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AE beamforming method for damage inspection of aircraft structures

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Abstract

A near-field acoustic emission (AE) beamforming method is introduced to localize the AE source arisen from damage of aircraft structures. A series of pencil lead break tests at various regions of a thin steel plate are conducted to validate the effectiveness of the AE beamforming method. The results show that the proposed beamforming method is able to efficiently localize AE sources. It is demonstrated that AE beamforming method is a useful tool to detect the position of damage of aircraft plate structures.

Keywords: Location; Acoustic emission; Beamforming; Structure damage

1. Introduction

The aim of present design for an aircraft is that it may serve for at least 20 to 25 years and up to 90000 flights. To reach this target, the structure of an aircraft must be superior in durability, damage tolerance capability and corrosion resistance. In addition, it is essential to apply one or more approaches to monitor the damage of the aircraft structure in inspection process, as it is required by the enhanced airworthiness regulations. The non-destructive testing (NDT) technology is an effective tool to detect the damage of an aircraft structure through all phases of its life cycle. It is used to monitor the quality of aircraft structures at all stages, such as design and development, structural testing, manufacturing quality control, in-service monitoring, repairs and inspections [1]. To be in compliance with the requirements of aircraft airworthiness, the NDT technology are developed [2].

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In general, conventional NDI/NDT technologies include Visual Inspections, X-Ray, Ultrasonic Testing (UT), Eddy Current Testing (ET) and Resonance frequency analysis, etc. Nowadays, some methods are proposed, developed and even used in practical applications, for example, the Acoustic Emission (AE) method. AE refers to the generation of transient elastic waves during the rapid release of energy from localized sources within a material [3]. It is a passive dynamic method capable of continuously testing and in situ monitoring structures under supervision without the need of their stoppage/shutdown or injecting signals from outside to the object. Due to its potential advantages in kinematic damage monitoring and source localization, AE technique has led to applications in aerospace industry. The studies of AE applications to inspect structures have been implementing since 1980s. M. N. Bassim [4] used AE for continuous surveillance of aircraft structures. C. M. Scala et al [5] had developed AE for structural integrity monitoring of aircraft. Since Modal acoustic emission (MAE) approach was developed by M. R. Gorman for signal processing of AE [6]， the combination of AE parameter and waveform analysis based on MAE has advanced the AE applications in aircraft structures. For example, R. Geng [7] studied the roles of MAE in monitoring the conditions of aircraft structures during a fatigue test and in the evaluation of environment-related corrosion, his research results show AE is a promising method in new aviation material studies like health monitoring of aircraft structures.

Source location of structural damage is one of the most important pieces of information applications of AE techniques to be gained from AE techniques. Time difference of arrival (TDOA) is a conventional AE method validated its utilization in laboratory settings and has become the most popular tool to estimate AE source location to date [8]. But previous studies have indicated the accuracy of TDOA is influenced by some factors like noise, frequency dispersion and energy attenuation during propagation process of waves [9]. To offer an effective and economically feasible solution, McLaskey et al. [10] proposed an AE beamforming method particularly suited for civil engineering field applications on large plate-like reinforced concrete structures. This AE beamforming technique is more suitable for non-destructive evaluation of large structures than conventional methods because it reduces the need for large amount of sensors distributed in the structures, high sampling rates and precise time synchronization between spatially distant sensors. However, the specimens estimated in their work are large reinforced concrete structures in civil engineering while the structures generally seen in aviation fields are thin plates and shells. They have different material/structure characteristics and propagation modes of AE signals. In addition, the AE sources generated from damage of plate structures are generally considered as point AE sources. These facts consequently limit the application of far-field AE beamforming method for analysis of aviatic structural parts.

This paper attempts to explore the possibility of acoustic emission source localization in thin plates by using near-field AE beamforming techniques. To validate the effectiveness of this method, a series of tests are conducted. The results show that the AE beamforming method is a promising tool to evaluate the location of damage of plate structures.

2. Delay-and-sum beamforming

Acoustic beamforming is a technique to locate sound sources by processing the measured signals coming from microphones arrays [11]. Among all the beamforming techniques, the delay-and-sum beamforming is simple but powerful array signal processing algorithm. The idea of this processing algorithm is to apply the proper delay to each transducer, such that the overall system has a maximum respond at a certain direction of arrival (DOA) [12]. The main object of this paper is to employ the acoustic beamforming technique to locate acoustic emission source.

Considering a group of M sensors arranged in a uniform linear array, of which the distance between AE source and array of sensors is shown in Fig. 1. A common rule of thumb is that the near-field sources are located at a distance of $r < 2L^2/\lambda$:

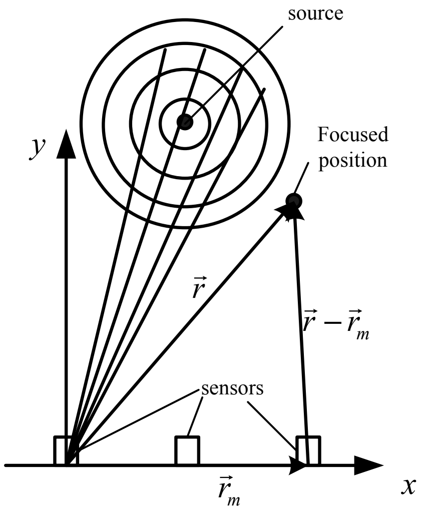

Fig. 1 Schematic diagram of focused beamforming

where r is the radial distance from an arbitrary array origin, L is the largest array dimension of the array and λ is the operating wavelength. The wavefront received from the sound source, in such conditions, is assumed spherical due to the transmission characteristics of waves. The far-field sources refer to those located at the distance r is larger than $2L^2/\lambda$ and their wavefront is assumed planar. Present study aims at the estimation analysis of source location in the near-field.

Theoretically, near-field beamforming method based estimation can determine the spatial location of sound source in three dimensional near-field. Fig. 1 illustrates that the incident waves are spherical when the array of sensors focuses on a source. Herein, the array output of spherical waves can be expressed by

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

where M is the number of the sensors and w_m the weighting coefficient applied to the channel of sensor m. The variable $x_m(t)$ represents the signal acquired from the No.m sensor and $\Delta_m(\vec{r})$ indicates the individual time delay of the No.m sensor 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. However, the signals cannot be aligned at the same wavefront when the array of sensors is focused on other positions. Fig. 1 shows the following relation

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

where $\vec{r}$ and $\vec{r}_m$ represent the distances of reference point to focus and the No. m sensor respectively. And c is the propagation speed of the sound wave.

3. Experimental Validation

A series of tests are conducted to validate the effectiveness of the estimation method. Many acoustic emission signals generated from structural damage are burst AE signals. Such signals are simulated by the signals emitted from the broken lead cord inclined to the surface of detected structure in pencil lead break tests. Signals are recorded by full-waveform acoustic emission apparatus. The sampling frequency in tests is 3 MHz. The steel plate specimen has the dimensions of 1000 mm length, 800 mm width and 5 mm height. And the array of sensors is arranged in a uniform linear array with an interelement spacing of 30mm as shown in Fig. 2.

The propagation speed of the AE signals recorded by TDOA method is 5400m/s in tests. Fig. 2 shows the locations of 10 AE sources which are simulated by breaking pencil lead in a two dimensional coordinate system. The coordinates of AE sources are respectively marked #1 (-90mm，600mm), #2 (0mm，600mm), #3 (60mm，600mm), #4 (90mm，600mm) #5 (180mm，600mm), #6 (-90mm，300mm), #7 (0mm，300mm), #8 (60mm，300mm), #9 (90mm，300mm), #10 (180mm，300mm) in tests. The results presented in Fig. 3 are given to indicate the power of the beamforming obtained from #1 source (-90mm，600mm). Fig. 3 shows that the accuracy in *x* direction is higher than the one in y direction. The identified AE source is locating by the position where the power value of beamforming is highest.

The location results of all the sources are shown in table 1. The AE source positions obtained by proposed beamforming method are compared with the experimental results. It is found the positions in *x* direction are precise according to real sources positions while the positions in *y* direction have deviations. This phenomenon is due to the influence of beamforming algorism based on linear array.

When the sources are aligned parallel to axis x, it is found that the locations of identified sources near to the center of the array are not as precise as those far from the center. In authors' viewpoint, this phenomenon is due to the frequency dispersions. In lamb wave theory, frequency dispersions are defined that the wave propagation manners under different frequencies are different, whereas the wave number and phase rate are the same. Since the propagation speeds of AE signals acquired at various positions are different, it is obvious that the identified locations of signals achieved by same speeds are deviated from their real locations.

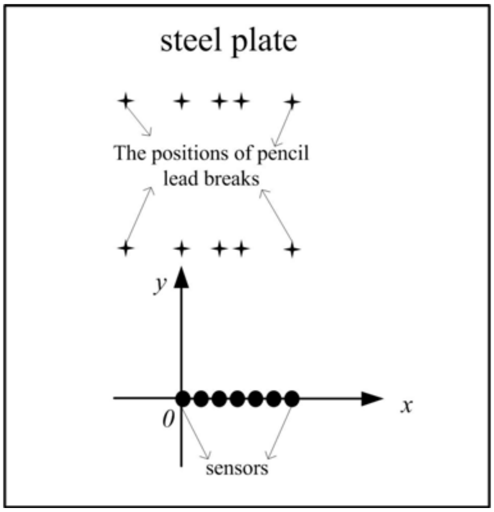

Fig. 2 Schematic diagram of focused beamforming

Results of table 1 show the source location identified by this beamforming based estimation method is accurate in the direction parallel to the array of sensors, whereas its accuracy in the direction normal to this array is slightly decreased. Hence the array of sensors may be intentionally arranged depending on various purposes. For example, in order to improve the accuracy of a cyclic AE source location, two individual tests, in which the arrays of sensors are placed at perpendicular directions separately, can be performed.

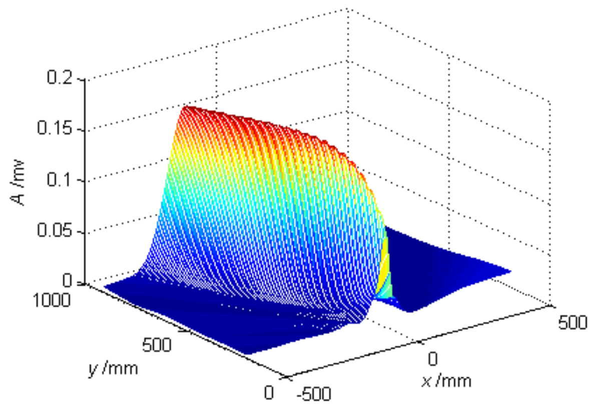

Fig. 3 The power of beamforming from source (-90mm, 600mm)

Table 1. Comparison between real and identified sources of AE signals

Sources		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Real positions (mm)	*x*	-90	0	60	90	180	-90	0	60	90	180
	y	600	600	600	600	600	300	300	300	300	300
Identified positions (mm)	*x*	-90	0	60	100	180	-90	0	60	90	180
	y	571	578	620	634	620	298	291	284	305	347

4. Summary and conclusions

This paper introduces a feasible near-field beamforming method into acoustic emission source location of thin plate, which is a typical aircraft structure. The superiority of this approach to conventional methods, such as TDOA method, is in ease of design implementation and reduction of cost. A series of pencil lead break tests at various regions of a thin steel plate are conducted to analyze the accuracy of this estimation method for AE source localization. Instead of using a distributed array of sensors in conventional methods, the AE beamforming approach utilizes a small number of sensors closely placed at local region of the plate. This is an easily implemented way to localize the AE source.

By comparing the positions of the identified sources and those of real sources, it is concluded that the proposed beamforming method can localize AE sources and it is an effective tool for damage inspection of aircraft structures. It is found in tests that the accuracy of beamforming based analysis relies on the spatial layout of the array in the tested structure. For example, in the case array of sensors is linearly aligned, the accuracy of AE source locations in direction parallel to the array is higher than that in the normal direction.

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