Ultrasonics 54 (2014) 737–745

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

A novel acoustic emission beamforming method with two uniform linear arrays on plate-like structures

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ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form 9 September 2013
Accepted 20 September 2013
Available online 2 October 2013

Keywords:
Localization
Acoustic emission
Beamforming
Uniform linear array
Finite element

ABSTRACT

A novel acoustic emission (AE) source localization approach based on beamforming with two uniform linear arrays is proposed, which can localize acoustic sources without accurate velocity, and is particularly suited for plate-like structures. Two uniform line arrays are distributed in the *x*-axis direction and *y*-axis direction. The accurate *x* and *y* coordinates of AE source are determined by the two arrays respectively. To verify the location accuracy and effectiveness of the proposed approach, the simulation of AE wave propagation in a steel plate based on the finite element method and the pencil-lead-broken experiment are conducted, and the AE signals obtained from the simulations and experiments are analyzed using the proposed method. Moreover, to study the ability of the proposed method more comprehensive, a plate of carbon fiber reinforced plastics is taken for the pencil-lead-broken test, and the AE source localization is also realized. The results indicate that the two uniform linear arrays can localize different sources accurately in two directions even though the localizing velocity is deviated from the real velocity, which demonstrates the effectiveness of the proposed method in AE source localization for plate-like structures.

1. Introduction

Acoustic emission (AE) is defined as the class of phenomena where by transient elastic wave is generated by the rapid release of energy from a localized source of damage [1]. Various types of AE sources, such as fiber breakage [2], fatigue cracks [3], rubbing [4], and impact of foreign objects [5] can generate the propagation of AE waves. Since most of the damage information of structures is contained in AE signal, AE technique (AET) is probably the most sensitive non-destructive technique [6]. Compared with other non-destructive testing (NDT) techniques, AET is distinctive in testing because AET can simply detect the energy released by an object rather than supply energy to the object under examination. Moreover, AET can directly detect damage/crack extension and it is used to deal with dynamic processes in structures [7]. Due to its potential advantages in damage monitoring and source localization, AET has been used in a variety of fields such as material [8] and manufacturing processes [9], especially in plate-like structures which are commonly used in civil, aerospace and other applications.

To accurately localize and evaluate the damage in plate-like structures, four necessary steps are needed with increasing levels of difficulty for AET. Step 1: qualitative indication of the occurrence of damage. Step 2: quantitative assessment of the position of damage. Step 3: quantitative estimation of the severity of damage. Step 4: prediction of structural safety, e.g. residual service life [10]. Therefore, it is absolutely clear that the AE source localization is one of the most important pieces of information to be gained from the AET. The ability to localize the AE source is a step in whole damage identification process, by which the accurate source location can indicate information about the characteristic of the damage and even the size of the crack with relatively few sensors on large and complex structures.

Currently localization of AE sources is normally performed by using the time difference of arrival (TDOA) technique which 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. Arrival time information is a most important parameter as this arrival is predominantly used for source location of TDOA [11]. However, when the AE wave propagates in the solid medium, the signals may be significantly affected by multi-mode, dispersion, energy attenuation and other factors [12], which make it difficult to accurately determine the arrival time. When structures and materials are complex, it is common to be accompanied with large errors. In order to solve this problem, some techniques to improve the accuracy of arrival time are introduced. To decrease the influence of multi-mode and dispersion on plate wave propagation, Gorman [13] introduced plate wave theory to determine the orientation of

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0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.09.020

a source mechanism based on the amplitudes of the different wave modes. It indicates that the wave theory can be used to improve source location. A probabilistic approach was developed by Niri and Salamone [14] to decrease the uncertainties in the wave velocity and the time of flight measurements. Ahadi and Bakhtiar [15] conducted the localization of continuous AE sources by using an intelligent locator since time delays cannot be simply estimated. But lots of repeated training must be carried out before localization by intelligent locator. Besides, when there is more than one AE source, the arrival time information may be confusing. This issue is also one key problem of TDOA. To make the localization simple but effective, McLaskey et al. [16] introduced the AE beamforming method to localize AE source in civil structure, and it was improved by He et al. [17] to plate-like structure, and used by Nakatani et al. [18,19] to study AE source localization on an anisotropic structure. Although beamforming has been successfully used in damage localization by many scholars, a difficulty is involved that this technique assumes constant wave speed in all propagation directions and it is a velocity dependent method in direction normal to the array [16]. The propagation velocity of AE wave is not constant due to the multi-mode and dispersion in the solid structure. It is not only changed with propagating directions in anisotropic structure [20], but also affected by the wave modes and frequencies of AE signal in isotropic structure [16,21]. Therefore, the localization accuracy of beamforming will be significantly influenced by the propagation characteristics. In order to reduce the effect of those factors on AE beamforming, He et al. [22] revealed the mechanism of AE propagation characteristics on the localization accuracy of beamforming. Their results showed that the beamforming is not sensitive to the velocity along the array direction, but it changes significantly in the direction normal to the array. Then an approach for accurate localization velocity was presented by combined with plate wave theory and wavelet packet transform. However, in these studies, the beamforming method is dependent on the accurate localization velocity.

This paper aims to propose a novel AE source localization approach based on beamforming for plate-like structures when accurate velocity is unavailable. The novel AE beamforming localization method is established by arranging two uniform linear arrays. In order to verify this proposed method, the AE signals obtained from both finite element (FE) simulation and pencil-lead-broken (PLB) test are analyzed for the source localization. Moreover, a plate of carbon fiber reinforced plastics (CFRP-plate) is taken as the PLB medium. Also, the obtained AE signals are used to test the function of the localization method. The AE source localization results indicate that this method is effective to localize the AE source for plate-like structures.

2. Principles

In typical beamforming method, the detailed information of the sound source, especially the source localization is obtained through a set of microphone array distributed in fixed positions. Delay-and-sum is the most widely used one among various beamforming algorithms, which is simple but very effective [23].

The basic principle of near-field beamforming based on the delay-and-sum algorithm is illustrated in Fig. 1. When the array is focused on a point source at limited distance, the array output of incident waves in an isotropic plate is expressed by [17]

$$b(\vec{r},t)=\frac{1}{M}\sum_{m=1}^{M}w_m x_m(t-\Delta_m(\vec{r})) \quad (1)$$

where M is the index of sensors, w_m the weighting coefficient for the channel of sensor m and $x_m(t)$ the measured signal of sensor m. $\Delta_m(\vec{r})$ indicates the individual time delay of sensor m to the reference point. By adjusting time delay $\Delta_m(\vec{r})$, the signals associated with the spherical waves, emitting from sound source focus, will be aligned in time before they are summed. If the focused point is the real source, the signals are aligned at the same wave front and the energy output of the sensor array is maximum. However, the signals cannot be aligned at the same wave front when the sensor array is focused on other positions, and the energy output is not the maximum.

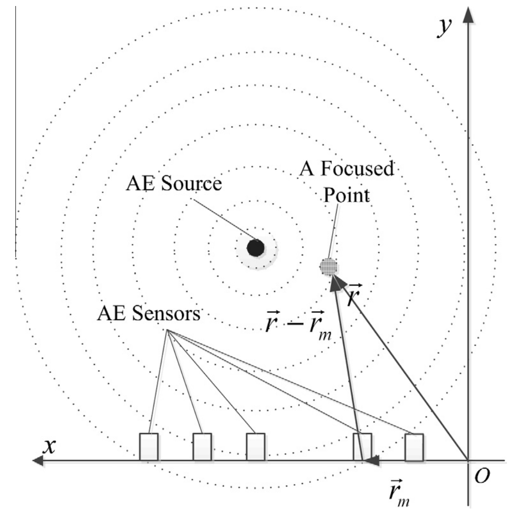

Fig. 1. Illustration of delay-and-sum beamforming.

As shown in Fig. 1, $\Delta_m(\vec{r})$ can be obtained by

$$\Delta_m(\vec{r})=\frac{|\vec{r}|-|\vec{r}-\vec{r}_m|}{c} \quad (2)$$

where $\vec{r}$ represents the distance of the reference to the focus point, $\vec{r}_m$ the distance between reference point and sensor m, and c the propagation velocity of sound.

The literature [19] indicates that the resolution is high in the direction along the array, but it is low in y-axis direction. Moreover, the beamforming is not sensitive to the velocity in the direction along the sensor array while it is velocity-dependent in the direction normal to the sensor array no matter the S_0 wave or A_0 wave is used. Although the sensitivity of beamforming to the localization velocity error was discussed in references [17,22], the emphasis of these two papers is to obtain high localization accuracy by improving accuracy of the localization velocity used in AE beamforming.

3. The presented beamforming method with two uniform linear arrays

The proposed technique aims at localizing AE source by arranging two uniform linear arrays, regardless of the accurate velocity. Refer to [22], the localization accuracy of beamforming method is not sensitive to the velocity along the array direction (x-direction), while it changes significantly in the y-direction at various velocities. Although this is a drawback of beamforming, the localization accuracy is robust along the array direction and it is velocity-independent. Therefore, if two uniform linear arrays are distributed in the x-axis direction and y-axis direction respectively, the accurate coordinates of AE source can be well determined, whereby the x and y coordinate values are calculated by the sensor array along x direction and y direction respectively. Thus, even if the measured velocity has a large error, the accurate AE source location can be obtained.