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Acoustic source localization in anisotropic plates with “Z” shaped sensor clusters

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ABSTRACT

A new sensor cluster orientation is proposed to localize an acoustic source in a plate from the time difference of arrival (TDOA) with the help of only four to eight sensors. This technique requires neither *a priori* knowledge of the plate material properties nor a dense array of sensors to localize the acoustic source in isotropic as well as anisotropic plates. It is achieved by placing four sensors in a cluster in the shape of letter “Z” over a small region of the plate and a second Z-shaped cluster at another location of the plate. Experimental results show that it is possible to accurately localize the acoustic source with this new configuration. It reduces the number of sensors required for acoustic source localization in an anisotropic plate. Although one cluster in principle is capable of localizing the acoustic source in absence of any experimental error for accurate source localization in presence of experimental error two such Z-shaped clusters are needed. In the currently available technique three L-shaped clusters having a total of 9 sensors are needed to achieve the same level of confidence in the acoustic source localization. Thus, the proposed new technique reduces the number of sensors by 1 (from 9 to 8) for confidently and accurately predicting the acoustic source.

1. Introduction

Plates are widely used in engineering structures such as car body, pressure vessels, liquid storage tanks, airplanes and space crafts, to name a few. Acoustic source localization in these structures is necessary to detect possible hot spot regions where cracks maybe formed due to impact of foreign objects or fiber breakage [5]. The conventional triangulation technique [6] requires the plate to be isotropic with known acoustic velocity. If the acoustic velocity is unknown then the calculation process becomes more complicated. However, it is still possible to localize the acoustic source. Most techniques for source localization in isotropic and anisotropic plates require an optimization algorithm to solve a system of non-linear equations and known velocity information [3].

Kundu et al. [4] proposed a technique that requires neither a solution of a system of non-linear equations nor *a priori* knowledge of the direction dependent velocity profile. This technique requires six to nine sensors to monitor a large anisotropic plate. The sensors are placed in two or three L-shaped sensor clusters. This technique has been successfully used by others to detect and localize impacts [1]. Various source localization techniques available today have been reviewed by Kundu et al. [2] and are not repeated here.

In this work, the sensor cluster geometry is modified from L to Z shape so that the acoustic source can be localized using only four to eight receiving sensors instead of six to nine. The four sensors are placed in one cluster that is shaped like letter “Z”. It is shown here how two “Z” shaped clusters with 8 sensors can replace three L-shaped clusters with nine sensors for accurately localizing the acoustic source.

2. Formulation

One Z-shaped configuration of four sensors is composed of two overlapping L-shaped clusters (see Fig. 1, the left figure). Four sensors are placed with a distance d between the neighboring sensors. The distance d must be much smaller than the distance from the source to the sensors. Therefore, for every right-angle cluster the inclination angles α and β of the propagation direction from source P to sensors ($S_1S_2S_3$ or $S_2S_3S_4$) should be approximately the same (see Fig. 1, the left figure). Then the received signals at the sensors can be assumed to be almost the same but slightly time shifted. The velocity in the direction from the source P to the three sensors

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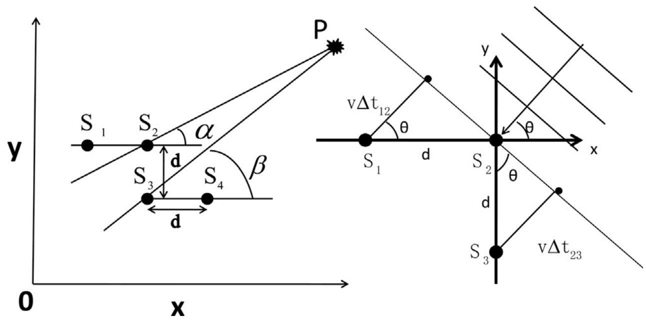

Fig. 1. Four sensors (S_1, S_2, S_3 and S_4) are arranged in a Z-shaped cluster. Acoustic source is at point P (left figure). Plane wave front at the sensor cluster location (right figure).

placed at right-angles ($S_1S_2S_3$ or $S_2S_3S_4$) also should be almost identical even for an anisotropic plate.

The direction of waves propagating from an acoustic source to a sensor cluster composed of three sensors can be determined by analyzing the time difference of arrival of acoustic signals at the sensors [4].

Four receiving sensors placed in a Z-shaped cluster are shown in Fig. 1 on the left. If the coordinates of S_1, S_2, S_3 and S_4 are (x_1,y_1), (x_2,y_2), (x_3,y_3) and (x_4,y_4), respectively then clearly $x_2 = x_1+d$, $y_2 = y_1$, $x_3 = x_2$, $y_3 = y_2-d$, $x_4 = x_3+d$ and $y_4 = y_3$. Let the acoustic source be located at point P (x_A, y_A).

As shown by Kundu et al. [4] one can obtain the wave propagation direction at the cluster location by analyzing the time difference of signal arrival at three sensors (S_1, S_2, S_3). This direction α is measured from the acoustic source S_2 as shown in Fig. 1 (in the right figure replace θ by α) and is obtained from the following equation.

$$\tan\alpha = \frac{\sin\alpha}{\cos\alpha} = \frac{\frac{\Delta t_{23}\times c_2}{d}}{\frac{\Delta t_{21}\times c_2}{d}} = \frac{\Delta t_{23}}{\Delta t_{21}} \quad (1)$$

where Δt_{ij} is the time difference of wave arrival between sensors i and j; c_i is the wave speed for the propagation path from the acoustic source to sensor S_i.

Similarly, another set of three sensors (S_2, S_3, and S_4) can measure the wave direction β from sensor S_3 (see Fig. 1, the left figure shows β, in the right figure replace θ by β):

$$\tan\beta = \frac{\sin\beta}{\cos\beta} = \frac{\frac{\Delta t_{32}\times c_3}{d}}{\frac{\Delta t_{34}\times c_3}{d}} = \frac{\Delta t_{32}}{\Delta t_{34}} \quad (2)$$

Two unknown coordinates x_A and y_A of the acoustic source can be uniquely obtained from Eq. (3). This solution gives the intersection point of two straight lines showing the wave propagation directions in Fig. 1.

$$\begin{cases} \tan\alpha = \frac{y_A - y_2}{x_A - x_2} \\ \tan\beta = \frac{y_A - y_3}{x_A - x_3} \end{cases} \quad (3)$$

3. Experimental investigation

The following experiment was conducted using an oscilloscope, a single channel ultrasonic transmitter and receiver system and two 150 kHz ultrasonic sensors as shown in Fig. 2. In absence of a 4-channel oscilloscope (not available in the laboratory where the experiment was conducted) we had to be more creative to conduct this experiment with the available simple devices listed above for the proof of concept. First, locations of the four receiving sensors for Z-shaped cluster configuration were marked on a 500 mm × 500 mm anisotropic striped marble plate of thickness 15 mm. Experimentally measured angle dependent guided wave speeds in this natural anisotropic plate are shown in Fig. 3.

For the proof-of-concept experiment one ultrasonic transducer acting as the transmitter was placed at a specific location of the plate while the other transducer acting as the receiver was placed in marked positions for S_1, S_2, S_3 and S_4 in four different experiments. If a 4-channel oscilloscope is available then the recorded time histories at all four receiving sensors can be obtained from one experiment. Travel times of the wave from the source to the individual receivers were recorded by conducting the experiment four times for four different positions of the receiver. Then the time differences of arrival Δt_{ij} for different sensor pairs were obtained simply by subtracting the arrival time values from one another.

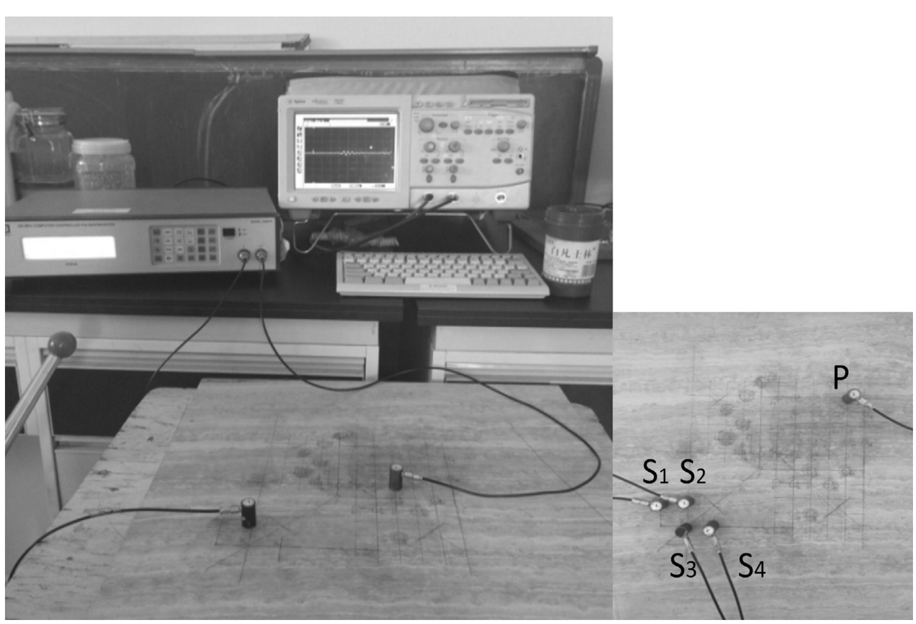

Fig. 2. Locations of two transducers in contact with the anisotropic striped marble plate - one transducer is the transmitter placed at the acoustic source position and the other transducer is the receiver which is placed in marked positions for sensors S_1, S_2, S_3 and S_4 alternately.