Research on Impact Load Localization Based on Piezoelectric Fibers with Metal Cores

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Abstract. Using a metal core piezoelectric fiber (MPF) as a sensing element and utilizing its directional characteristics, a shock load localization method based on the MPF flower structure is proposed. This method does not need to know the propagation speed of stress waves in the structure. At the same time, experimental research on impact load positioning of plate structures was conducted using this method. The research results showed that the method based on MPF flower shaped composite structure can be used for impact load positioning, and the positioning accuracy is high.

Keywords: piezoelectric fiber with metal core, impact load, positioning, MPF flower structure.

1. Introduction

There are two main methods for traditional structural impact load localization. One is to locate by measuring the time when the stress wave signal generated by the impact load reaches the sensor [1]; The second type is based on neural networks or other algorithms for localization, such as Shaw et al. who proposed using measurement of impact load strain amplitude and neural networks for localization [2]. Akhavan et al. also used optical fibers and neural networks to locate impact loads [3]. However, traditional positioning methods based on measuring the time when stress waves reach the sensor require knowledge of the propagation speed of stress waves in the structure. When monitoring complex or anisotropic structures, it is difficult to obtain the propagation speed of stress waves. The use of neural networks and other methods for localization requires a large amount of sample training, which increases the complexity of localization and results in low localization accuracy.

Using metal core piezoelectric fiber (MPF) [4-5] as the sensing element, a method for impact load localization based on MPF flower structure is proposed, utilizing its directional characteristics of sensing. This method is simple and feasible, and does not require knowledge of the propagation speed of stress waves in the structure, nor does it require a large number of training samples. At the same time, this article utilized this method to conduct experimental research on the impact load localization of plate structures.

2. piezoelectric fiber with metal core

Figure 1 is a geometric schematic diagram of the piezoelectric fiber (MPF) with a metal core. Its center is a metal core, with a piezoelectric ceramic in the middle. The ceramic is coated with a metal layer, so the metal core in the center and the external metal layer can serve as two electrodes, so a single MPF can be used as a sensor or driver [4-5].



Figure 1 Geometric Outline of MPF Figure 2 60 ° MPF Flower Structure

3. Positioning principle based on piezoelectric fibers with metal cores

Resistance strain patterns are often used in mechanical measurements. When the force and strain of the structure are unknown, the direction and magnitude of the main strain that the structure bears can be obtained through the strain pattern. According to the same principle, when conducting impact load positioning, the stress wave generated by external impact in the structure will inevitably cause changes in the strain field when it propagates from the impact point to the adhesive sensor, and the direction of the main strain is the direction of stress wave propagation. Therefore, a combination of flower shaped sensors can also determine the direction of the main strain field of stress waves caused by impact loads in the structure, which is the propagation direction of stress waves. MPF is very suitable for forming flower shaped structures for structural impact load localization due to its strong directionality in stress wave sensing.

Formulas (1) and (2) are the two main strain calculation formulas for 60 $^{\circ}$ strain rosette measurement. Equation (3) can be obtained by adding sub equations (1) and (2). From equation (3), it can be seen that in a 60 $^{\circ}$ strain rosette, the sum of the strain values measured by three strain gauge is constant for a specific measurement. Because the sum of the amplitudes of the three sensors at 60 $^{\circ}$ strain is constant, it is beneficial for normalization processing. Based on the principle of strain flower, this study also selected a 60 $^{\circ}$ MPF flower structure combination (as shown in Figure 2) for the positioning of impact loads.

$$\begin{split} \varepsilon_{\max} &= \frac{\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120}}{3} + \sqrt{(\varepsilon_0 - \frac{\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120}}{3})^2 + \frac{1}{3}(\varepsilon_{60} - \varepsilon_{120})^2} \\ \varepsilon_{\min} &= \frac{\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120}}{3} - \sqrt{(\varepsilon_0 - \frac{\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120}}{3})^2 + \frac{1}{3}(\varepsilon_{60} - \varepsilon_{120})^2} \\ \varepsilon_{\max} + \varepsilon_{\min} &= \frac{2(\varepsilon_0 + \varepsilon_{60} + \varepsilon_{120})}{3} \end{split}$$

From equation (3), it is known that the sum of the voltage response peaks of the three MPFs measured using a sensor combination similar to a 60 $^{\circ}$ strain pattern structure is a constant, and then the following normalization processing is performed:

$$\hat{A}_{i} = \frac{3}{2} \frac{A_{i}}{\sum_{k}^{3} A_{k}}$$
 $i, k \in [1,3]$

In the formula, Ai is the amplitude of each MPF in the flower shaped structure, and A_i is the relative amplitude of the normalized single MPF.

The amplitude of the impact signal obtained from MPF sensing is mainly determined by the angle between the impact source and the length direction of the MPF θ , The distance r between the impact source and the sensor and the magnitude of the impact force F are determined. The normalized amplitude obtained from equation (4) eliminates the influence of the distance between the impact source and the sensor, as well as the magnitude of the impact force, and is the angle θ . The only function of, which is $A = f(\theta, r, F, \cdots)$ changed from to $\hat{A} = f'(\theta)$. The $\hat{A} = f'(\theta)$ expression obtained through experimental fitting method can be used to calculate the angle between the impact source and the MPF axis through the measured signal peak. By using two MPF flower structures, two angles can be determined, and their intersection point is the impact source. The specific positioning principle is shown in Figure 3.

The response signal of MPF to impact load includes characteristic quantities such as amplitude, frequency, and arrival time of amplitude. The proposed 60 degree MPF flower structure positioning method in this study only needs to know the response amplitude of MPF in the flower structure, without knowing characteristic quantities such as frequency and signal propagation time. Therefore,

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this method can adapt to the impact load positioning of complex structures that are difficult to measure signal propagation time.



Figure 3 Schematic diagram of impact load positioning

Figure 3 is a schematic diagram of impact load positioning. When the structure is subjected to external impact, the stress waves generated at the impact point rapidly propagate around and are sensed by sensors attached to the surface of the structure. The stress wave signals induced by two sets of MPF units are collected and the peak voltage response of MPF is extracted according to the above method for normalization. In an ideal situation, the formulas obtained from the above processing for two sets of MPF units $\hat{A} = f'(\theta)$ are the same. However, considering the differences between individual MPF units, the MPF pasting situation, and other factors in practice, the corresponding fitting formulas for the two sets of MPF combinations are obtained here

$$\begin{cases} \hat{A}_1 = f'_1(\theta) \\ \hat{A}_2 = f'_2(\theta) \end{cases}$$
(5)

When the structure is subjected to impact load, the normalized peak extracted by the MPF combination ϕ^2 can be used to calculate the angle ϕ^1 and the position coordinates of the impact point according to formula (5).

4. Experimental research

4.1 Directional Experiment

The test piece selected is an isotropic metal aluminum plate (Young's modulus YAI=70 GPa, Poisson's ratio θ =0.34, density Å=2700 kgm-3), with a size of $1.2m \times 1.2m \times 0.002m_{\odot}$ Select an MPF with a length of 20mm for positioning experiments. The distance between the symmetrical centers of two sets of MPF units is 40cm. MPF is pasted in the middle of the aluminum plate, with free boundaries. The stress wave signal of MPF sensing is amplified by a charge amplifier and collected by the NI PCI-6115 data acquisition card. The sampling frequency of the data acquisition card is 1 MHz, and 5000 data are collected each time.

Take the arithmetic mean of the three sets of experimental data measured by two sets of MPF units, and use the averaged data as the sample points. Then, perform data fitting processing. Figures 4 and 5 respectively show the MPF directional sensing curves obtained after fitting processing.

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Figure 4 Fitting Curve of MPF Rosette1 Figure 5 Fitting Curve of MPF Rosette

4.2 Positioning experiment

To verify the positioning effect of the above method, 9 target impact points (A-I) were randomly selected on the specimens. Figure 6 shows the raw signals collected by each MPF sensor during the impact experiment at point B.



Figure 6 Impact Signal of MPF Sensing

Figure 7 shows the final positioning results of each target impact point mentioned above. From the figure, it can be seen that except for point D, the positioning results of all other points are very close to the true position. The significant positioning deviation of point D is mainly due to its location on the central axis of MPF Rosette1, which is perpendicular to the axis of MPF1, resulting in a small signal sensed by MPF1 and a low signal-to-noise ratio, resulting in a significant positioning error.



Figure 7 Positioning Results of Impact Load Experiment

5. Conclusion

The research results indicate that the method proposed in this paper based on MPF flower shaped composite structure can be used for impact load positioning, and the positioning accuracy is high. The positioning error may be mainly caused by the longer size of the MPF selected in the experiment and the low signal-to-noise ratio. Reducing the size of the MPF flower shaped composite structure and improving the experimental signal-to-noise ratio is expected to further improve positioning accuracy.

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