Experimental study on the effect of propagation characteristics of guided waves under uniaxial static stress

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Abstract

Structural health monitoring (SHM) plays an important role in ensuring the safe use of aerospace, architecture and other fields. At present, SHM based on piezoelectric and guided waves is a hot spot for real-time monitoring and nondestructive testing. However, the effect of operational load may mask the signal changes caused by damage and lead to failure of guided wave SHM methods. In this paper, the influence mechanism of the static load on the propagation characteristics of the guided wave is analysed. An experiment is performed to study the propagation characteristics of the guided wave on an aluminium plate under static tensile load of different magnitudes. Piezoelectric constitutive equation expressing the coupling of mechanical and electrical quantity becomes more complicated because of the stress. Amplitude of the guided wave along the stress direction increases with the increasing of the tensile stress, while the amplitude of the wave in the vertical stress direction will decrease, and about 10% changes of the guided wave amplitude is caused by the tensile stress of 90 MPa. The existence of acoustic elastic effect will result in the influence of the guided wave propagation speed. Waveguide velocity along the stress direction increases as the increasing of the tensile stress, but the group velocity of the wave in the vertical stress direction will decrease, and about 0.3% changes of the guided wave group velocity is caused by the tensile stress of 90 MPa.

Keywords: Structural health monitoring, Guided wave, Environmental load, Piezoelectric constitutive equation, Acoustic elastic effect

1. Introduction

In recent years, a growing number of theoretical research work and practical application in engineering of SHM based on piezoelectric and guided waves, are the results of the advantages about guided waves in non-destructive real-time monitoring gradually understood and used. In a SHM method based on piezoelectric guided waves, the piezoelectric sensor is used to actuate and sense the guided wave signals, which is often pasted on the surface of the structures or embedded into the internal[1], and some guided wave integrated monitoring systems in signal acquisition[2-3] gradually developed that will be conducive to the application in engineering practice. The piezoelectric wafers used in the damage detection method has the advantages of fast response speed, low power consumption, low cost and small size, resulting in especially suitable for integrated into structures. Guided waves are sensitive to small damage and can achieve regional monitoring. Since the method is based on the interaction between guided waves and damage, the propagation of guided waves will also be affected by environmental factors when the engineering is monitored in the actual working environment. It is well known that aerospace structures conducted real-time on-line SHM are usually subjected to various prestress and damage at the same time, such as the prestressing force generated during the manufacturing process and the environmental loads during the operation, etc. The external load imposed by the aircraft will directly affect the sensor signal features, resulting in the damage diagnosis is not carried out reliably. Therefore, how to guarantee the reliability of damage monitoring under time-varying environment is a key problem in the practical application of SHM technology. From the present research reports, based on the piezoelectric and guided waves SHM affected by the load in the wave amplitude is mainly reflected on the piezoelectric sensor-electric transformation characteristics under stress[4-7]. According to Kang and Han's research results, by fitting the piezoelectric constant
\[ d_{31} \] curve under stress, bring the obtained \[ d_{31} \] into the piezoelectric equation to carry out the whole process simulation of guided wave excitation - propagation - response. The change of the waveguide phase is mainly determined by the influence of the load on structures, that is, the propagation velocity will change with the change of load due to the existence of acoustic elastic effect. The effect of the load on structures is finally reflected in the change of the waveguide phase \([7-8]\). However, there are few researches on the effect of load on the combined influence of piezoelectric and guided waves in the real monitoring system. Therefore, this paper discusses the influence mechanism of piezoelectric and guided wave by load, designs and implements the experiment to find out the effect of uniaxial static tensile on the propagation of guided wave based on piezoelectric wafers in thin plate.

Based on the above discussion, we arrange this paper content is as follows: in the second part, discuss the influence mechanism of load on piezoelectric and guided waves, and introduce the experiment and the implementation process according to the mechanism. In the third part, get the experimental results from the experimental data processing, and analyse the experimental results; In the fourth part, summarize the conclusions and make a certain prospect.

2. Experiment principles, settings and process under load

2.1 Experiment principles under load

Taking the guided wave propagation of the simplest flat sheet structure under uniaxial static tension load as an example to illustrate the experimental principles of load effect, the schematic diagram of the load and guided wave acting on the structure is shown in Fig. 2.1. In the process of excitation-propagation-response, the influence mechanism of the load is summarized as following three aspects\([7,9-11]\):

1. Load effect on excitation and response performance of piezoelectric wafers: This effect is mainly reflected in the change of electromechanical transform characteristics of piezoelectric ceramics under external load, which leads to the change of excitation and response characteristics of guided wave causing the wave amplitude to change with the stress.
2. Load effect on the coupling properties of the bond: the adhesive only acts as a shear force, and very thin, so the impact of the load on the bond can temporarily not be considered.
3. Load effect on the propagation of the guided waves: This effect is mainly reflected in the acoustic elastic effect on structures subjected to the outside load, leading to changes in the velocity of guided waves, causing the change of the guided waves in the time of flight (TOF).

The useful information of guided wave signals used in SHM under stress, namely the amplitude and velocity of guided waves, were analyzed respectively above. At the same time, it can be understood that if in other same conditions, the different signal information in a guided wave signal under different load conditions, that is, the change of the derivative amplitude and the propagation speed can be reduced to the two different influence factors.

![Fig.2.1 Transmission schematic diagram of guided wave in the load structure](image)

In order to further analyze the effect of load on the guided waves, the engineering structure can be simplified to achieve the same phenomenon under laboratory conditions. At the present stage, the experimental study on effect of guided waves under load is simplified as follows:

(a) Quasi-static load state: in most cases, the frequency of the large external load that can affect the propagation of the guided waves is generally low, about 0-20 Hz. And the excitation
frequency of the guided wave is generally more than 50kHz, and the waveguide excitation - propagation - response takes less than 1ms (1kHz). Therefore, the influence of the external load can be approximated to be quasi-static (static) state load for guided waves.

(b) Uniaxial tensile load condition: at present study, the effect of the simple structure on the one-way load is initially considered. For the tensile specimen and static test, the loading form is relatively simple, that is, the one-way load as shown in Fig. 2.1, and the fixed end while the other end is stretched.

According to the above mechanism of load impact and simplification of experimental study, we can set the influence of static load on the propagation characteristics of guided wave to study the influence law about environmental factors on the amplitude and propagation velocity of Lamb wave signal in aluminum plate.

2.2 Experiment settings

In this experiment, the Lamb wave signals in the aluminum plates subjected to static tensile load in different directions are collected. The PXI scanning system is used to collect the Lamb wave signal; a 2024 aluminum plate with piezoelectric wafers and strain gauges is mounted. The specimen size is 510mm × 510mm × 3mm, and the material properties are: Young's modulus 70GPa, density 2700kg / m³, Poisson's ratio 0.33. Fig. 2.2 (a) shows the overall the test device, Fig. 2.2 (b) shows the specimen clamped by tensile machine.

(a) Schematic diagram of experimental apparatus (b) Drawing of clamping specimen

Fig 2.2 Schematic diagram of experimental apparatus

The specific size of the specimen and the placement of the piezoelectric wafers are shown in Fig. 2.3.

Fig 2.3 Specimen size and piezoelectric wafers layout drawing

In this experiment, the test state of aluminum plate is divided into two parts according to the stretching direction, namely the transverse tensile and longitudinal tensile states. Change the load magnitude in each experimental state and obtain the lamb wave signals by frequency scanning.
2.3 Experiment process

According to the measurement data of loading and strain gauges before test, the loading width of aluminum plate is 0~81 kN, the interval is 9 kN (the stress range of the middle piezoelectric wafer is about 0~90 MPa, the interval is about 10 MPa), a total of 10 loads.

Specific test steps are shown as following:
- Debugging equipment and laying Specimen: Open the oil source, fan and control system of the drawing machine, the test pieces are fixed to the drawing machine by clamping device, and the left and right symmetry is maintained; At the same time, the strain gauge is connected and the sensor and PXI scan system are connected through the wire.
- Cycle of load and acquisition signals: A one-way static tensile load was applied to the specimen, and after the stable loading, the Lamb signal was collected and the strain value of all the piezoelectric plates was collected. Follow the above steps to carry out three load cycles and collect data.
- Change direction and repeat trial: Unload to 0 kN, rotate the specimen 90° to load, repeat the above test steps for signal acquisition.
- Uninstall and take off the specimen: Unload to 0 kN and take off the specimen.
- Turn off the systems: Close the control system of the drawing machine, the oil source and the fan, and the signal acquisition system, arrange the equipment.

3. Experimental results and discussion of load impact

Aluminum plate loading direction to Fig.2.3 for the first time applying pull up and down direction, the experiment acquisition of two strain gauge position as shown in Fig.2.3, the second loading direction applying tension, as Fig.2.3 on the left and right two strain experiment acquisition position respectively at 4 and 5 of piezoelectric patches. Stress strain information is shown in Tab.3.1.

The first loading direction of the aluminum plate is applied to the up-down direction of Fig. 2.3. The two strain gauges positions collected in the experiment are shown in Fig. 2.3. And the second loading direction is applied to the direction of the left-right direction of Fig. 2.3. The two strains of the strain positions collected at the experiment are at the piezoelectric wafers at 4 and 5 places respectively. The stress and strain information are shown in Tab. 3.1.

<table>
<thead>
<tr>
<th>number</th>
<th>Test load tension (kN)</th>
<th>1_measured strain (με)</th>
<th>1_measured stress (MPa)</th>
<th>2_measured strain (με)</th>
<th>2_measured stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
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<td>169</td>
<td>11.8</td>
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<tr>
<td>3</td>
<td>18</td>
<td>258</td>
<td>18.0</td>
<td>333</td>
<td>23.3</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>392</td>
<td>27.4</td>
<td>486</td>
<td>34.0</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
<td>528</td>
<td>37.0</td>
<td>631</td>
<td>44.2</td>
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<tr>
<td>6</td>
<td>45</td>
<td>664</td>
<td>46.5</td>
<td>773</td>
<td>54.1</td>
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<tr>
<td>7</td>
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<td>798</td>
<td>55.9</td>
<td>917</td>
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<td>1206</td>
<td>84.4</td>
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<td>95.6</td>
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</table>

From the above table, it can be found that the aluminum sheet used in the test is relatively uniform, but the stress at different piezoelectric plates is also a certain degree of different. Because the difference is not too big, it is a stress uniform plate for the time being.
Due to the symmetry of specimen size and load, according to the experimental purpose, the signal of typical channel 2 - 5 (piezoelectric wafer number) and typical frequency of 250 kHz are selected.

Firstly, Fig. 3.1-3.4 shows the center frequency 250 kHz how $S_0$ mode and $A_0$ mode change of amplitude and TOF under different direction stress. Measurement of TOF change is used to indirectly measure the group velocity changes.

(a) Figure of load effect on $S_0$ amplitude (b) Figure of load effect on $S_0$ TOF

Fig. 3.1 Influence of parallel load on $S_0$ mode of the center frequency 250kHz

Fig. 3.3 Influence of parallel load on $A_0$ mode of the center frequency 250kHz
The results show that the amplitude and group velocity of the guided wave are approximately linearly changed with the load in the range of 0-90MPa. At the same time, according to the experimental data processing results, the amplitude of the guided wave is about 10% increases at 90MPa when the guided wave propagation channel and the load are parallel, the linear fitting slope of \( S_0 \) mode is about 3.84mV/MPa, the linear fitting slope of \( A_0 \) mode is 1.17mV / MPa; while the TOF increases about 0.3% at 90MPa namely the group speed down 0.3%, \( S_0 \) linear fitting slope is \( 1.08 \times 10^{-9} \) s/MPa, \( A_0 \) linear fitting slope is \( 1.68 \times 10^{-9} \) s/MPa. The amplitude of the guided wave is reduced by about 10% of 90MPa at 250kHz when the wave propagation path and the load are vertical, the slope of the \( S_0 \) linearity is -3.14mV/MPa, the linear fitting slope of \( A_0 \) is -1.96mV/MPa; the group velocity is increased by 0.3%, the \( S_0 \) linear fitting slope is \( -1.02 \times 10^{-9} \) s/MPa, and the \( A_0 \) linear fitting slope is \( -1.26 \times 10^{-9} \) s/MPa.

From the above quantitative results can also be found in the same load change conditions and the same guided wave propagation path, \( S_0 \) mode amplitude changes are larger than the \( A_0 \) mode, proved \( S_0 \) mode amplitude of load changes more sensitive, while \( A_0 \) mode group velocity changes are slightly larger than the \( S_0 \) mode, proved \( A_0 \) mode group velocity of load changes more sensitive.

4. Conclusion

In this paper, the effect of static load on the propagation characteristics of guided wave was studied based on the mechanism of amplitude and velocity. According to the quantitative analysis of the experimental data, the following conclusions are obtained: (1) the variation of amplitude under static load mainly depends on the properties of piezoelectric ceramics under load: amplitude of the wave propagating in the direction of parallel load increases with the increasing load but deceasing under vertical load. The amplitude is linearly varying with the load between 0-90MPa, and the amplitude changes about 10% of 90 MPa. (2) the change of group velocity of guided wave mainly depends on the acoustic elastic effect of guided wave in structures: the velocity of guided waves in the direction of parallel load increases with the increasing load but decreasing under vertical load. The change of group velocity is about 0.3% at 90 MPa.

According to the above basic simple structure and simple load effect, the influence law of static load on guided wave propagation characteristics can be further analyzed. At the same time, according to the influence mechanism of in-depth discussion under various and with complex structures in the actual engineering application should be given.
5. Acknowledgements

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References