

Acoustic Emission Source Linear Localization Based on an Ultra-Short FBGs Sensing System

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Abstract: An acoustic emission (AE) linear location system was proposed, which employed fiber Bragg gratings (FBGs) as AE sensors. It was demonstrated that the FBG wavelength could be modulated as the static case when the grating length was much shorter than the AE wavelength. In addition, an improved AE location method based on the Gabor wavelet transform (WT) and threshold analysis was represented. The method was testified through AE linear location experiments based on a tunable narrow-band laser interrogation system using ultra-short FBG sensors as AE sensors. Results of the experiments showed that 86% of the linear location errors were less than 10 mm.

Keywords: Acoustic emission (AE) linear location, fiber Bragg gratings (FBGs), Gabor wavelet transform (WT), threshold analysis

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1. Introduction

The fiber Bragg grating (FBG) sensor has been expected as an ideal candidate for acoustic emission (AE) detection, because FBGs are not susceptible to the electromagnetic field, have multifunctionality, and enable multiplexing [1, 2]. In previous study, Aldo Minardo *et al.* found the actual influence of ultrasonic wave (US) perturbation on the shape and central wavelength of the grating peak [3]. Jung-Ryul Lee *et al.* designed an FBG AE sensor for mechanical tests and demonstrated that the ultrasonic vibration could propagate along the optical fiber with low attenuation [4–6]. The AE source location is an effective technique in structure health monitoring and has attracted great interest among researchers. Kwon *et al.* provided a source location method using the inverse wavelet transform

[7]. Jeong *et al.* reported a location method using the wavelet transform based on the Gabor wavelet to distinguish the different modes of the AE wave [8]. In this paper, the response of FBGs to AE waves is theoretically analyzed first, and the FBG based AE sensors and the interrogation system based on a tunable narrow-band laser are designed. An improved AE location method based on the Gabor wavelet transform (WT) and threshold analysis is deduced. And finally, an AE linear location system and experiments are conducted.

2. Theory

2.1 Principle of FBGs response to AE wave

The reflective wavelength of the FBG under matched condition is defined as

$$\lambda_{B0} = 2n_{\text{eff}0} \Lambda_0 \quad (1)$$

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where λ_{B0} is the reflective wavelength of the FBG, $n_{\text{eff}0}$ is the effective refractive index of the fiber core, and A_0 is the period of the gratings. Both $n_{\text{eff}0}$ and A_0 will be changed by environmental conditions, such as temperature, strain, and AE waves. When the AE wave travels along the fiber axis, for $\lambda_s/L \gg 1$, the reflective wavelength of the FBG can be expressed as

$$\Delta\lambda_0 = \lambda_{B0} \varepsilon_m \left\{ 1 - \left(\frac{n_{\text{eff}0}^2}{2} \right) \cdot [P_{12} - \nu(P_{11} + P_{12})] \right\} \quad (2)$$

where ε_m denotes the displacement amplitude of the AE wave, and $\Delta\lambda_0$ is the amplitude of the FBG wavelength modulation induced by the AE waves. From (2), we can see that under the condition of $\lambda_s/L \gg 1$, the grating response in terms of a central wavelength shift is the same as that in the static case [9].

2.2 Frequency analysis of AE wave using Gabor based WT

AE waves propagating in plate-like structures mainly contain two wave modes: the flexural wave (A_0) with the low frequency and high amplitude and the extensional wave (S_0) with the high frequency and low amplitude. In order to improve the accuracy of the AE source location, we can extract a single frequency component from the raw AE signal using the wavelet transform. Supposing an AE wave containing two harmonic unit waves with slightly different frequencies ω_1 and ω_2 propagates in the x -direction in certain plate-like structure, i.e.:

$$u(x, t) = e^{-i(k_1x - \omega_1t)} + e^{-i(k_2x - \omega_2t)}. \quad (3)$$

Introducing

$$\begin{aligned} (k_1 + k_2)/2 &= k_c; (\omega_1 + \omega_2)/2 = \omega_c \\ (k_1 - k_2)/2 &= \Delta k; (\omega_1 - \omega_2)/2 = \Delta\omega \end{aligned} \quad (4)$$

then, (4) can be rewritten as

$$u(x, t) = 2 \cos(\Delta kx - \Delta\omega t) e^{-i(k_c x - \omega_c t)}. \quad (5)$$

The Gabor wavelet has been proved by researchers to be the most suitable wavelet for discrimination of AE modes [8]. Hence, we use the Gabor wavelet as the analyzing wavelet, and the WT of $u(x, t)$ can be obtained as

$$\begin{aligned} (Wu)(x, a, b) &= \sqrt{a} [e^{-i(k_1x - \omega_1b)} \hat{\psi}_g(a\omega_1) \\ &+ e^{-i(k_2x - \omega_2b)} \hat{\psi}_g(a\omega_2)]. \end{aligned} \quad (6)$$

And the magnitude of the WT is

$$\begin{aligned} |(Wu)(x, a, b)| &= \sqrt{a} \left\{ [\hat{\psi}_g(a\omega_1)]^2 + [\psi_g(a\omega_2)]^2 \right. \\ &+ 2\hat{\psi}_g(a\omega_1)\psi_g(a\omega_2) \cos(2\Delta kx - 2\Delta\omega b) \left. \right\}^{1/2}. \end{aligned} \quad (7)$$

If $\Delta\omega$ is small enough such that $\hat{\psi}_g(a\omega_1) \approx \psi_g(a\omega_2) \approx \psi_g(a\omega_c)$, we can obtain

$$|(Wu)(x, a, b)| \approx \sqrt{2a} |\hat{\psi}_g(a\omega_c)| [1 + \cos(2\Delta kx - 2\Delta\omega b)]^{1/2}. \quad (8)$$

The result shows that $|(Wu)(x, a, b)|$ gets its maximum value when $a = \omega_0/\omega_c$ and $b = (\Delta k/\Delta\omega)x = x/c_g$. That is, for the fixed x , the magnitude of the WT reveals a peak at $a = \omega_0/\omega_c$ and $b = (\Delta k/\Delta\omega)x = x/c_g$ on the time-frequency plane. Therefore, the peak of the magnitude of the WT corresponds to the propagation of a wave with the group velocity at the frequency ω_c [8].

3. Experiments and results

A schematic of the experimental setup is shown in Fig. 1, which is a narrow-band tunable laser interrogation and direct reflectometric demodulation system. The FBGs had a grating length of 1mm (much shorter than the AE wavelength) according to the condition of $\lambda_s/L \gg 1$ and had central wavelengths of 1553.260 nm and 1553.250 nm, respectively. Both FBG1 and FBG2 were fabricated under the same condition, and their reflection ratios were above 80%. And they were glued to the surface of the plate. As shown in Fig. 1, the output light power from the circulator was transformed by the photodiode into the electrical power which was processed and recorded by the computer. In order to meet the requirement of the interrogation system, the wavelength of the tunable fiber laser was set at 1553.160 nm, which was the left mid-reflection wavelength of the FBGs to achieve the ideal match demodulation. And the output power was chosen as 9mW.

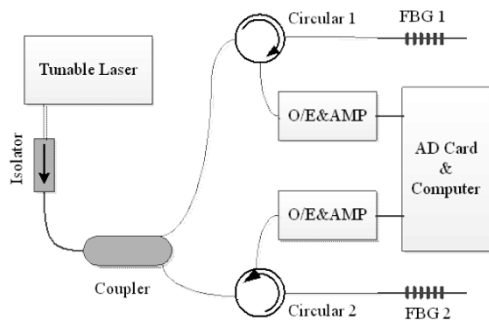


Fig. 1 Experimental setup for the FBG-based AE location sensing system.

Lead break signals were used as simulated AE signals. The typical waveform of 30° lead break signal on a marble slab with dimensions $600\text{ mm} \times 400\text{ mm} \times 5\text{ mm}$ is shown in Fig. 2(a). The signal recorded was 400 mm away from the FBG sensor. To determine the arrival time of the simulated AE signal at a single frequency, we used 100 kHz in the WT analysis. This frequency was chosen because the spectral analysis as shown in Fig. 2(b) showed that this was one of the typical frequencies presented in the captured waveforms. From Fig. 2(c), we can see that the WT analysis of the AE signal contains multiple peaks. The first peak represented the arrival time of the S_0 mode wave, and the second represented the arrival time of the A_0 mode wave. Because the A_0 mode wave propagated much slower than the S_0 mode wave and the A_0 mode wave had much larger magnitude than the S_0 mode wave, these two peaks were clearly distinguishable and separated in time. The following peaks indicated the stationary vibration of the plate or the reflective pulses of the signal.

In the AE location performance, it is important that we use the WT coefficient of the identical mode for the accurate source location. There may be cases where it is difficult to distinguish the two modes in WT data of the AE signal when the AE source is too close to the sensor thus the two modes are not that separated. So an efficient way has to be sought to identify the arrival time of the same mode of an AE signal. Here, we set a threshold, which was 80% of the maximum magnitude of each event. Hence, the

first peak after the threshold crossing indicates the arrival time of the A_0 mode wave traveling with the A_0 mode wave group velocity in the plate. In this way, after measuring the group velocity of the A_0 mode wave at 100 kHz , we can locate the AE source through the WT and threshold analysis.

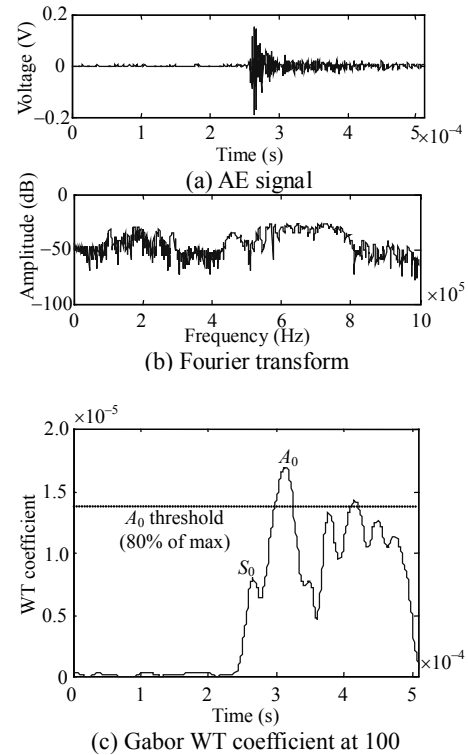


Fig. 2 Lead break signal 400 mm away from the sensor.

100 pencil lead break signals were performed on the marble slab to testify the location method of the WT and threshold analysis. Setting the y -direction coordinate of the FBG sensors as zero, the coordinates of FBG 1 and FBG 2 were $(0, 0)$ and $(600, 0)$, separately. And lead breaks were conducted at $(230, 0)$. In the experiments, AE signals were first sensed by the FBG sensors, then transformed into electrical signals and recorded to the computer. Finally, they were analyzed using the WT wavelet and threshold analysis to identify the exact position of the AE source. The result showed that 86 of the 100 events (86%) had errors less than 10 mm . In the other 14 events, 9 of them had errors less than 20 mm , and 5 of them had errors less than 30 mm .

4. Conclusions

A novel ultra-short FBG sensor used to detect AE signals was developed, and the interrogation scheme utilizing the tunable narrow laser was verified. In addition, an improved AE location method based on the Gabor wavelet transform and threshold analysis was deduced and verified in AE linear location experiments using the ultra-short FBG sensors. With the new AE location method, we can avoid distinguishing the two modes contained in the AE signal and achieve the arrival time difference of different sensors simply and correctly. Since the AE detection and AE source location have the extensive application foreground, the future research will regard the theoretical analysis of the FBG to AE wave and the improved AE location algorithm. Although experiments were done on a marble slab, we expect it to be extended to the problems with all thin-plate structures.

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