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Locating the acoustic source in thin glass plate using low sampling rate data

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ABSTRACT

Acoustic source localization is an important step for structural health monitoring (SHM). There are many research studies dealing with localization based on high sampling rate data. In this paper, for the first time, acoustic source is localized on an isotropic plate using low sampling rate data. Previous studies have mainly used a cluster of specific sensors to easily record high sampling rate signals containing qualitative time domain features. This paper proposes a novel technique to localize the acoustic source on isotropic plates by simply implementing a combination of two simple electret microphones and Loci of k-Tuple Distances (LkTD) from the two sensors with low sampling rate data. In fact the method proposes substitution of previous methods based on solving the system of equations and increasing the number of sensors by implementing the selection of LkTD. Unlike most previous studies, estimation of time difference of arrival (TDOA) is based on the frequency properties of the signal rather than it's time properties. An experimental set-up is prepared and experiments are conducted to validate the proposed technique by prediction of the acoustic source location. The experimental results show that TDOA estimations based on low sampling rate data can produce more accurate predictions in comparison with previous studies. It is also shown that the selection of LkTD on the plate has noticeable effects on the performance of this technique.

1. Introduction

Acoustic emission (AE) is one of the most important and effective nondestructive methods for structural health monitoring. Acoustic waves can be emitted by the impact of external objects, crack formation, structural failure or even pipeline leakage [1,2]. All of these events result in the propagation of elastic waves which can be recorded by various sensors. Several methods have been proposed in the literature to find the location of events by analyzing the data. All of these methods can be classified according to whether the material property of the medium such as its velocity profile is known or not [1]. A comprehensive review of the latest methods is given by Kundu [1]. These methods are briefly reviewed here. The most popular acoustic emission localization (AEL) technique is called Triangulation [3,4]. Many source localization studies are based on optimization of an error function (Kundu et al. [5,6], Hajzargerbashi et al. [7] and Koabaz et al. [8]). These error functions tend to decrease computational complexity while increasing the number of sensors. Recently, researchers have extended the technique which does not need material properties and can be applied to anisotropic plates (Kundu et al. [9–11]). Moreover, Niri et al. [12–16] provided a probabilistic framework based on nonlinear Kalman Filtering methods to estimate the location of AE sources in isotropic and anisotropic plates whether or not the velocity profile is known. However, AEL without knowing the velocity profile in an anisotropic medium is one of the most challenging areas in this field.

The accuracy of the previous methods is based on calculating Time Differences of Arrival (TDOA) for signals from different sensors. Because of the high sound velocity in structures, any small error in the TODA calculation causes the acoustic source location prediction to be far from real. In practice, improving the TDOA estimation is based on increasing the sampling rate. There are considerable limitations on earlier analyses such as (1) Variation of some sensors from 3 to 6 depending on whether the plate is isotropic or anisotropic. (2) All present techniques are developed only for single acoustic source excitations [17]. (3) Severe contamination of background noise and the required high sound impact levels. (4) High sampling data acquisition requirements (Combination of (1) and (4) causes heavy computations and experimental complexities). Also, there are some obstacles on the way of extending AEL methods to industry, such as system size, cost and energy consumptions [18]. However, the acoustic source localization in plates

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Nomenclature

SHM	structural health monitoring
LkTD	Loci of k-Tuple Distances
TDOA	time difference of arrival
AE	acoustic emission
AEL	acoustic emission localization
C.C.	cross correlation
WT	wavelet transform
CWT	continuous wavelet transform
WPT	wavelet packet transform
MRA	multiresolution analysis
t	time
C	wave travel velocity
S	symmetric Lamb mode
A	antisymmetric Lamb mode
V	approximation wavelet space
W	detail wavelet space
h	low-pass filter
g	high-pass filter
Greeks	
δ	increment
ϕ	orthogonal wavelet basis
ψ	high-pass wavelet basis
μ	average of feature vector
α	feature vector dimension
Subscripts	
P	acoustic source
N	maximum signal sample
n	sample time
L	interpolation factor
j	subspace depth
p	number of subspaces

with a low sampling rate, remains a challenging task which still needs to be solved.

This paper discusses the solution of the AEL problem for plates with known material properties. The proposed method deals with analytical solutions which use two low sampling rate acoustic sensors and introduces a strategy for the selection of points on the Loci of k-Tuple Distances (LkTD) from the two sensors.

The novelties presented in this paper include: (1) discussing how to calculate the TDOA when using low sampling rates; (2) presenting a method to classify the selection of LkTD when dealing with frequency properties; and (3) carrying out experiments to verify the proposed new method. The paper highlights the following four new considerations:

(1) Use of low sampling rate acoustic sensors.
(2) Reducing the number of sensors to two.
(3) Use of the frequency content instead of the standard time arrival differences to estimate source locations.
(4) Proposing strategy for selection of LkTD.

This paper discusses the problem and the required algorithms in Section 2. It presents the experimental set-up in Section 3 and finally the results, discussion and conclusion are mentioned in Section 4.

2. Material and methods

2.1. Problem statement

Two acoustic sensors (receivers) are installed on a plate while their diaphragms are mounted on the surface. The acoustic source which is generated by external or internal events propagates Lamb waves through the plate structure at time T. The signals recorded by sensor #1 and sensor #2 are shown in Fig. 1(a), at time T_1 and T_2 known as clock times [1]. Despite the fact that the clock times are not accessible, the calculation of TDOA, t_i, is possible according to Eq. (1)[1]:

$$t_{12} = t_1 - t_2 = T_1 - T_2 = T_{12} \tag{1}$$

The coordinates of the two sensors are defined to be (x_1, y_1), (x_2, y_2), respectively. The coordinates of the unknown acoustic source are (x_p, y_p). Therefore, the distance of the acoustic source from the i-th sensor can be calculated using Eq. (2), while C is the velocity of the wave traveling in the plate.

$$\left|\sqrt{(x_1-x_p)^2+(y_1-y_p)^2}-\sqrt{(x_2-x_p)^2+(y_2-y_p)^2}\right| = Ct_{12} \tag{2}$$

Two approaches are available to calculate the unknown variables, x_p and y_p. The first approach is through solving the system of equations by increasing the number of sensors like previous studies such as Liang et al. [4]. The second is the approach proposed in this study, using LkTD. However, the most challenging issue here is how to calculate TDOA, t_i, using low sampling rate data. Although decreasing sampling rate affects the accuracy of TDOA, the result can be upgraded by taking the frequency domain features into account. The determination of t_{12} and design of LkTD are discussed in Sections 2.1.1 and 2.1.2, respectively.

2.1.1. Determination of t_{12}

The accuracy of TDOA calculation affects the performance of source localization techniques. All AEL methods are based on the calculation of TDOA. Previous studies can be classified into two main classes as follows.

(1) Cross correlation (C.C.) has been utilized whether the medium is air [19,20] or plates [1,9,11,17,21,22]. This technique is the most popular one. However, it is sensitive to the reflected waves. Therefore, the exact calculation of TDOA may not be achievable in air medium with non-free field conditions[20] and the experiment zones should be assumed to be far enough from the edges in plates.
(2) Time–frequency analysis [23] is based on the magnitude of Continuous Wavelet Transform (CWT). The energy distribution of a CWT is referred to as a scalogram [24], and it is usually defined as the squared modulus of a CWT. In this technique, the energy density of signal is calculated by a complex Morlet wavelet and is used to estimate TDOA.

Certainly, low sampling rate data influences the accuracy of these methods. This effect is expected to be much more severe especially in the time domain cross correlation method compared with that of the time–frequency method.

To prove this, a comparison between recent studies in each class (Nakatani et al. [17] as a typical cross correlation approach and Ciampa et al. [24] as a time–frequency analysis representative) and the proposed approach in this article is done for low sampling rate data (for example, 13.5 kHz). The results are illustrated in Fig. 2. As the Figure shows it is not easy to highlight the maximum