Optik 127 (2016) 493–498

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Multi-source acoustic emission localization technology research based on FBG sensing network and time reversal focusing imaging

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ARTICLE INFO

Article history:
Received 15 October 2014
Accepted 8 September 2015

Keywords:
Fiber Bragg grating (FBG)
Multi-source acoustic emission (AE) localization
Time reversal focusing
Shannon wavelet transform

ABSTRACT

A novel acoustic emission (AE) localization method and a detection system were proposed to complete multi-source AE localization based on time reversal focusing imaging and fiber Bragg grating sensors network. The principle of time reversal focusing was analyzed. Localization system was built with four FBG sensors. Signal demodulation was completed by narrow band laser edge filter technology. Shannon wavelet transform was used to extract specific frequency narrow band signal and calculate the modulus value. According to time reversal focusing model, multi-source AE imaging localization was implemented. The localization method and detection system were verified in 400 mm × 400 mm monitoring area which is on 6061 aluminum alloy plate. The experimental result indicates that this method and system can effectively realize localization and imaging, and the average error is 7.3 mm. The proposed detection system and localization method are provided for multi-source AE detection and localization with high accuracy.

1. Introduction

Acoustic emission (AE) detection is one of the important means of structure health monitoring. Compared with other non-destructive testing methods, the advantages of AE are real time, dynamics and wide coverage. To accurately localize and evaluate the damage in plate-like structures, there are four necessary steps for AE detection. Step 1: qualitative indication of the occurrence of damage. Step 2: quantitative assessment of the location of damage. Step 3: quantitative estimation of the severity of damage. Step 4: Prediction of structural safety [1]. It is absolutely clear that the AE source localization is the priority issue of AE detection.

Currently localization of AE source is normally performed by using the time difference of arrival (TDOA) technique and artificial intelligence technique. TDOA applies the propagation velocity in a material to derive the source location in one, two or three dimensions from the arrival delay between sensors based on first threshold crossing. Chen et al. [2] proposed the corresponding smooth pseudo Wigner–Ville distribution to improve the threshold-based arrival time difference estimation and the location accuracy of AE source. Dong et al. [3] proposed *P*-wave velocity by analytical solutions and arrival time to obtain AE source coordinates on granite rock. However, the methods are influenced by dispersion effect and signal attenuation. Their average errors are 12 mm and 14 mm, respectively. When more than one AE event occurs simultaneously, the arrival time information may be confusing. This issue is one key problem of TDOA [4]. To make the localization simple but effective, artificial intelligence technique is introduced. Cheng et al. [5] proposed Shuffled Frog Leaping Algorithm to Wavelet Neural Networks for acoustic emission source location. Yu et al. [6] implemented a novel approach to accurately localize AE source using multi-output support vector regression. The average errors of their results are 14 mm and 17 mm, respectively. However a large set of reference data is required in their experiments. The practicability of their methods is poor for multi-source AE localization. On the other hand, new AE sensors occur in technical field. Han and Liu et al. [7,8] used FBG and phase-shift FBG to detect AE signal, respectively. FBGs offer many advantages compared to electronic sensors. They are small, lightweight, durable, immune to electromagnetic interference. But few new FBG sensors are utilized to determinate AE source.

In this paper, we proposed time reversal focusing imaging method to completed multi-source AE localization. A detection network was built with FBG sensors. Narrow band laser edge filtering was used to realize signal demodulation. Specific frequency narrow band signal and modulus value were obtained by Shannon wavelet transform. According to time reversal focusing, localization was implemented by imaging searching method, and experimental result is excellent.

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http://dx.doi.org/10.1016/j.ijleo.2015.09.067
0030-4026/

2. Detection principles

2.1. Principle of FBG sensor and demodulation

When a fiber grating is irradiated with a beam of light, the grating will reflect a narrow band light with unique center wavelength, which is defined by Bragg condition. The center reflection wavelength of the grating is determined by:

$$\lambda_{B0} = 2n_{\text{eff0}}\Lambda_0 \tag{1}$$

where λ_{B0} is the reflection wavelength of FBG. n_{eff0} is the average refractive index of optic fiber and Λ_0 is the Bragg grating period [9,10]. The reflection wavelength of FBG shifts in response to the fiber refractive index (n_{eff0}) and the grating period (Λ_0), which vary with the changes in strain. Therefore, the reflection wavelength shift can be expressed as:

$$\Delta\lambda = \lambda_{B0}\varepsilon_m\left\{1-\left(\frac{n_{\text{eff0}}^2}{2}\right)[P_{12}-\nu(P_{11}+P_{12})]\right\} \tag{2}$$

where ε_m is the applied strain. P_{ij} is Pockel's (piezo) coefficients of stress-optic tensor. ν is Poisson's ratio [11].

AE event causes elastic waves to propagate through the structure. According to Eq. (2), the reflection wavelength of FBG will shift when the high frequency dynamic strain act on FBG. We can realize the AE signal detection through identifying the reflection wavelength shift of FBG.

In order to acquiring AE signal, the method of tunable narrow band laser filtering is used. The principle is illustrated by Fig. 1. The output light intensity is overlapping region of laser spectrum and FBG reflection spectrum. Hence the output light intensity will change when the reflection wavelength of FBG shifts. AE signal is obtained by detecting the change of output light intensity.

2.2. Time reversal focusing principle

AE localization algorithm is based on the principle of time reversal focusing. AE response signals of all sensors are treated with time reversal method, and then are re-emitted back to AE source along the opposite direction of their propagation from AE source to sensors by theoretical reasoning. When all signals are superimposed in AE source point, a maximal peak is obtained. Time reversal focusing is illustrated in Fig. 2. There are n sensors on slab structure. $H_{\text{AE}i}$ and $H_{\text{AE}ii}$ represent the transfer function spectrums of AE signals propagating from AE source to sensor i and from sensor i to AE source. $H_{\text{NAE}i}$ is the transfer function spectrum of AE signal propagating

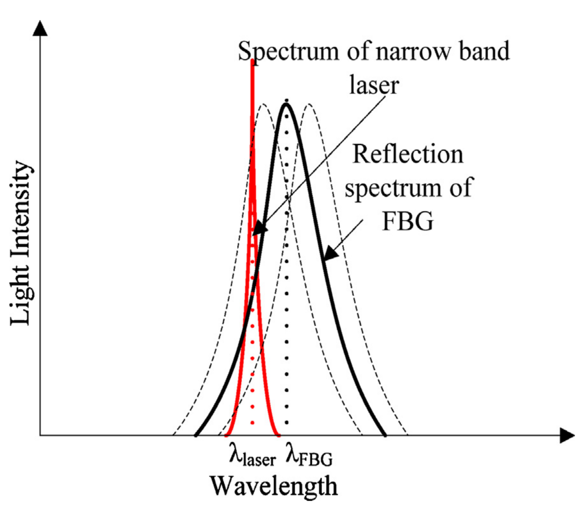

Fig. 1. The principle of tunable narrow band laser filtering.

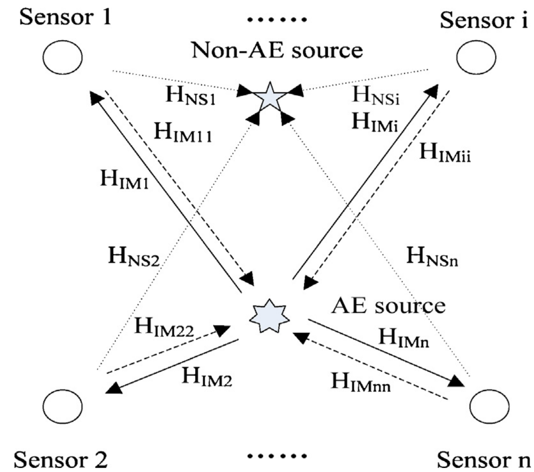

Fig. 2. Illustration of time reversal focusing process.

from sensor i to non-AE source. The response signal spectrum of sensor i can be represented as:

$$E_i = H_{\text{AE}i}E_{\text{AE}} \tag{3}$$

where E_{AE} is AE signal spectrum. Time reversal of response signal of sensor i can be expressed as complex conjugate of E_i. According to the spatial reciprocity of linear wave equation, there is $H_{\text{AE}i} = H_{\text{AE}ii}$. With response signals of all sensors time reversal focusing equation can be expressed as:

$$E_{\text{AEF}} = \sum_{i=1}^{n} H_{\text{AE}ii}E_i^* = \sum_{i=1}^{n} H_{\text{AE}i}H_{\text{AE}i}^*E_{\text{AE}}^* \tag{4}$$

where $H_{\text{AE}i}H_{\text{AE}i}^*$ is real positive even function [12]. The Fourier inverse transform of Eq. (4) is the synthetic superposition of time reversal signals in AE source. The correlation peak will be obtained. Time reversal focusing of AE signals is implemented in AE source. The signal equation [13] in non-AE source is:

$$E_{\text{NAE}} = \sum_{i=1}^{n} H_{\text{NAE}i}E_i^* = \sum_{i=1}^{n} H_{\text{NAE}}H_{\text{AE}i}^*E_{\text{AE}}^* \tag{5}$$

According to Eq. (5), signals can not focus in non-AE source.

According to Eq. (4), the key of time reversal focusing is the transfer functions of response signals. In general, pencil lead break is used to simulate AE event. In slab structure pencil lead break signal is dominated by A_0 mode. Transfer function spectrum can be expressed as:

$$H(r,\omega) \approx \pi A(\omega)e^{-jk_{A0}r} \tag{6}$$

where $A(\omega)$ is amplitude item. $k_{A0} = \omega/\nu$ is wave number. ν is wave velocity, and r is propagation distance. Whether or not signals can focus in AE source, phase item play a pivotal role in time reversal focusing process. Thus, Amplitude item can be ignored. Only phase item is retained in transfer function spectrum. The essence of phase item is time delay in time domain. Hence time reversal focusing is that AE response signals of all sensors are treated by time reversal, time delay and superposition. According to Eqs. (4) and (6), time domain equation of time reversal focusing module value is:

$$|e_s(t)| = \left|\sum_{i=1}^{n} e_i\left(\frac{\tau - t + d_i}{\nu}\right)\right| \tag{7}$$

where $e_i(t)$ is AE narrow band response signal. τ is the time length. d_i is the distance from AE source to sensor i. ν is the group velocity [13]. The tendency of signal can be reflected by modulus value.