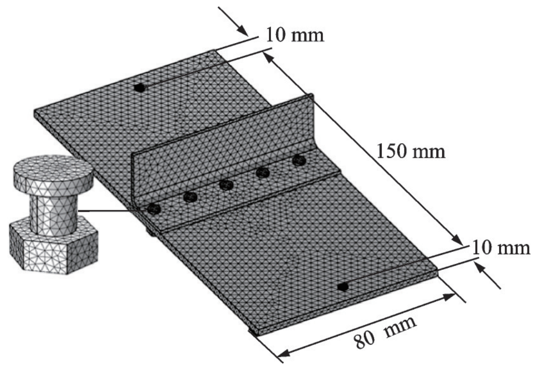

Fig.7 Finite element mesh diagram of multi-layer riveted structure

After the above piezoelectric guided wave modeling settings are completed, the simulated applied pretension force is 500 N. As shown in Fig.8, the pretension force is distributed along the axis of the bolt. According to the finite element analysis results, the stress value is larger in the area where the pretension force is applied near the bolt shaft, and the stress value is distributed at a minimum at both ends as the distance from the pretension force area increases.

According to Figs.9 and 10, when the bolt pretension force is applied, the amplitude of vibration generated by the pretension force becomes larger in an extremely short time, and then gradually decays over time. The reason is that the pretension force will be regarded as an impact in transient analysis. After the structure is impacted, the bolt position of the structure will instantly become the source of stress wave, and the sensor will receive the stress waves after a period of time and convert them into voltage signals according to the piezoelectric effect. After starting the transient analysis, the voltage signal brought by the stress wave is at the order of magnitude of 10^{-1}, which is much larger than the order

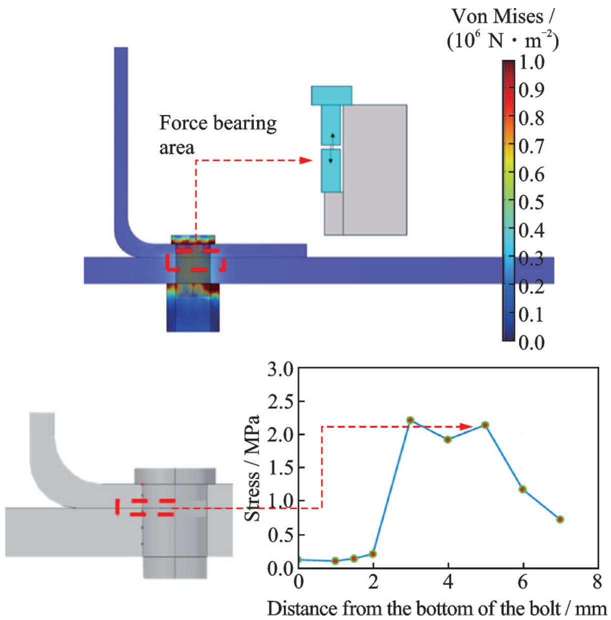

Fig.8 Stress distribution of the bolt after applying pretension force

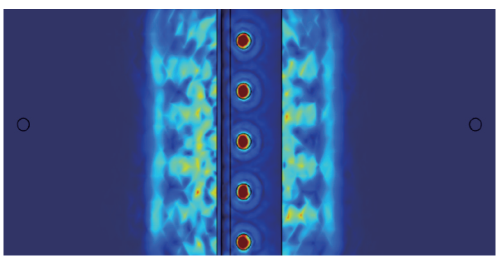

Fig.9 Mechanical wave caused by pretension force

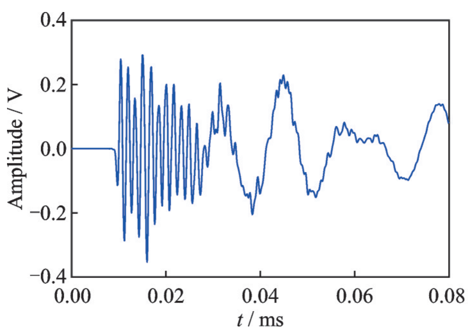

Fig.10 Signal caused by pretension force

of magnitude of 10^{-5} of the voltage signal brought by the guided wave excitation. If the mechanical wave caused by the pretension force is not made to decay in a certain way, the stress wave will submerge the sensor signal, and the signal generated by the guided wave excitation will not be collected.

By slowly applying the pretension force and phased damping proposed in this paper, Fig.11 shows that the bias voltage caused by the vibration brought by the pretension force can quickly decay to the magnitude of 10^{-5}. The time when the signal caused by the pretension force is less than 10^{-5} V is 2.479 ms.

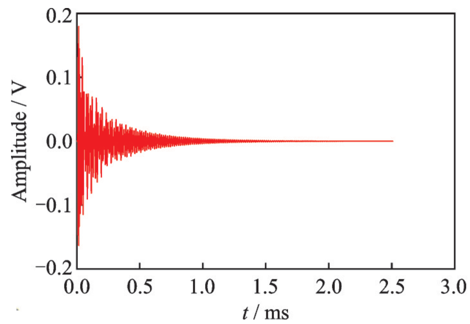

Fig.11 Impact signal received after slowly applying pre-tension force and damping decay

After the impact signal caused by the pretension force has completely decayed, the excitation is a narrowband five-peak sine-modulated voltage signal, with a frequency of 180 kHz and an amplitude of 70 V. The wave field diagram is shown as Fig.12.

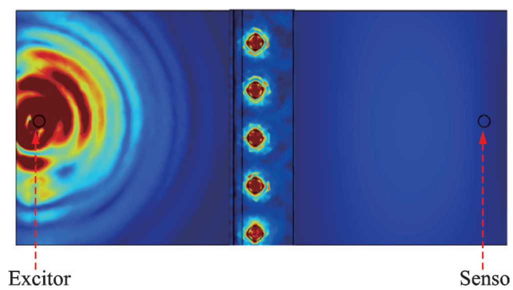

Fig.12 Simulated signal wavefield when the pretension force is applied

Experiments are carried out for comparison and verification, with the setup shown in Fig.13. The sensor layout is consistent with the simulation, and the excitation signal is also consistent. In the experiment, different torques are applied to the bolts using a numerical control torque wrench to control the pretension force.

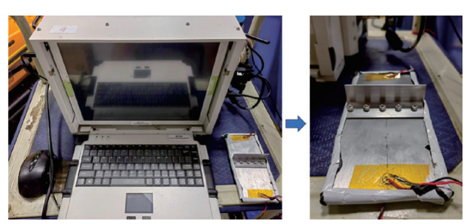

Fig.13 Experimental setup for the propagation of piezoelectric guided wave in multi-layer riveted structures

The sensor receives the signal wave field diagram as shown above. After filtering the signal, Fig.14 shows that the DC component is almost eliminated. The signal amplitude drops relative to the original signal, and the phase change is not obvious.

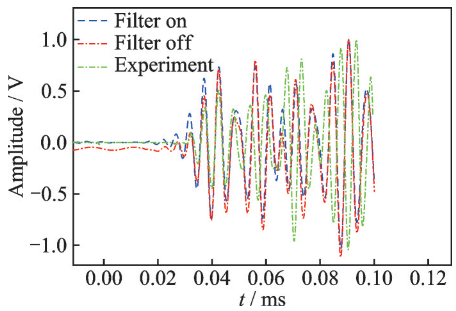

Fig.14 Simulated signal wave field under pretension load

2.2 Comparison of different signals with varying pretension forces

In order to study the influence of pretension force on guided wave propagation, the pretension forces with different values are defined for bolts in the simulation model to study changes in guided wave propagation characteristics under different pretension forces. Fig.15 shows the comparison of simulated guided wave signals under different pretension forces. The bolt used in the experiment is M3×50. According to the national standard manual GB/T 3098.6—2000, the breaking torque of this bolt is 1.1 N·m. Combined with engineering experience, 50% of the breaking torque is taken as the corresponding tightening torque, which is 0.55 N·m. The pretension force parameters are set around 60% above and below the tightening torque, which are converted into torques as 0.22, 0.44, 0.66, and 0.88 N·m. At the same time, experiments are carried out for comparison and verification shown in Fig.16. The sensor layout is consistent with the simulation, and the excitation signal is also consistent. In the experiment, different torques are applied to the bolts using a numerical control torque wrench to control the pretension force.

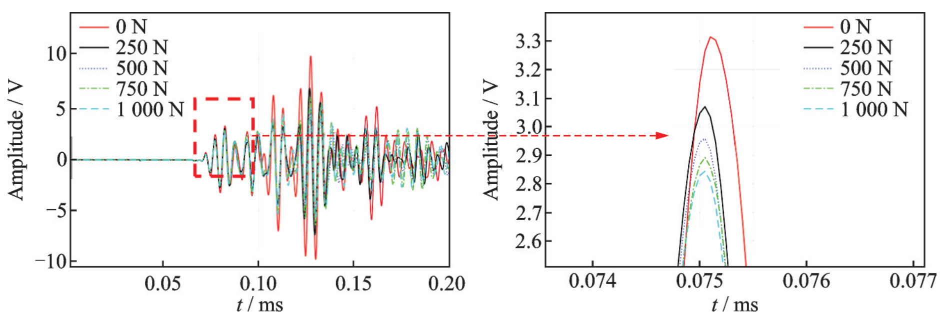

Fig.15 Comparison of simulated guided wave signals under different pre-tension forces

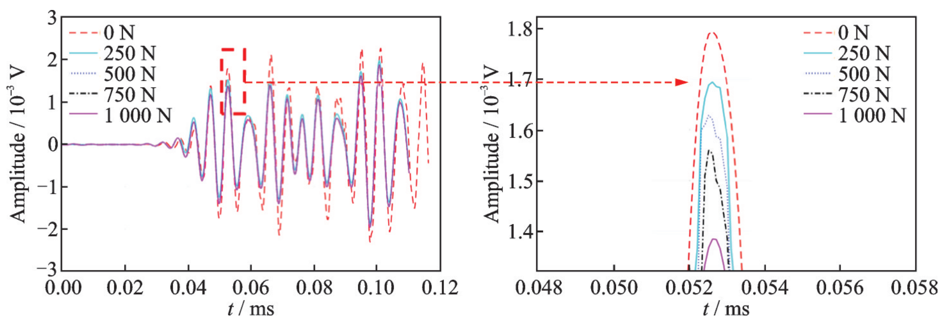

Fig.16 Comparison of experimental guided wave signals under different pre-tension forces

From the signal analysis in Figs.16, 17, it can be seen that under the interaction of different pretension forces, the guided wave S0 mode signal exhibits the significant attenuation. Whether in simulations or experiments, under the action of gradually increasing pretension force, the guided wave S0 mode signal exhibits significant attenuation. When the guided wave propagates to the contact area between the stringer and the aluminum plate, the stress field changes due to the interaction between the ultrasonic guided wave and the structure. As the bolt pretension force increases, the contact between the stringer and the aluminum plate becomes tighter. Since guided waves are essentially stress waves, and stress waves are related to strain, when the pressure in the contact area between the stringer and the aluminum plate changes, part of the strain energy generated by the excitation signal is transferred to the stringer when the strain is transmitted to the stringer, resulting in signal energy loss and a decrease in the guided wave amplitude. Experimental results have been verified and compared with the simulation results, and consistent conclusions have been obtained, indicating that the proposed simulation method is effective.

The following shows the changes in the simulation signal under different coefficients of friction, by changing the coefficient of friction from 0.1 to 0.4. This causes the guided wave to change as shown in Fig.17. By observing the difference in the signals, it is found that the amplitude of the guided wave decreases with the increase of the coefficient of friction.

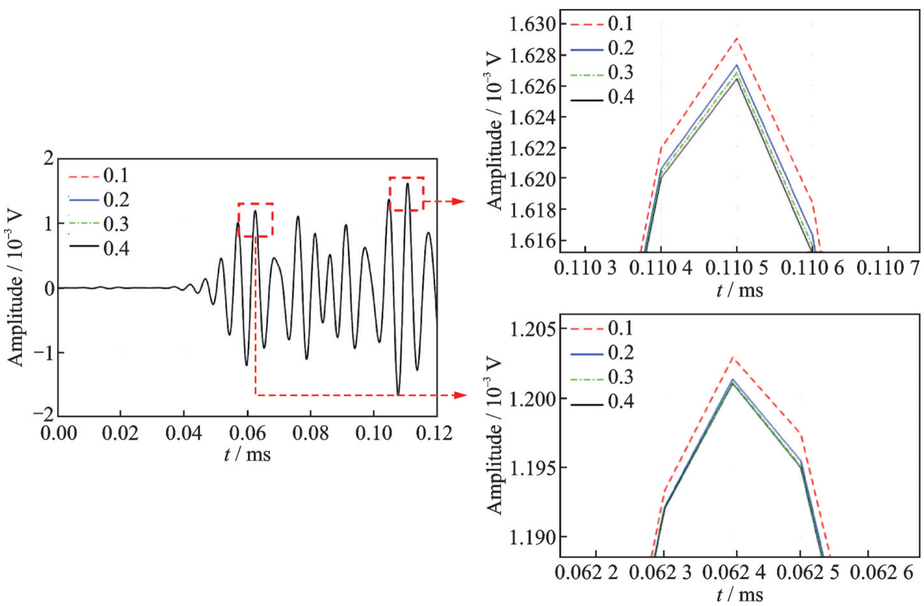

Fig.17 Comparison of guided wave signals for different coefficients of friction

Cracks are applied to the structure as shown in Fig.18. The cracks are elongated and generated around the bolt holes by the method of tensile cutting. The lengths are 1, 2, and 2.5 mm, respectively. Guided wave signals are excited according to the above simulation steps, and the guided wave signals are as shown in Fig.19. It is observed that as the crack increases, the amplitude of the S0 wave packet of the guided wave decreases, indicating the damage monitoring capability of the guided wave for complex multi-layer riveted structures.

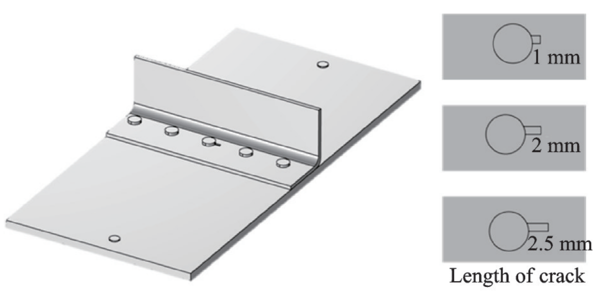

Fig.18 Conditions of crack application in multi-layer riveted structures

2.3 Simulation of guided wave propagation on multi-layer stringer splice joint structure

The excitation signal is set on the excitor on the aluminum plate, and the sensor is stuck on the middle part of the stringer as shown in Fig.20. According to the sensor layout in Fig.20, the signal of the sensing channel is extracted to obtain the simulation signal. From the wave field diagram, it can be seen that the simulation signal is excited on the aluminum plate, then reaches the stringer structure. According to the contact between the stringer struc-

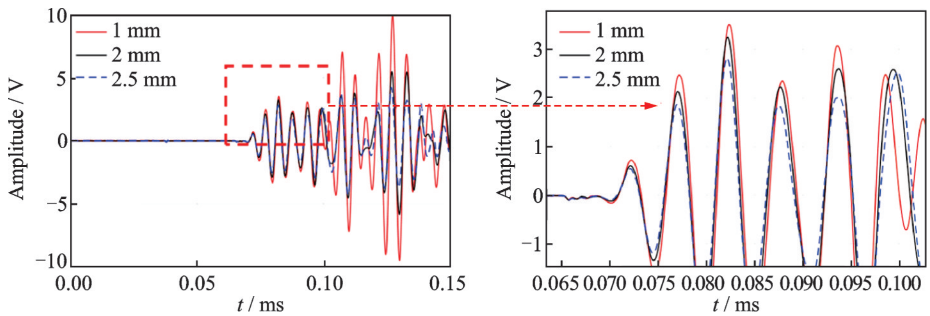

Fig.19 Simulated guided wave signals under the influence of different cracks

ture and the aluminum plate, the guided wave propagates to the stringer along the contact part of the structure, and propagates along the surface of the stringer. Based on the above pretension force guided wave simulation method, the simulation of guided wave propagation in a multi-layer stringer splice joint structures is carried out. The multi-layer stringer butt joint structure and the generation of finite element mesh are shown in Fig.21. The propagation of the guided wave in the multi-layer stringer splice joint structure is shown in Fig.22. The guided wave signal obtained by sensor shown in Fig. 23 is compared with the actual experiment which lays the foundation for the subsequent monitoring simulation of the multi-layer stringer butt joint structure.

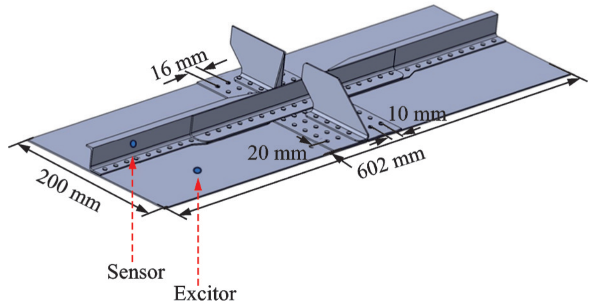

Fig.20 Dimensions of the multi-layer stringer splice joint structure

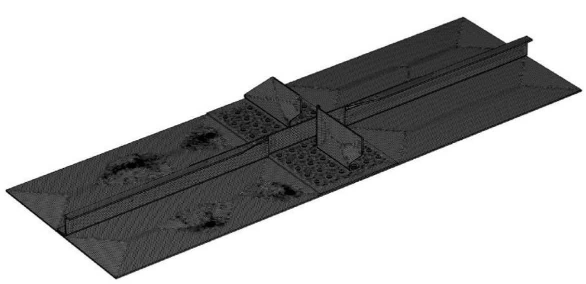

Fig.21 Generation of mesh of the multi-layer stringer splice joint structure

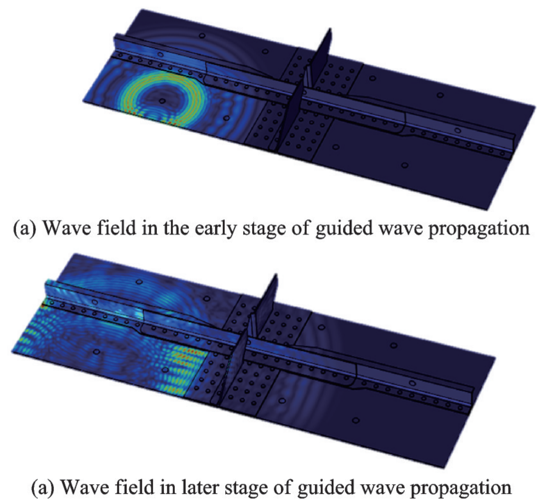

Fig.22 Guided wave field of multi-layer stringer splice joint structure

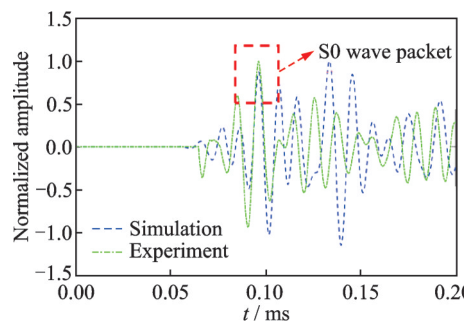

Fig.23 Comparison of experimental and simulated guided wave signals

From Fig.23, the S0 wave packet of both signals is anastomotic. The wavelength of A0 mode is only 8.6 mm and the mesh size should be less than 1 mm. It will lead to a huge amount of computation and a normal computer with 16 GB RAM cannot support such computation. That is the reason why this paper only considers S0 mode. The result shows this simulation model can provide a similar propagation result compared with the real guided wave propagation. It lays strong foundation for the further study of guided waves.

3 Conclusions

This paper proposes a simulation method for the propagation of piezoelectric guided waves in multi-layer riveted structures. The work can be summarized as follows:

(1) This study has established a simulation method for the propagation of piezoelectric guided wave in multi-layer riveted structures. On this basis, effects of pretension force and friction coefficient on guided wave propagation have been revealed. The signal amplitude of the guided wave decreases when passing through the connected parts under the action of pretension force, and similarly, the amplitude of the guided wave also decreases when the friction coefficient increases in the contact area of the connected parts.

(2) Considering that there are still differences between the boundary conditions of the guided wave experiment and those in the simulation model, the simplified boundary condition in the simulation is the extrusion of the bolt hole on the bolt shank. Under the above simplified boundary conditions, the time-domain signals of guided waves from the simulation and the experiment have good amplitude consistency in the S0 wave packet, indicating that the simulation model is effective in modeling the direct S0 wave signal. At the same time, there is no delay in the phase of the direct S0 wave. Simplifying the extrusion between the hole and the bolt shank does not affect the guided wave signal results, and the amplitude-frequency characteristics of the simulated guided wave signal in the S0 mode are relatively consistent with the experimental signal.

(3) By modeling the multi-layer stringer splice joint structure and carrying out guided wave propagation simulation on this structure, the simulation reveals the propagation phenomenon of piezoelectric guided wave on multi-layer riveted structures. The guided wave can effectively propagate to the next area along the connected area of the connection, laying the foundation for the subsequent monitoring simulation of the spar butt joint structure.

This paper presents a simulation method dedicated to the propagation of piezoelectric guided waves in multi-layer riveted structures. The method specifically addresses the research gap regarding the propagation rules of guided waves under pretension, and further establishes a scientifically effective simulation model for guided wave propagation in such structures. The specific application prospects are as follows:

(1) For the guided wave propagation simulation model under pretension force, when using the transient solver in COMSOL to solve the guided wave field, the pretension force will also generate stress waves in the transient solution. Guided waves are essentially stress waves, and the amplitude difference between the weak stress waves generated by the piezoelectric patch and the stress waves generated by the pretension force is significant, so the guided wave signals carrying defect characteristics are submerged. This paper studies the guided wave submergence phenomenon, and the proposed modeling method can be further applied to the modeling and simulation of guided wave propagation with pretension force, which can effectively avoid the problem of useful signal submergence and improve the accuracy of experimental results.

(2) This paper proposes three methods for attenuating stress waves caused by pretension force, which increase the convergence probability of the model and reduce the maximum number of Newton iterations. The proposed smooth preload loading function, step damping function, delayed excitation measures, and signal filtering can effectively solve the problem of guided wave signal submergence. The smooth preload loading function can gradually increase the boundary conditions, which is helpful for model convergence. The setting of step damping can attenuate the interference stress waves in a short time, thereby avoiding affecting the guided wave signals. When the interference stress waves are attenuated sufficiently, the excitation and reception of guided wave signals are started. As a traditional guided wave signal processing method, the signal filtering can filter out redundant frequency components and retain the main frequency components of the signal.

References

[1] LEE H, CHO H, PARK S. Review of the F-16 individual aircraft tracking program[J]. Journal of Aircraft, 2012, 49(5): 1398-1408.

[2] MARKS J M. The individual aircraft tracking program (IATP) for the FAA flight inspection aircraft fleet—An examination of the translation of measured flight parameters to potential crack growth at critical areas to the projection of inspection[J]. Journal of Aerospace, 1997,106: 202-215.

[3] IHN J B, CHANG F K. Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: Ⅱ. Validation using riveted joints and repair patches[J]. Smart Materials and Structures, 2004, 13(3): 609.

[4] STOLZE F H, WORDEN K, MANSON G, et al. Fatigue-crack detection in a multi-riveted strap-joint aluminum aircraft plate using amplitude characteristics of diffuse lamb wave field[J]. Materials, 2023, 16(4): 1619.

[5] CHEN J, WU W, REN Y, et al. Fatigue crack evaluation with the guided wave-convolutional neural network ensemble and differential wavelet spectrogram[J]. Sensors, 2021, 22(1): 307.

[6] ASADI S, KHODAEI Z S, ALIABADI M H, et al. A baseline free methodology for crack detection in metallic bolted joints[J]. AIP Conference Proceedings, 2023, 2848(1): 020038.

[7] LISSENDEN C J, CHO H, KIM C S. Fatigue crack growth monitoring of an aluminum joint structure[J]. AIP Conference Proceedings, 2010, 1211(1): 1868-1875.

[8] NIRBHAY M, DIXIT A, MISRA R K. Finite element modelling of lamb wave propagation in 3D plates and brass tubes for damage detection[J]. Russian Journal of Nondestructive testing, 2017,53: 308-329.

[9] QIU L, YAN X, LIN X, et al. Multiphysics simulation method of lamb wave propagation with piezoelectric transducers under load condition[J]. Chinese Journal of Aeronautics, 2019, 32(5): 1071-1086.

[10] HE J, RAN Y, LIU B, Et al. A fatigue crack size evaluation method based on lamb wave simulation and limited experimental data[J]. Sensors, 2020, 102: 2097.

[11] DE LUCA A, PERFETTO D, POLVERINO A, et al. Finite element modeling approaches, experimentally assessed, for the simulation of guided wave propagation in composites[J]. Sustainability, 2022, 14(11): 6924.

[12] VEIT G, BELANGER P. An ultrasonic guided wave excitation method at constant phase velocity using ultrasonic phased array probes[J]. Ultrasonics, 2017, 17(9): 2097.

[13] HERVIN F, MAIO L, FROMME P. Guided wave scattering at a delamination in a quasi-isotropic composite laminate: Experiment and simulation[J]. Composite Structures,2021, 275: 114406.

[14] BHUIYAN M Y, SHEN Y, VICTOR G. Guided wave based crack detection in the rivet hole using global analytical with local FEM approach[J]. Materials, 2016, 9(7): 602.

[15] MEIAND H, VICTOR G. Guided wave excitation and propagation in damped composite plates[J]. Structural Health Monitoring, 2019, 18(3): 690-714.

[16] YANG C, YE L, SU Z, et al. Some aspects of numerical simulation for Lamb wave propagation in composite laminates[J]. Composite Structures, 2006, 75(1): 267-275.

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多层铆接结构中压电导波传播的仿真方法

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摘要: 多层铆接结构在飞机上有着广泛的应用。在使用过程中,由于铆钉孔存在应力集中,这些结构内部可能会出现裂纹。导波监测已被证明是解决这一问题的有效方法。然而,对于这类结构中的波传播过程的了解还不够充分。本文提出了一种压电导波模拟方法,旨在揭示导波在多层铆接结构中的传播规律。研究了预紧力、摩擦系数和裂纹等可能影响导波特性的因素。将导波仿真信号与实验结果进行了对比,结果验证了该仿真模型的有效性。随后,进一步在更复杂的长桁对接结构中进行了导波传播仿真。

关键词: 多层铆接结构;压电导波模拟;导波监测;预紧力