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Acoustic emission source location in plates using wavelet analysis and cross time frequency spectrum

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ABSTRACT

In this study, the theories of wavelet transform and cross-time frequency spectrum (CTFS) are used to locate AE source with frequency-varying wave velocity in plate-type structures. A rectangular array of four sensors is installed on the plate. When an impact is generated by an artificial AE source such as Hsu–Nielsen method of pencil lead breaking (PLB) at any position of the plate, the AE signals will be detected by four sensors at different times. By wavelet packet decomposition, a packet of signals with frequency range of 0.125–0.25 MHz is selected. The CTFS is calculated by the short-time Fourier transform of the cross-correlation between considered packets captured by AE sensors. The time delay is calculated when the CTFS reaches the maximum value and the corresponding frequency is extracted per this maximum value. The resulting frequency is used to calculate the group velocity of wave velocity in combination with dispersive curve. The resulted locating error shows the high precision of proposed algorithm.

1. Introduction

The acoustic emission technique (AE) has for many years been considered as the prime candidate for structural health and damage monitoring in loaded structures such as liquid petroleum, gas tanks, fire extinguishers, oxygen gas tank, and etc. Source location has always been regarded as one of the main advantages of AE testing [1]. When a material structure is distorted or damaged by an internal or external force or micro structural changes occurred in the particle, it will release elastic waves propagated through the material. Crack growth, friction and corrosion are some micro structural changes mentioned above. Different approaches have been developed to locate AE sources. The traditional method for this procedure is determining arrival times using threshold, which means the time when a signal crosses the threshold for the first time. Ziola et al. [2] discussed about substantial errors of source localization results by this procedure. More accurate methods have also been used to consider actual time of arrival at the different sensors. A hyperbola obtained using different arrival times and wave velocity, represents possible locations of the source for each pair of sensors. Tobias [3] derived an exact solution for the configuration of three sensors in a plate. The location of the source on the plate is determined at the intersection points of two hyperbolas. Scholey et al. [4] published a method where a map was generated on the plate with arrival time differences for each pair of sensors. The time difference (Δt) was calculated using sensor distances and wave velocity dependency on the fiber orientation. This technique is named as “best match point search method”. Necessity to a large number of training points is an important disadvantage of this method. Elastic waves based on their mechanical behavior can propagate through the materials at different modes named as extensional and flexural. The separation of these modes could make it possible to elicit exact information about the source of elastic waves. This is an appropriate technique for source locating using one sensor [1]. Ding et al. [5] developed a new waveform analysis to estimate AE wave arrival times using wavelet transform. Variety of techniques were compared in proposed method such as threshold crossing, cross correlation and wavelet packet transform and a method based on wavelet decomposition is recommended as the most consistent and accurate method for determining arrival time. Davoodi et al. [6] proposed an algorithm based on wavelet transform, filtering and cross correlation techniques for leak locating in pressurized gas pipe and error percent of less than 5% was resulted in leak locating. Masoumi et al. [7] used two approaches to identify damage in plate-type structures. The first one was to form uniform load surface by using mode shapes of damaged structure and then using 2-D wavelet transform for detecting damage. The second one was based on forming generalized flexibility matrix using mode shapes of damaged structure and then 2-D wavelet transform was applied. Yang et al. [8]

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proposed a method for impact source localization in a plate based on the multiple signal classification (MUSIC) and wavelet analysis. The direction of arrival of the wave estimated using MUSIC method and the time delay was estimated using the continuous wavelet transform. They used a constant group velocity for their experiments. Sedlak et al. [9] compared the first-arrival determination results for thin plate obtained from two-step AIC picker with Kurz's method, STA/LTA method and standard threshold crossing technique. Jeong et al. [10] applied the WT to fracture source location using the dispersive waves in isotropic plates.

In this study a reliable and precise algorithm to detect and locate AE source in plate-type structures is proposed. A combination of wavelet packet decomposition and cross time frequency spectrum with frequency-varying wave velocity is used in this algorithm to calculate the time delay and location of AE source. By wavelet decomposition, a specified range of frequency is considered and by taking short time Fourier transform of cross correlation for selected frequency ranges the CTFS, time delay and corresponding frequency-dependent wave velocity are obtained. The experiments are carried out for verification of mentioned algorithm.

2. Acoustic emission source location principle

2.1. Wavelet transform

The wavelet packet method is a generalization of wavelet decomposition that offers a richer range of possibilities for signal processing. In wavelet analysis, a signal is split into an approximation and detail. The approximation is then itself split into a second level approximation and detail. So for n-level decomposition there are $n+1$ possible ways to decompose the signal. In the wavelet packet analysis the details can also be split as well as the approximations. This yields 2^n different ways to encode the signal. Continuous wavelet transform (WT) of function $f(t)$ is represented as:

$$WT_f(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)dt \tag{1}$$

where $a, b \in R$ and $a > 0$ they are shifting and scaling parameters., respectively. The superscript $(*)$ denotes a complex conjugation. The analysis function for the WT can be defined as:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \tag{2}$$

where ψ is a fixed function, called the mother wavelet, that is localized in both time and frequency. The function $\psi_{a,b}(t)$ is obtained by applying the shifting operation (b-translation) in the time domain and scaling in the frequency domain (a-dilation) to the mother wavelet [8]. We can reconstruct the first signal aging by the following equation:

$$f(t) = \frac{1}{C_\psi^2}\int_a\int_b \psi_x^\psi(a,b)\psi\left(\frac{t-a}{b}\right)dbda \tag{3}$$

which C_ψ is a constant value and depends on used wavelet. Reversibility of transform and ability to complete reconstruction depends on this constant value. It is generally called admissibility constant and it is as follow [6]:

$$C_\psi = \left(2\pi\int_{-\infty}^{\infty}\frac{\left|\hat{\psi}(\xi)\right|^2}{|\xi|}d\xi\right)^{1/2} < \infty \tag{4}$$

which $\hat{\psi}$ shows Fourier transform of ψ.

2.2. Cross-time–frequency spectrum principle

For elastic wave propagation in plate, with the increase of propagation distance, the energy and the amplitude of vibration reduce gradually. It is the attenuation phenomenon and main contains dispersion, scattering and absorption [11]. The acoustic signals caused by artificial defect (Hsu–Nielsen method of pencil lead breaking) were acquired at four spatially separate points using acoustic sensors mounted on the plate in rectangular array as shown in Fig. 1. The sensors captured signals are mathematically modeled as:

$$\left\{\begin{array}{l} S_1(t) = L(t) + n_1(t) \\ S_2(t) = \partial L(t-D_1) + n_2(t) \\ S_3(t) = \partial L(t-D_2) + n_3(t) \\ S_4(t) = \partial L(t-D_3) + n_4(t) \end{array}\right\} \tag{5}$$

where $S_1(t) - S_4(t)$ are sensors outputs, $L(t)$ is the AE source signal, $n_1(t) - n_4(t)$ are un-wanted signals and ambient noises, ∂ is attenuation factor caused by the acoustic path differences and $D_1 - D_3$ are time differences. In this study, the geometrical coordinates of S1 position is considered as (0, 0) and others are chosen following S1. The position of AE source is $O(x, y)$. The sensor-source distances can be obtained by:

$$\begin{array}{l} r_1 = V \times t_1 \\ r_2 = V \times t_2 \\ r_3 = V \times t_3 \\ r_4 = V \times t_4 \end{array} \tag{6}$$

where, V is the value of propagation velocity and t_i is the time of propagation of waves from acoustic emission source to sensor S_i. The time-delay of propagation of acoustic waves from acoustic source to S1 and S2 can be determined as:

$$\Delta t_1 = t_1 - t_2 = (r_1 - r_2)/V \tag{7}$$

Determining wave arrival times and propagation velocity are the important parameters in AE source localization. The time delay between two collected signals $(y_1(t), y_2(t))$ can be determined using cross correlation-function as:

$$R_{y_1y_2}(\tau) = \sum_{t=1}^{T} y_1(t)y_2(t+\tau) \tag{8}$$

The parameter (τ) which maximizes the cross-correlation function $(R_{y_1y_{22}(\tau)})$ provides an estimation of time delay. In Eq. (6) it is found that a constant wave velocity in plate must be known in

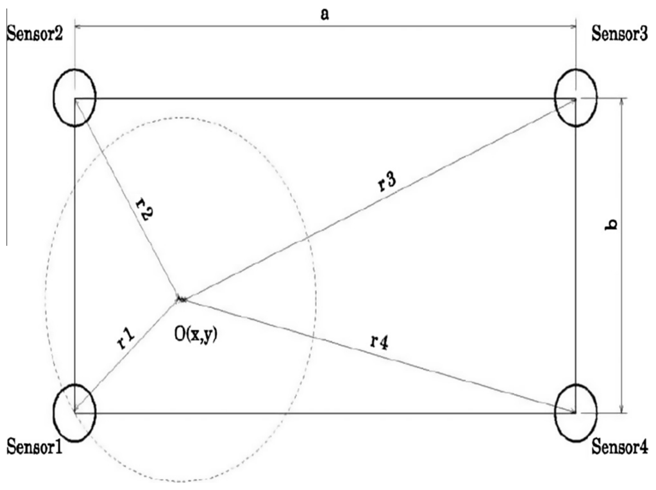

Fig. 1. Sensors and acoustic source positioning for 4-channel measurement, $O(x, y)$: acoustic source position, r_1, r_2, r_3, r_4: sensor-to-source distances.