

Research Article

Acoustic Emission Source Localization System Using Fiber Bragg Grating Sensors and a Barycentric Coordinate-Based Algorithm

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Structures and machines are very susceptible to some barely visible defects; acoustic emission (AE) is an effective technique of detecting defects and examining growth and location of these defects. In this paper, a new method was proposed to predict the position of the AE source. The dynamic strain signal from the AE source was acquired by fiber Bragg grating (FBG) sensors. Complex Morlet wavelet transform was used to extract narrowband signals from AE waves. It was proposed that the barycentric coordinate-based localization algorithm can be used to predict the coordinates of the AE source. The validation tests based on the designed AE detection system were performed on a 500 mm × 500 mm × 2 mm Al-alloy plate. The experimental results show that the proposed method is feasible.

1. Introduction

The degradation of structural properties is well considered as an enormous threat for security and performance of structures and machines. Structural health monitoring (SHM) utilizes several kinds of sensors attached to or embedded in the monitored structures to detect the appearance, location, and severity of damage. Thus, SHM is imperative for damage detection and structural failure. Various methods have been researched for structural damage detection. These methods can be divided into two categories: model-based and signal-based approaches. The former develops suitable model and analyzes changes that relate to damage in the model; the latter extracts features and establishes a relationship between these features and potential damage [1–3]. Acoustic emission (AE) is one of the effective signal-based means implemented for damage detection [4].

AE wave is generated by energy release due to a propagating crack or friction in structures. AE technique is used to detect, locate, and assess defects. To obtain AE wave, some AE sensors have been widely used, such as piezoelectric

sensors (PZT) and capacitive AE sensors [5–8]. However, the traditional AE sensors have the disadvantages such as complex structure, weak antielectromagnetic interference, and unsuitability for distributed measurement. At present, fiber Bragg grating (FBG) sensors have been expected as an alternative because of their excellent performance. FBG sensors can be easily embedded in the monitored structure without destructive effect, due to their small size and light weight [9]. Furthermore, FBG sensors are immune to electromagnetic interference [10]. In addition, long-distance distributed measurement can be realized by using FBG sensors [11]. Therefore, some scholars have done several researches on AE source localization using FBG sensors [12, 13]. Yu et al. [14] investigated the effective length of the FBG sensor from the AE source on the composite plate. Yu et al. [15] proposed an AE source identification method based on the algebraic reconstruction algorithm and 3D imaging technique.

Recently, an increasing number of AE source localization methods was developed based on the intelligent algorithm [16, 17]. Cheng et al. [18] applied an optimized wavelet

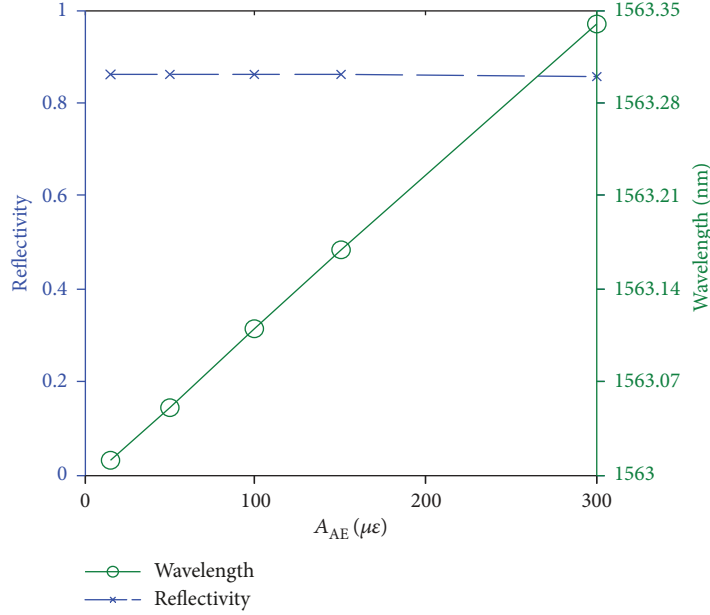


FIGURE 1: Relation between A_{AE} and reflectivity and wavelength of FBG.

neural network to realize AE source location in rotating machinery. Sadegh et al. [19] applied the genetic algorithm and artificial neural networks to extract features of AE signals for monitoring lubrication conditions of a journal bearing. However, in the intelligent algorithms used in those studies, lots of training samples were needed, which led to inefficiency and complexity of the localization process. Furthermore, AE source localization in plate-like structures usually requires lots of sensors. In particular, those approaches are usually accurate only within the convex area surrounded by sensors.

Based on the previous studies, this paper presented a novel AE detection system based on FBG sensors and a new AE source location method. The AE signal was collected by the FBG sensor which was pasted on the structural surface. Barycentric coordinate-based location method was used to predict positioning. Different from the approaches mentioned above, the proposed method was developed based on only range measurements between sensors, not training samples. The AE source is not required to lie inside the convex area formed by sensors. At last, AE source location experiments were carried out to verify this new designed system and localization algorithm. The results show that it is an efficient and feasible method for AE source localization.

2. Theoretical Principle

2.1. FBG AE Sensing Principle. The dynamic strain field along the FBG generated by AE wave can be simplified as a time-dependent cosine-Gauss function:

$$\varepsilon_{AE}(t) = A_{AE} e^{-((t-t_0)^2/a^2)} \cos\left(\frac{2\pi}{\lambda_{AE}} z - \omega_{AE} t\right), \quad (1)$$

where A_{AE} is the amplitude of AE wave propagating in a material to be monitored, λ_{AE} is the wavelength of AE wave,

ω_{AE} is the angular frequency of AE wave, t_0 is the arrival time, and a is the duration of AE wave.

The alternation of wavelength of FBG is mainly attributed to two factors: one is the modulation of the grating period Λ (geometric effect), which causes the axial deformation of FBG, and the other is the change of the effective refractive index of FBG \bar{n}_{eff} (photoelastic effect).

In consideration of the geometric effect and photoelastic effect, the expression of the effective refractive index of FBG under AE wave is obtained:

$$\begin{aligned} n_{eff}'''(z', t) = & n_{eff0} - \Delta n \sin^2\left(\frac{\pi}{\Lambda_0} z\right) \\ & - \frac{n_{eff0}^3}{2} \cdot [P_{12} - \nu(P_{11} + P_{12})] \\ & \cdot A_{AE} e^{-(t-t_0)^2/a^2} \cos\left(\frac{2\pi}{\lambda_{AE}} z' - \omega_{AE} t\right), \end{aligned} \quad (2)$$

where $z' = z + \int_0^z \varepsilon(\xi) d\xi$, P_{11} and P_{12} are the photoelastic coefficients of FBG, and ν is Poisson's ratio [20].

Based on the mentioned theory above, the spectrum characteristics of FBG under AE waves are simulated and analyzed. When the wavelength of AE wave λ_{AE} is 100 nm, the length of grating L is 10 mm and the amplitudes of AE waves A_{AE} are 15 $\mu\epsilon$, 50 $\mu\epsilon$, 100 $\mu\epsilon$, 150 $\mu\epsilon$, and 300 $\mu\epsilon$, respectively. Relation between A_{AE} and reflectivity and wavelength of FBG is shown in Figure 1. The center of FBG shifts towards the longer wavelength as A_{AE} increases when λ_{AE} is greater than L . Results also show that there is a good linear relation between central wavelength and A_{AE} . The maximum reflectivity of the FBG reflection spectrum keeps invariant as the change of A_{AE} .

2.2. Complex Morlet Wavelet Transform. The collected AE waves often contain some mutation-shaped peaks or

nonstationary components. Morlet wavelet transform is employed to extract the narrowband signal of AE waves.

The continuous wavelet transform of AE wave $\varepsilon_{AE}(t)$ can be defined as

$$W_\varepsilon(\alpha, \tau) = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{+\infty} \varepsilon_{AE}(t) \overline{\phi}\left(\frac{t-\tau}{\alpha}\right) dt, \quad (3)$$

where $1/\sqrt{\alpha}\overline{\phi}(t-\tau/\alpha)$ is the complex conjugate of the scaled wavelets $1/\sqrt{\alpha}\phi(t-\tau/\alpha)$ obtained by zooming and panning the mother wavelet, α is the zoom factor, and τ is the shift factor.

The complex Morlet wavelet can be expressed as [21, 22]

$$\phi(t) = \frac{1}{\sqrt{\pi}f_b} e^{-(t^2/f_b)} e^{i2\pi f_c t}. \quad (4)$$

The Fourier transform of the above function is defined by

$$\varphi(\omega) = e^{-\pi^2 f_b (\omega - f_c)^2}, \quad (5)$$

where f_b and f_c are the bandwidth factor and center frequency of the complex Morlet wavelet, respectively. The wavelet is a complex exponential function with the shape of a Gaussian window. Hence, the narrowband signal with center frequency f_c can be extracted by Morlet wavelet transform. The bandwidth is limited in the range of $((\omega_c - \omega_b)/2, (\omega_c + \omega_b)/2)$. The complex Morlet wavelet filter can be constructed as

$$WT(f_b, f_c) = F^{-1}[E_{AE}(\omega)\overline{\varphi}(\omega)], \quad (6)$$

where F^{-1} denotes the inverse Fourier transform, $E_{AE}(\omega)$ and $\varphi(\omega)$ are the Fourier transform of $\varepsilon_{AE}(t)$ and $\phi(t)$, respectively.

When considering the propagation distance z , the AE wave $\varepsilon_{AE}(z, t)$ can be express as

$$\varepsilon_{AE}(z, t) = e^{-j(n_1 z - \omega_1 t)} + e^{-j(n_2 z - \omega_2 t)}, \quad (7)$$

where n_1 and n_2 are the wave numbers. Denote

$$\begin{aligned} \frac{n_1 + n_2}{2} &= n_0, \\ \frac{n_1 - n_2}{2} &= \Delta n, \\ \frac{\omega_1 + \omega_2}{2} &= \omega_0, \\ \frac{\omega_1 - \omega_2}{2} &= \Delta \omega, \end{aligned} \quad (8)$$

$$\overline{\varphi}(\alpha\omega) = \overline{\varphi}(\alpha\omega_1) = \overline{\varphi}(\alpha\omega_2).$$

The module value of AE wave is acquired by the complex Morlet wavelet transform

$$|WT(z, \alpha, \tau)| = \sqrt{2a}|\varphi(\alpha\omega_0)|\sqrt{1 + \cos(2\Delta n z - 2\Delta\omega\tau)}. \quad (9)$$

When $\tau = \Delta n z / \Delta\omega = z/V$, the module value is maximum, where V is the group velocity of AE wave. Therefore, the arrival time difference Δt can be obtained by finding the peak values of the module values:

$$\Delta t = \tau_1 - \tau_2. \quad (10)$$

According to the arrival time difference and the distance difference, the wave velocity v_{AE} can be calculated on the monitored material:

$$v_{AE} = \frac{\Delta z}{\Delta t}. \quad (11)$$

2.3. Barycentric Coordinate-Based Location Algorithm. In 1827, the barycentric coordinate was developed to characterize the relative position of a point with respect to other points [23–26]. In the plane, for a point k and other three points l , m , and n , the barycentric coordinate of point k with respect to points l , m , and n can be defined as $\{a_{kl}, a_{km}, \text{ and } a_{kn}\}$ that satisfies

$$p_k = a_{kl}p_l + a_{km}p_m + a_{kn}p_n, \quad (12)$$

where p_k, p_l, p_m , and p_n are the Euclidean coordinates of points k, l, m , and n , respectively.

Consider an AE event k occurs on the plate with three sensors l, m , and n nearby, the AE signal is detected by each of the sensors. Then, the absolute values of the barycentric coordinates a_{kl}, a_{km} , and a_{kn} can be computed as

$$\begin{aligned} |a_{kl}| &= \frac{|S_{\Delta kmn}|}{|S_{\Delta lmn}|}, \\ |a_{km}| &= \frac{|S_{\Delta knl}|}{|S_{\Delta lmn}|}, \\ |a_{kn}| &= \frac{|S_{\Delta klm}|}{|S_{\Delta lmn}|}, \end{aligned} \quad (13)$$

where $S_{\Delta kmn}, S_{\Delta knl}, S_{\Delta klm}$, and $S_{\Delta lmn}$ are the signed areas of the corresponding triangles $\Delta kmn, \Delta knl, \Delta klm$, and Δlmn . These areas can be solved according to

$$S_{\Delta kmn}^2 = -\frac{1}{16} \begin{vmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & d_{km}^2 & d_{kn}^2 \\ 1 & d_{mk}^2 & 0 & d_{mn}^2 \\ 1 & d_{nk}^2 & d_{nm}^2 & 0 \end{vmatrix}, \quad (14)$$

where d_{km}, d_{kn} , and d_{mn} are the distance measurements among the AE source k and sensors m and n , respectively.

In the plane, three adjacent sensors l , m , and n are not collinear to avoid the case that $S_{\Delta lmn} = 0$. Thus, it remains to determine the sign patterns of the barycentric coordinates for obtaining the barycentric coordinates. In addition, note that $a_{kl} + a_{km} + a_{kn} = 1$. Therefore, given $|a_{kl}|$, $|a_{km}|$, and $|a_{kn}|$, the problem of determining the sign of the barycentric coordinate is equated with solving the following equation:

$$\sigma_{kl}|a_{kl}| + \sigma_{km}|a_{km}| + \sigma_{kn}|a_{kn}| = 1, \quad (15)$$

where σ_{kl} , σ_{km} , and σ_{kn} take values of either 1 or -1 . The available information to determine the sign patterns should be limited to the pairwise distance measurements between the AE source k and sensors l , m , and n .

As shown in Figure 2, there are only 7 possible sign patterns (σ_{kl} , σ_{km} , and σ_{kn}) of the barycentric coordinates (as the pattern $(-1, -1, -1)$ is not a possible solution for (15)). Therefore, the plane can be divided into 7 zones: I $(1, 1, 1)$, II $(1, -1, -1)$, III $(1, 1, -1)$, IV $(-1, 1, -1)$, V $(-1, 1, 1)$, VI $(-1, -1, 1)$, and VII $(1, -1, 1)$. It turns out that sometimes the sign pattern can be uniquely determined from (15), but sometimes this cannot be done. When the sign pattern cannot be uniquely solved from (15), we consider two cases in the following.

In the first case, one of $|a_{kl}|$, $|a_{km}|$, and $|a_{kn}|$ equals to zero. That is, the AE source k lies on the line aligned with one of the three edges of the triangle formed by the three adjacent sensors, according to (13). Without loss of generality, say $a_{kl} = 0$. For this case, we can take

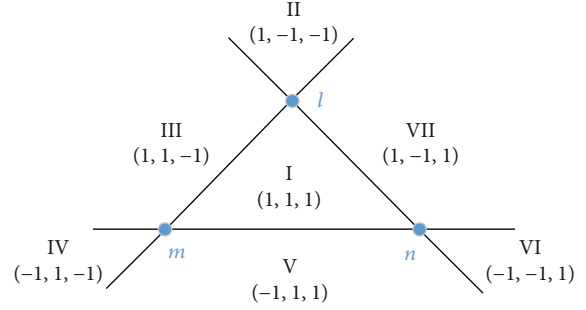


FIGURE 2: 7 sign patterns for $(\sigma_{kl}, \sigma_{km}, \text{ and } \sigma_{kn})$.

$\sigma_{kl} = 1$ (without loss of generality). Then, the other two signs σ_{km} and σ_{kn} can be determined according to the following criterion.

$$(\sigma_{kl}, \sigma_{km}, \sigma_{kn}) = \begin{cases} (1, 1, 1) & \text{if } |a_{km}|, |a_{kn}| \leq 1, \\ (1, 1, -1) & \text{if } |a_{km}| > 1, |a_{km}| > |a_{kn}|, \\ (1, -1, 1) & \text{if } |a_{kn}| > 1, |a_{kn}| > |a_{kl}|. \end{cases} \quad (16)$$

In the second case, one of $|a_{kl}|$, $|a_{km}|$, and $|a_{kn}|$, saying a_{kl} , satisfies $|a_{kl}| = 1$ and $|a_{km}| = |a_{kn}| \neq 0$. For this case, suppose $\angle lmn$ is an acute angle, the sign pattern $(\sigma_{kl}, \sigma_{km}, \text{ and } \sigma_{kn})$ can be determined according to the following criterion.

$$(\sigma_{kl}, \sigma_{km}, \sigma_{kn}) = \begin{cases} (-1, 1, 1) & \text{if } d_{mk} = d_{ln}, d_{nk} = d_{lm}, d_{lk}^2 = 2d_{lm}^2 + 2d_{ln}^2 - d_{mn}^2, \\ (1, 1, -1) & \text{if } d_{mk}^2 < d_{lm}^2 + d_{ln}^2, \\ (1, -1, 1) & \text{if } d_{mk}^2 > d_{lm}^2 + d_{ln}^2. \end{cases} \quad (17)$$

3. AE Source Location Experiments

In this work, all the experiments are performed on a 6061 aluminum alloy (Al-alloy) plate. The dimension of the Al-alloy plate is $500 \text{ mm} \times 500 \text{ mm} \times 2 \text{ mm}$. The diagram of the experimental setup is shown in Figure 3. The data sampling frequency is set at 2 MHz. Three FBGs are glued on the preselected points of the Al-alloy plate, whose coordinates are $A = 100 \text{ mm}, 200 \text{ mm}$; $B = 400 \text{ mm}, 200 \text{ mm}$; and $C = 250 \text{ mm}, 350 \text{ mm}$. A normalized pencil lead break source (HSU) is used as an AE source.

According to Section 2.3, the location method based on barycentric coordinates needs the distance measurements among AE source S , point A , point B , and point C . The AE source location geometry is shown in Figure 4. As the

distance measurements between three sensors (A , B , and C) are known before the experiment, there are three unknown distances, d_{SA} , d_{SB} , and d_{SC} .

Because of the isotropic characteristic of the Al-alloy plate, the AE wave travels at the same speed in all directions. As shown in Figure 4, AE wave velocity measurement is carried out at point P . Point P is laid on the line BC and the coordinate is $(200, 200)$. When there is an AE event happens at point P , the AE signals obtained by FBGs (B and C) are shown in Figure 5. The frequency responses of FBG signals are shown in Figure 6. It is known that the AE signal is a broadband signal with a range from 50 kHz to 300 kHz. The Morlet wavelet transform is utilized to extract a narrowband signal with central frequency of 100 kHz. As shown in Figure 7, the module

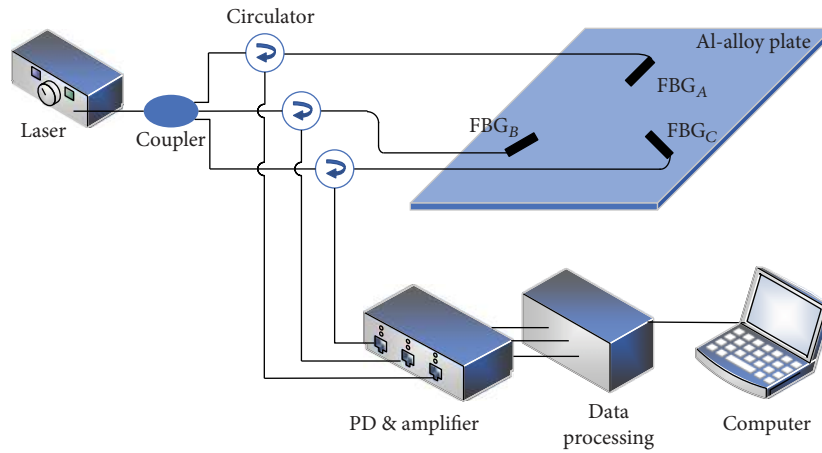


FIGURE 3: The schematic of the experimental setup.

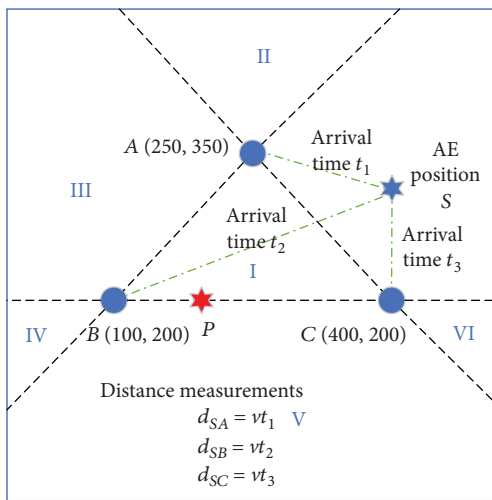


FIGURE 4: The AE source location geometry.

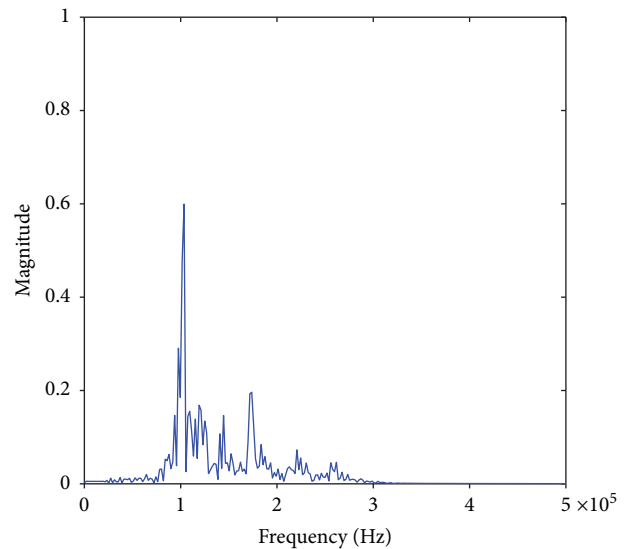


FIGURE 6: Frequency response of the detected signal.

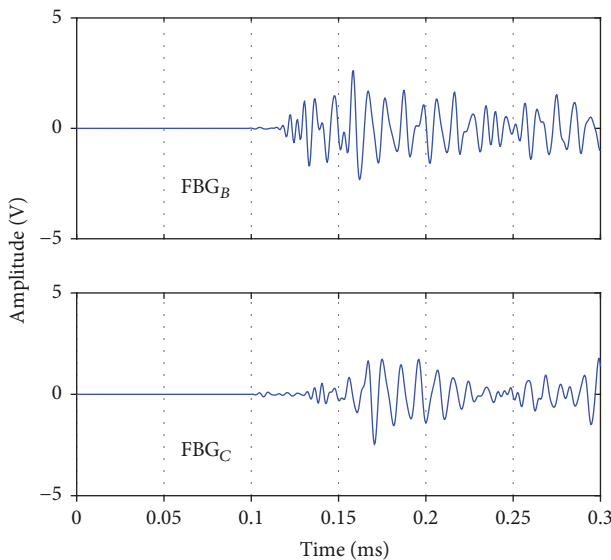


FIGURE 5: AE waves detected by FBG_B and FBG_C.

values of the extracted narrowband signals are obtained and the first peaks of the module values are used to compute the time difference Δt between FBGs (B and C). Depending on the time difference and the distance difference measured between PB and PC, the AE wave velocity v_{AE} can be obtained. In order to reduce the measurement error, the same experiment is repeated for 10 times and the results are shown in Figure 8. Based on the above method, the average wave velocity is 2454.1 m/s and the estimation error is less than 0.25%.

The threshold value method is an effective and simple technique to obtain the arrival times. At the beginning, according to the detected velocity v_{AE} and the arrival time of the AE wave from point P to point C, t_{PC} is calculated as $t_{PC} = d_{PC}/v_{AE}$. In Figure 7, the absolute module value corresponding to t_{PC} is set as the threshold value. In the next experiment, when the module value of the FBG signal is greater than the preset threshold value, this moment is the arrival time of the AE wave. Based on this process,

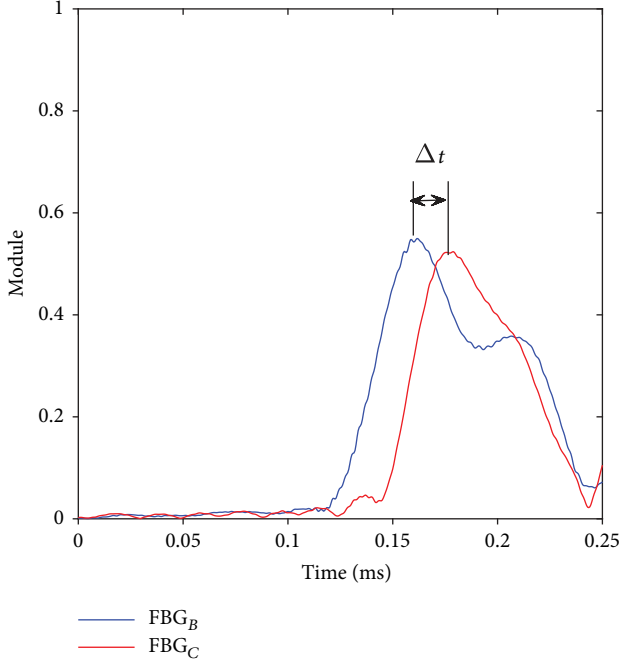


FIGURE 7: Module values of the extracted narrowband signals.

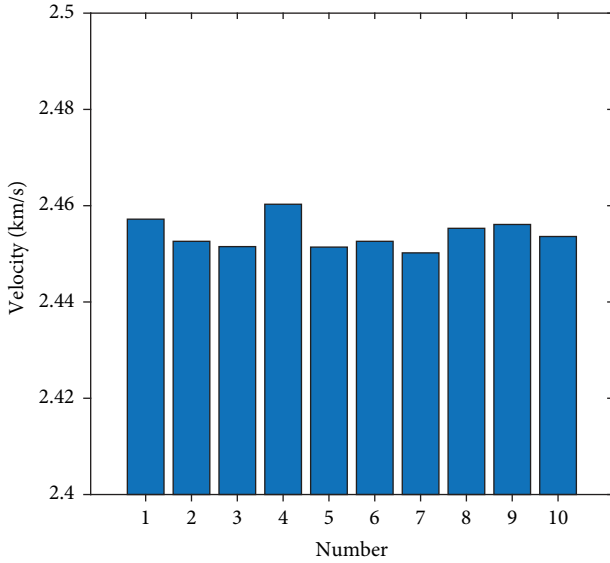


FIGURE 8: Measurement results of wave velocity.

arrival times (t_1 , t_2 , and t_3) of AE waves in Figure 4 can be computed.

4. Results

Impact is applied on the plate using a steel ball at randomly selected location of S (400 mm, 300 mm), as shown in Figure 4. The AE waves detected by FBGs are shown in Figure 9. After complex Morlet wavelet transform, the narrowband signals are illustrated in Figure 10. According to the narrowband signals, the arrival times of AE signals

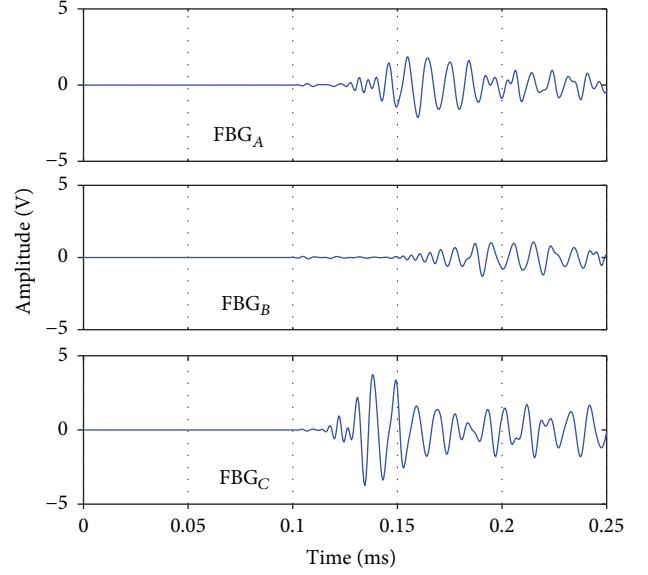


FIGURE 9: AE waves detected by FBGs.

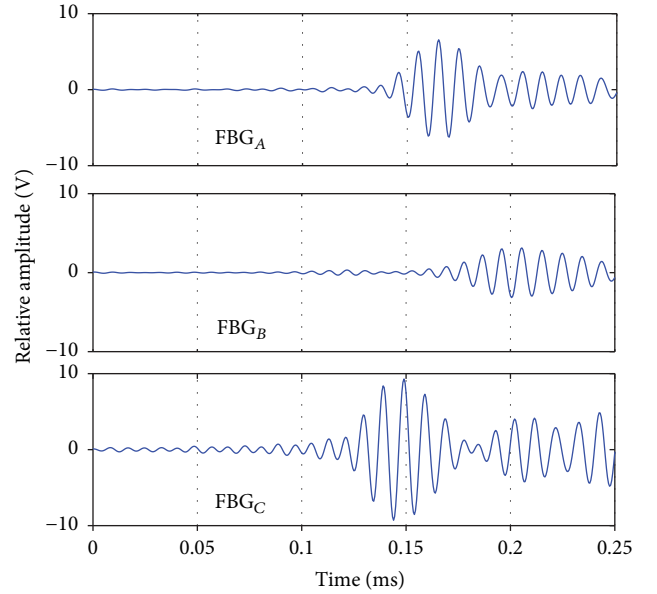


FIGURE 10: Narrowband signals extracted from the detected signals.

are computed. Based on the calculated velocity v_{AE} , the distance measurements among AE source S , point A , point B , and point C are $d_{AB} = 150\sqrt{2}$, $d_{AC} = 150\sqrt{2}$, $d_{BC} = 300$, $d_{AS} = 50\sqrt{10}$, $d_{BS} = 100\sqrt{10}$, and $d_{CS} = 100$, respectively. Then, absolute values of the barycentric coordinates $|a_{SA}|$, $|a_{SB}|$, and $|a_{SC}|$ are calculated. According to (15), (16), and (17), the sign patterns (σ_{SA} , σ_{SB} , and σ_{SC}) can be deduced as (1, -1, 1); therefore, the position of impact is correctly found at the zone VII. The Euclidean coordinate p_S of the AE source S is calculated.

In each zone, two positions are randomly selected to verify the results of the proposed location method. The location results are presented in Figure 11 and Table 1.

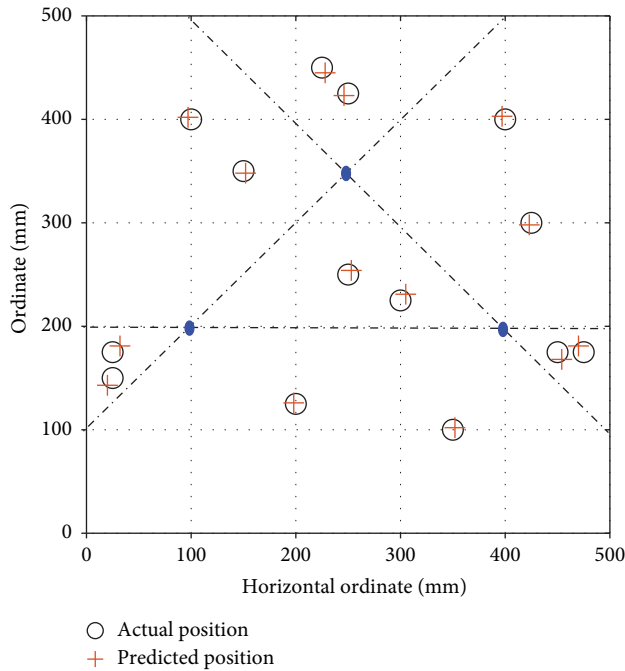


FIGURE 11: The localization results.

TABLE 1: Location results in 7 zones.

	Actual position (mm)	Predicted position (mm)
I	(250, 250)	(253, 254)
	(300, 225)	(305, 231)
II	(250, 425)	(246, 423)
	(225, 450)	(228, 445)
III	(150, 350)	(152, 348)
	(100, 400)	(97, 402)
IV	(25, 175)	(32, 181)
	(25, 150)	(20, 143)
V	(200, 125)	(198, 126)
	(350, 100)	(352, 102)
VI	(450, 175)	(454, 168)
	(475, 175)	(470, 181)
VII	(425, 300)	(423, 298)
	(400, 400)	(397, 403)

The results show that the average and maximum location errors that correspond to the horizontal direction are, respectively, 3.6 and 7 mm. The average and maximum location errors that correspond to the vertical direction are 3.9 and 7 mm, respectively. Also, mean square deviation is employed to calculate the AE source location error using the proposed localization method.

$$E = \sqrt{(x_p - x_a)^2 + (y_p - y_a)^2}, \quad (18)$$

where (x_p, y_p) is the Euclidean coordinate of the predicted AE source and (x_a, y_a) is the Euclidean coordinate of the

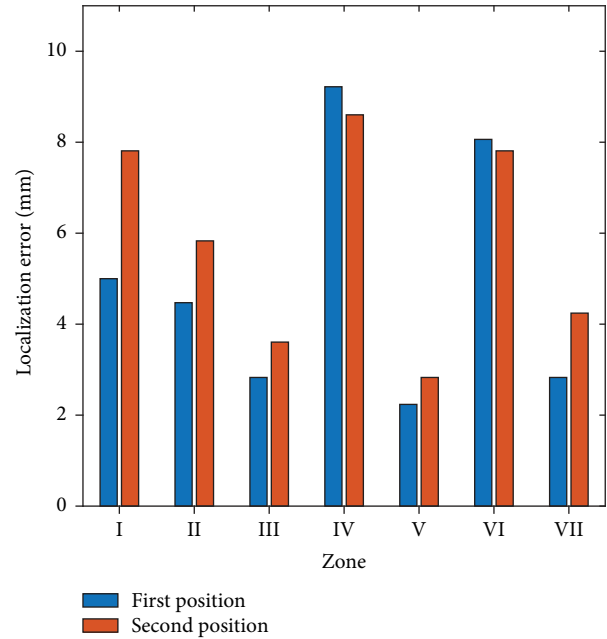


FIGURE 12: The AE source localization errors.

actual AE source. The location errors based on the proposed location method are indicated in Figure 12. The results show that the average and maximum location errors are 5.4 and 9.2 mm, respectively.

5. Conclusions

In this paper, we have introduced an easy realizable AE source localization method based on the AE waves obtained by FBG sensors. The edge filter method-based FBG interrogation system is used to satisfy the high-speed signal demodulation needs. To realize the barycentric coordinate-based location method, the Morlet wavelet transform is utilized for velocity and arrival time calculation. Then, the AE source location method based on barycentric coordinates is proposed. In the end, impact experiments with random selected positions are carried out for verification of the proposed location method. This research provides an easy and efficient method to safety monitoring of structures.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

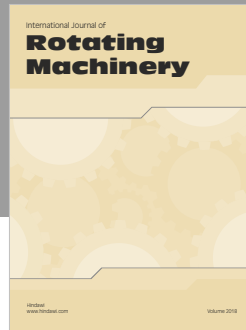
The authors declare that they have no conflicts of interest.

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