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ABSTRACT
Axial stress monitoring in arbitrary cross sections is a challenging task. Stringers are the main axial load carrying components of aircraft skin structures and have typical complex cross sections. This paper investigates the strategy of axial stress monitoring in an arbitrary cross section based on acoustoelastic guided waves using piezoelectric lead zirconate titanate (PZT) sensors. To select appropriate guided wave frequencies and modes sensitive for axial stress monitoring in an arbitrary cross section, the feature guided waves are investigated using acoustoelastic theory combined with the semianalytical finite element method. The mode shapes are derived, which show that these longitudinal-like modes are more sensitive to axial stress. A PZT transducer array is also considered to maximize desired modes. Piezoelectric sensors are used to excite and detect the guided waves in the experiments. Results from acoustoelastic measurements on a T-type stringer are presented, showing the feasibility of this method for axial stress monitoring.

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I. INTRODUCTION
The measurement of stress levels is a challenging task in the field of nondestructive testing (NDT) and structural health monitoring (SHM), particularly relevant to arbitrary cross sections. Stringers are the key elements in aircraft structures, as the major axial load carrying components, and are typical arbitrary cross sections. The fatigue life of these components is critical for the safety of aircraft structure. It is necessary to monitor the axial stress in stringers to avoid the risk of buckling and ensure safety of aircraft structure.

Guided waves are a popular practical tool in the engineering field of NDT and SHM. Due to its long propagation distance, large inspection range, and reliable response, guided waves are widely used in damage detection and localization. It is also known that guided waves can be influenced by propagation environments, such as temperature, stress, and so on. Currently, many scholars are trying to use guided waves to measure the state of propagation environments in waveguides. It is proposed that the measurement of guided wave propagation change can be used to determine stress in structures. In addition, the advantage of guided waves in stress monitoring is that they can be also used to detect damage. The development of stress monitoring with guided wave propagation is the current research subject in the field of structural health monitoring.

Most techniques to measure stress are based on acoustoelastic theory, which refers to the variation of wave propagation velocities with applied stress. Acoustoelastic effects have been investigated for propagation of guided waves in some typical structures such as plates, rod-like structures, and arbitrary cross sections. The theory of acoustoelasticity was initially developed by Hughes and Kelly...
in isotropic materials subjected to static predeformation.\textsuperscript{15} They applied Murnaghan’s theory to derive equations relating bulk elastic waves to applied stress. Gandhi and Michaels\textsuperscript{16} investigated the theory of Lamb wave propagation in an anisotropic stressed plate; both theoretical predictions and experimental results were shown for the multiple Lamb wave modes. Then, Michaels\textsuperscript{17} developed a strategy for in situ estimation of a biaxial stressed plate using distributed PZT sensors. di Scalea\textsuperscript{12} derived a simplified acoustoelastic formulation method in cylindrical waveguides and investigated stress measurement and defect detection in seven-wire strands. Liu\textsuperscript{20} presented the experimental observations of L (0,1) mode ultrasonic guided wave propagation in the stressed strand. Dubuc\textsuperscript{21} focused on higher order guided wave propagation in prestressing strands and used acoustoelastic theory on a rod to study the effect of stress on wave velocity. di Scalea\textsuperscript{22} proposed a methodology using nonlinear ultrasonic waves to monitor prestress levels in multiwire steel strands by measuring the nonlinear parameter as a function of applied stress. However, guided wave propagation characteristics in arbitrary cross sections are more complicated. Wilcox and Loveday\textsuperscript{23–25} analyzed the prestressed viscoelastic wave guides. This paper highlights the influence of initial stress on dispersion characteristics was large for low order modes at low frequencies but small for higher order modes.

Less research has been focused on higher order modes for stress measurement in arbitrary cross sections because of the added complexity of considering material inelasticity in guided wave propagation. Wu and Yang\textsuperscript{27} developed an AE-SAFE method for investigating guided wave propagation in axial stressed arbitrary cross sections. The dispersive solutions were obtained in terms of phase velocities, group velocities, and velocity sensitivity to stress variations in these structures. This paper shows that the inclusion of material inelasticity has a significant effect on the response of a guided wave to axial stress at high frequency or higher order modes. However, the studies on acoustoelastic guided wave propagation in axial stressed arbitrary cross sections focused exclusively on theory and some numerical methods. It has seen few practical applications. The motive of this paper is to develop a strategy for axial monitoring in an arbitrary cross section based on acoustoelastic guided waves using piezoelectric sensors.

This paper is organized as follows. First, in Sec. II, multiple potential feature guided modes in a stressed stringer are presented by using acoustoelastic theory combined with the semianalytical finite element (AE-SAFE) method. Then, in Sec. III, the strategy of axial stress monitoring is performed based on the results of Sec. II, including mode and frequency selection, transducer array, and axial stress prediction methods. Experimental results on this stringer are presented and discussed in Sec. IV. Finally, in Sec. V, the paper concludes with the direction for future work.

II. FEATURE GUIDED WAVES IN AN AXIAL STRESSED STRINGER

A. AE-SAFE modeling

To identify and understand guided modes existing in a stressed arbitrary cross section, acoustoelastic theory combined with the semianalytical finite element (AE-SAFE) method was applied by Wu and Yang.\textsuperscript{27} An axial stress along the waveguide axis (x axis) is considered. The stiffness matrix for this transversely isotropic material is represented by\textsuperscript{28,29}

$$\begin{align*}
\mathcal{C} = \begin{bmatrix}
\tilde{C}_{11} & \tilde{C}_{12} & \tilde{C}_{12} & 0 & 0 & 0 \\
\tilde{C}_{12} & \tilde{C}_{22} & \tilde{C}_{23} & 0 & 0 & 0 \\
\tilde{C}_{12} & \tilde{C}_{23} & \tilde{C}_{22} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{2}(\tilde{C}_{22} - \tilde{C}_{23}) & 0 & 0 \\
0 & 0 & 0 & 0 & \tilde{C}_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & \tilde{C}_{55}
\end{bmatrix}.
\end{align*}$$

The length of the arbitrary cross section structure is much longer than the cross section dimensions. We restrict our analysis to consider only an axial strain in the x direction. The expressions for the coefficients in the stiffness matrix derived from Ref. 27 are

$$\begin{align*}
\tilde{C}_{11} &= \lambda + 2\mu + \frac{(2l + 4m + 3\lambda + 6\mu)(\lambda + \mu)}{3\lambda\mu + 2\mu^2} \sigma, \\
\tilde{C}_{22} &= \lambda + 2\mu + \frac{(2l + 3\lambda)(\lambda + \mu)}{3\lambda\mu + 2\mu^2} \sigma, \\
\tilde{C}_{23} &= \lambda + \frac{(2l - 2m + n)(\lambda + \mu)}{3\lambda\mu + 2\mu^2} \sigma.
\end{align*}$$

Applying Hamilton’s principle, the AE-SAFE governing equation for the stringer with axial stress is given by

$$[K_1 + i\xi K_2 + \tilde{c}^2 K_3 - \omega^2 M] U = 0,$n

where the stiffness matrices are

$$\begin{align*}
K_1 &= \sum_{n=1}^{n_{\text{elements}}} \left[ \int_{\Omega_e} (B_i^T \tilde{C}_{ij} B_i) d\Omega_e \right], \\
K_2 &= \sum_{n=1}^{n_{\text{elements}}} \left[ \int_{\Omega_e} (B_i^T \tilde{C}_{ij} B_i - B_i^T \tilde{C}_{ij} B_i) d\Omega_e \right], \\
K_3 &= \sum_{n=1}^{n_{\text{elements}}} \left[ \int_{\Omega_e} (B_i^T \tilde{C}_{ij} B_i) d\Omega_e \right],
\end{align*}$$

and the mass matrix is obtained as

$$M = \sum_{n=1}^{n_{\text{elements}}} \left[ \int_{\Omega_e} (N^T \rho e N) d\Omega_e \right].$$

The solution of the AE-SAFE equation has also been reported by Wu and Yang.\textsuperscript{27} The AE-SAFE model is applied to the T-type stringer, whose geometry is shown in Fig. 1(a). Referring to Fig. 1(a), the initial homogeneous axial stress (\sigma) and guided wave propagating along the x direction are considered. The half cross section diagram of the T-type stringer is discretized, as shown in Fig. 1(b). The symmetric and antisymmetric modes are captured by setting two boundary conditions.\textsuperscript{31} The material of the stressed stringer is the same as 6061-T6 aluminum in Ref. 17. The material constants used are listed in Table I.

Figs. 2(a) and 2(b) present the family of symmetric and antisymmetric dispersion curves for a T-type stringer under uniaxial stress and for waves propagating in the stress direction. The curves were computed using the AE-SAFE method, with \sigma = 100 MPa.
FIG. 1. T-type stringer: (a) geometry for guided wave propagation in a stressed stringer and (b) cross section diagram of the element mesh for a half stringer.

TABLE I. Material constants for 6061-T6 aluminum.

| ρ     | λ       | μ       | l         | m         | n         |
|-------|---------|---------|-----------|-----------|-----------|
| 2704 kg/m³ | 54.308 GPa | 27.174 GPa | -281.5 GPa | -339.0 GPa | -416 GPa |

From Fig. 2, it can noted that the modes in a T-type stringer are more complicated.

B. Typical mode shapes

In order to choose proper guided modes for axial stress monitoring, the modal properties were investigated. In the frequency range of interest, there are multiple modes and more complications in complex arbitrary cross sections. The information provided by modal shape analysis could be useful to develop a prototype that is able to detect stress in arbitrary cross sections similar to this T-type stringer. Of course, the wave mode shape is not the only consideration; it may not even be the most important consideration, but it is the starting point.

Figure 3 shows the mode shapes of three typical modes. The torsional (T) mode [Fig. 3(a)] is an antisymmetric mode A1 at 4 kHz and is dominated by horizontal and vertical displacements. The modes dominated by vertical displacements were characterized as flexural (F) modes, and the mode shown in Fig. 3(b) is a symmetric mode S1 at 4 kHz. As shown in Fig. 3(c), the mode shape indicates that the wave field is dominated by axial displacement (in the x direction); hence it has been termed the longitudinal (L) mode. This mode is a symmetric mode S2 at 4 kHz. It can be noted that all the considered modes have non-negligible displacements. After analyzing the guided mode shapes, it is possible to investigate the energy propagation in the stringer region. Such energy distribution can affect the propagation velocities of these stressed stringer modes.

C. Effect of axial stress on guided wave propagation

As an example of the acoustoelastic effect caused by applied axial stress in the T-type stringer, dispersion curves at varying axial stresses σ for waves propagating along the loading direction are plotted in over a narrow frequency range for the S7 mode, as shown in Fig. 4. These changes in phase velocity are small. Figure 4(b) shows changes in phase velocity with varying axial stress for the same mode at a frequency of 100 kHz. Note that all phase velocity changes are calculated in the unstressed coordinate system. As noted in Refs. 17 and 18, it can be seen that the magnitude of changes in phase velocity [ΔC_p(f, σ)] are linear to the applied axial stress.
III. THE STRATEGY OF AXIAL STRESS MONITORING

Stress monitoring in an arbitrary cross section is performed by employing the complete process, as shown in Fig. 5. The acoustoelastic guided wave propagation characteristics are calculated using the AE-SAFE method. Then, appropriate points are selected for stress monitoring. The appropriate points should have a good dispersive characteristic and high stress sensitivity. The next step is the design of an exciter array aimed at generating the desired guided waves in the arbitrary cross section. Finally, the selected points are used for stress monitoring.

This axial stress monitoring strategy in arbitrary cross sections is of great significance for the realization of aircraft stringer stress monitoring. For further application, third-order elastic constants for the test material are also important. By considering material inelasticity and combining multi-mode characteristics and mode shape analysis, the axial stress monitoring strategy has considerable applications based on acoustoelastic guided waves. However in
practical applications, third-order constants for the test material cannot always be obtained accurately. The slight mismatch between AE-SAFE modeling and the experiment is probably due to the well-known difficulties in accurately obtaining third order elastic constants. Just the lack of accurate constants can affect acoustoelastic constant prediction but cannot disturb the mode and frequency selection for axial stress monitoring. Therefore, additional measurements should be performed to independently measure third-order elastic constants for the specific material under consideration.

A. Mode and frequency selection

Since each point on a dispersion curve has a unique wave structure, group velocity, and stress sensitivity, it is possible to select a mode and frequency of vibration that can effectively monitor axial stress. Displacement is maximized at the nodes of the stringer, which are marked in red in the provided figure. By selecting the appropriate mode and frequency, the stress sensitivity can be maximized for effective stress monitoring.

FIG. 5. The complete process of stress monitoring in an arbitrary cross section.

FIG. 6. Dispersion curves for waves propagating in a T-type stringer to an axial stress of 0 MPa; (a) group velocity curves and (b) phase velocity curves.
mode and frequency that provide the most desirable point for the stress monitoring application. Due to the geometrical complexity of the arbitrary cross section, it is necessary to get the dispersion curves and velocity sensitivity curves of guided waves to stress variations.

The results can be utilized to select the appropriate modes, which is significant for stress measurement.

The phase and group velocity dispersion curves for the unstressed T-type stringer are shown in Fig. 6. The curves were
The phase velocity sensitivities of the symmetric modes and antisymmetric modes are shown in Figs. 7(a) and 7(b). It can be seen that most antisymmetric modes are not sensitive to axial stress. Ignoring the sensitivity in the cutoff frequency, S3 in 90–110 kHz, S7 in 121–125 kHz, and S11 in 194–204 kHz have high sensitivity and good stability. As shown in Fig. 8, these modes are all longitudinal-like modes. Their displacement fields in the axial direction are non-negligible. It can be clearly observed that longitudinal-like modes are fairly sensitive to the variations of axial stress.

Figure 9 shows the changes in phase velocity of the S7 mode in particular. The unstressed group velocity of the mode is also shown. It can be seen that this mode has the fastest group velocity and the change in phase velocity is stable and sensitive to axial stress at these frequencies. These features may therefore be more important for stress measurement applications.

\[ K_{CP}(f) = \frac{\Delta Cp(f, \sigma)}{\sigma} = \frac{[Cp(f, \sigma) - Cp(f, 0)]}{\sigma}, \quad (6) \]

where \( f \) refers to the frequency of the wave, \( \Delta Cp(f, \sigma) \) refers to the change of phase velocity sensitivity, and \( Cp(f, \sigma) \) and \( Cp(f, 0) \) refer to the stressed and unstressed phase velocity, respectively. The phase velocity sensitivities of the symmetric modes and antisymmetric modes are shown in Figs. 10(a) and 10(b). It can be seen that the most antisymmetric modes are not sensitive to axial stress. Ignoring the sensitivity in the cutoff frequency, S3 in 10–30 kHz, S7 in 90–110 kHz, S8 in 121–125 kHz, and S11 in 194–204 kHz have high sensitivity and good stability. As shown in Fig. 8, these modes are all longitudinal-like modes. Their displacement fields in the axial direction are non-negligible. It can be clearly observed that longitudinal-like modes are fairly sensitive to the variations of axial stress.

B. PZT sensor array

When a transducer is attached to the stringer to excite the guided waves, all the modes of propagation supported by this stringer can be excited. For practical application, simply exciting and detecting a mode efficiently is not enough; it is additionally necessary to maximize the desired modes and suppress information from the undesired modes.

As mentioned in Sec. III A, the selected modes have relatively similar physical characteristics in terms of their non-dispersive behavior, high stress sensitivity, and displacement distribution. Since the selected modes are longitudinal-like modes and the energy displacement fields focus on axial direction, they should provide symmetric axial excitation forces.

As shown in Fig. 10(a), a symmetric integral excitation pattern was applied to the T-type stringer. In the finite element model, the T-type stringer was discretized in an ABAQUS/STANDARD (dynamic implicit) model by 6-node linear triangular prism elements (C3D6), and the PZTs were discretized by 8-node linear piezoelectric brick elements (C3D8E). The incidence signals were 5-cycle Hanning windowed sinusoidal signals at different central frequencies. Following the 10–20 mesh-per-wavelength rule, the size of T-type stringer elements used was 2 mm in the longitudinal direction and 1.6 mm in the cross sectional direction. Figs. 10(b)–10(e) show the guided wave propagations at a symmetric integral excitation pattern at various selected frequencies: 25 kHz, 100 kHz, 124 kHz, and 200 kHz. It is difficult to achieve single mode excitation, but propagating modes can be controlled with different excitation patterns.

With this excitation pattern, it can be found that S3 at 25 kHz is the most excited one and S7 at 100 kHz is the main propagating mode. The quantities of guided wave modes increase at 124 kHz and 200 kHz. As shown in Fig. 10(d), it can be found that the S8 and S9 modes propagate at 124 kHz. It can also be observed that the modes except S11 superimpose and propagate, as shown in Fig. 10(e).

C. Axial stress prediction method

Phase velocity change was estimated from the experimental results using the time shift. Time shifts are measured by identifying the zero crossing values at the center of each direct arrival signal. This can be seen in Fig. 11, which shows the time change of the S11 mode in a T-type stringer at 200 kHz for a stress of 0 and 100 MPa of the transducer pair Total-Total (exciting on total transducers 1–26 and receiving on total transducers 1–26).

An approximation can be used to experimentally measure \( \Delta Cp \). The change in phase velocity can be calculated by

\[ \Delta Cp(f, \sigma) = \frac{-Cp(f, 0)^2 \times \Delta t(f, \sigma)}{d} = K_{CP}(f) \sigma, \quad (7) \]

where \( d \) is the propagation length subjected to stress, \( \Delta t(f, \sigma) \) is the time change at axial stress \( \sigma \) and frequency \( f \), and \( K_{CP}(f) \) is an acoustoelastic constant. Equation (7) is used to extract phase velocity changes from experimentally measured time shifts \( \Delta t \). Therefore, using the approximation for the phase velocity change, the axial stress can be predicted.
FIG. 10. (a) A symmetric integral excitation pattern applied to the T-type stringer; guided wave propagation at various selected frequencies: (b) 25 kHz, (c) 100 kHz, (d) 124 kHz, and (e) 200 kHz.

IV. EXPERIMENTAL INVESTIGATION

A. Test setup and procedure

The experiment was carried out on a 1 m length T-type stringer. An SDS–100 universal electro–hydraulic servo testing machine (Changchun Research Institute For Mechanical Science Co., Ltd., China) was used to apply tensile load to the stringer. Several piezoelectric lead zirconate titanate (PZT) transducers were placed in a pitch-catch configuration on the stringer, as shown in Fig. 12(a). Exciting and receiving transducers are placed exactly at the same position but on the other side of the stringer, as shown in Fig. 12(a). The distance between the exciting and receiving transducers was 0.6 m, and the exciting transducers were excited by a five-cycle Hanning window sinusoidal excitation signal.

The exciting and receiving transducer arrays can be seen in Fig. 12(b). In Fig. 12(b), when the exciting transducers were mounted on the side of the stringer, they produced only symmetric mode waves. Waveforms were recorded from 26-path receiving transducers, as shown in Fig. 12(b), at 11 axial loads (0–100 MPa in steps of 10 MPa). The choice of S7 in 100 kHz, S8 in 124 kHz, and S11 in 200 kHz were used to measure changes in phase velocity as a function of applied axial stress in the T-type stringer.
B. Experimental results

Figure 13 shows the received signals from the transducer pair Total-12 (exciting on total transducers 1–26 and receiving on transducer 12 at $f = 100$ kHz for a stress of 0: 10 MPa: 100 MPa. The zero crossing values at the center of each direct arrival signal were extracted to measure time shifts. The time shifts relative to zero stress are almost linear with load over the used load range. Also, the corresponding changes in phase velocity $\Delta Cp(f, \sigma)$ were calculated by Eq. (7).

In addition to the experimental results, the numerical phase velocity change based on dispersion curves is shown in Fig. 14. The plateau results in a stable velocity change across frequency. This stable behavior is therefore investigated within the T-type stringer. Figure 14(a) shows the linear variation of the changes in phase velocity with stress for propagation of S7 in 100 kHz along the axial stress. The experimental results (from the transducer pair Total-12) show similar linear changes in phase velocity to numerical results. Figs. 12(b) and 12(c) show the linear variation of the changes in phase velocity with stress for propagation of the S8 mode in 124 kHz and the S11 mode in 200 kHz, respectively. These modes are all longitudinal-like modes and exhibit nearly the same change in velocity.

Although the experimental and the numerical plots show a similar linear trend, it also shows the mismatch between the numerical and experimental slope. The numerical results were computed by considering the elastic properties of 6061-T6 aluminum due to the lack of information of third-order constants for the test material. The 6061-T6 aluminum material constants are listed in Table I. The choice of this material was motivated by the reasonable agreement with Lame’s constants of the test materials (aluminum-lithium alloy). The mismatch between the numerical and experimental phase velocity change was attributed to uncertainties in the
FIG. 14. Experimental phase velocity change for (a) S7 in 100 kHz, (b) S8 in 124 kHz, and (c) S11 in 200 kHz in a T-type stringer with applied axial stress. The numerical change overlies the experimental phase velocity change.

Material properties of the test stringer. The difficulty in getting accurate third order elastic constants is well known.\textsuperscript{17,20} Results from the AE-SAFE method and experiment present both linear changes in phase velocity showing the feasibility of this axial stress monitoring strategy.

However, to obtain a good match between AE-SAFE prediction and the experiment, a third order elastic constant adjustment is performed. The AE-SAFE method is utilized to compute acoustoelastic guided wave excitation and propagation in a T-type stringer with different third order elastic constant assumptions. The plausible values for the third order constants are $l = -261$ MPa, $m = -259$ MPa, and $n = -386$ MPa. Figure 15 shows the phase velocity change comparison of the prediction and experiment with different axial stress using modified third order elastic constants. Figs. 15(a)–15(c) show the linear variation of the changes in phase velocity with stress for propagation of S7 in 100 kHz, S8 in 124 kHz, and S11 in 200 kHz along the axial stress, respectively. These three theoretical curves are in excellent agreement with the experimental data.

V. SUMMARY AND CONCLUSIONS

This paper is aimed at further development of a stress monitoring strategy based on acoustoelastic guided waves in stringer-like arbitrary cross sections using PZT sensors. Some propagation characteristics of guided waves in a stressed stringer have been investigated on account of arbitrary cross sections by the AE-SAFE method. The acoustoelastic waveguides are frequency dependent and have multiple-mode and dispersion characteristics. The AE-SAFE model was used to predict the effect of stress on phase velocity of these modes. The mode shapes were also derived, where it was shown that these longitudinal-like modes are more sensitive to axial stress, like the S7 mode at 100 kHz.

The unstressed and stressed solutions of guided waves in a T-type stringer were obtained and were used to select the appropriate modes and frequency region. The features of the appropriate modes and frequency region for stress measurement applications include the propagation velocity with an obvious advantage, better nondispersive characteristics, high stress sensitivity, and stability across mode and frequency. The axial stress monitoring strategy in arbitrary cross sections is of great significance for the realization of...
aircraft stringer stress monitoring and the development of NDT and SHM systems.

The unstressed and stressed numerical solutions of guided waves in a T-type stringer were validated by experimental results. Both numerical and experimental results show the expected linear dependence of phase velocity changes to the applied axial stress. Since the third order elastic constants for the stringer were uncertain in the literature, it shows the systematic mismatch between the numerical and experimental results. It cannot disturb the mode and frequency selection for axial stress monitoring. However, for improving predictive accuracy of the AE-SAFE method and enhancing the reliability of the axial stress monitoring strategy, future work should accurately determine high order elastic constants for the specific material under consideration.

The effect of axial stress plays a significant role on the stringer-like arbitrary cross sections. However, it can be affected by other stress states, such as twisting and bending stress. These stress states affect acoustoelastic guide wave propagation and therefore increase the detection uncertainty of the guided wave-based stress monitoring system. Future research is aimed at developing an intact stress monitoring method that can independently measure different stress states.

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