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Improving accuracy of acoustic source localization in anisotropic plates

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ABSTRACT

The acoustic source localization technique for anisotropic plates proposed by the authors in an earlier publication ([1] Kundu et al., 2012) is improved in this paper by adopting some modifications. The improvements are experimentally verified on anisotropic flat and curved composite plates. Difficulties associated with the original technique were first investigated before making any modification. It was noted that the accuracy of this technique depends strongly on the accuracy of the measured time difference of arrivals (TDOA) at different receiving sensors placed in close proximity in a sensor cluster. The sensor cluster is needed to obtain the direction of the acoustic source without knowing the material properties of the plate. Two modifications are proposed to obtain the accurate TDOA. The first one is to replace the recorded full time histories by only their initial parts – the first dip and peak – for the subsequent signal processing. The second modification is to place the sensors in the sensor cluster as close as possible. It is shown that the predictions are improved significantly with these modifications. These modifications are then applied to another sensor cluster based technique called the beamforming technique, to see if similar improvements are achieved for that technique also with these modifications.

1. Introduction

The conventional triangulation technique, which is used for the acoustic source localization in isotropic plates [2], cannot locate the acoustic source in an anisotropic plate where the wave speed is direction dependent [3]. Kundu et al. [4,5] proposed an alternative method for source localization which is based on minimizing a nonlinear error function to obtain the point that satisfies all equations. They successfully detected the acoustic source point on a flat anisotropic plate. The source localization is also possible by acoustic beamforming analysis proposed by McLaskey et al. [6] that requires a small array of four to eight sensors. Nakatani et al. [7] generalized this technique for anisotropic structures. They successfully localized acoustic sources in a thin aluminum cylindrical plate and a carbon fiber reinforced composite cylindrical shell by the generalized beamforming technique.

Most methods proposed so far for source localization in anisotropic plates, however, require either the knowledge of the direction dependent velocity profile or a dense array of sensors. When considering a homogeneous constant-thickness plate, a reliable velocity profile requires an accurate knowledge of the material properties, that may be difficult to obtain for anisotropic materials. Because of the uncertainties associated with the material properties of a composite plate the theoretically obtained group velocity profile in a composite plate is not very reliable. The direction dependent group velocity profile can be measured experimentally for a specific frequency but it is generally not applicable to another frequency. Hence, any technique that requires the knowledge of the direction dependent wave speed in the plate is not of much practical use.

The strain rosette technique [8] that can predict the wave propagation direction in an isotropic plate without knowing its material properties cannot do the same for an anisotropic plate because the group velocity direction does not necessarily coincide with the principal strain directions for the anisotropic plate. The time reversal technique [9] that requires a large number of labor intensive IRF (impulse response functions) for the structure and/or a large number of sensors can localize the acoustic source in an anisotropic structure after processing a large amount of recorded data. Clearly, these techniques are computation intensive and time consuming for large structures. Recently a new technique has been proposed by the authors [1] to locate the acoustic source in large anisotropic plates and shells without knowing its material properties or the direction dependent velocity profile in the structure. They did it with the help of only six sensors. This technique does not need to solve a system of nonlinear equations that other techniques

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require. The technique was validated using an aluminum flat plate and a curved composite pate. The experimental results appeared to be promising although the predictions did not match perfectly with the exact acoustic source locations in some cases. The prediction accuracy of this technique is improved here by (1) modifying the signal processing, and (2) restricting the sensor spacing. The proposed modifications are applied to the beamforming technique [7,8] since this acoustic source localization technique also uses sensor clusters. It is attempted to see if the proposed modifications improve the accuracies of this technique also.

Applicability of the proposed modifications to another technique proposed by Ciampa et al. [10,11] that also used sensor clusters for acoustic source localization in anisotropic plates are not investigated here because that technique requires solution of a system of nonlinear equations, and therefore, computationally more demanding. For a review of different acoustic source localization techniques readers are referred to a recent review article by Kundu [12], where advantages and disadvantages of various techniques have been discussed. It should be noted here that similar to other acoustic source localization techniques the method discussed here works for single acoustic source. If multiple sources are excited exactly at the same time then this technique will not work.

2. Formulation for acoustic source localization

This section briefly reviews the acoustic source localization technique that does not require the solution of a system of nonlinear equations, or *a priori* knowledge about the anisotropic material properties, as proposed by the authors in an earlier publication [1]. Thus the proposed technique can localize the acoustic source without knowing the direction dependent velocity profile in the plate and without optimizing any objective function.

Three receiving sensors S_1, S_2 and S_3 are mounted on the plate with horizontal and vertical sensor spacing d as shown in Fig. 1. Let the coordinates of the three receiving sensors S_1, S_2 and S_3 be (x_1, y_1), (x_2, y_2) and (x_3, y_3), respectively. The coordinate of the acoustic source A is given by (x_A, y_A). The sensor spacing d should be much smaller than the distance D between the acoustic source A and the i-th sensor S_i, then the inclination angle θ_1 of lines AS_1, AS_2 and AS_3 can be assumed to be approximately the same. Because of this assumption the received signals at these three sensors should be almost identical but slightly time shifted and the wave velocity in the direction from the source point A to the sensors S_1, S_2 and S_3 should be almost same (except for the time shift) even for an anisotropic plate. After arriving at sensor S_1 the time taken by the wave front to reach sensors S_2 and S_3 can be denoted as Δt_{12} and Δt_{13}, respectively. These two time delays are given by,

$$\Delta t_{12} = \frac{d\cos\theta_1}{c(\theta_1)} \tag{1}$$

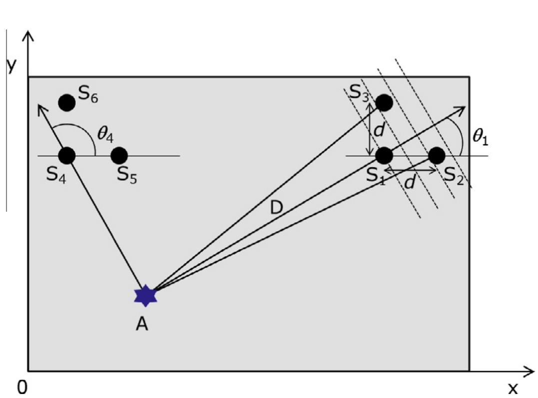

Fig. 1. Acoustic source A and two clusters containing three sensors each.

$$\Delta t_{13} = \frac{d\sin\theta_1}{c(\theta_1)} \tag{2}$$

where $c(\theta_1)$ is the wave velocity (energy velocity or group velocity) in the θ_1 direction. It should be noted that, as mentioned before, since the distance (D) of the acoustic source from the sensor cluster is much greater than the distance (d) between the sensors in a sensor cluster (or $D \gg d$, see Fig. 1) it can be assumed that the propagating wave has a plane wave front at the cluster position. It should be also pointed out that any inhomogeneity between the acoustic source and the sensor cluster does not deviate significantly the straight line path of the wave from the source to the sensor. From Eqs. (1) and (2) one can easily obtain,

$$\theta_1 = \tan^{-1}\left(\frac{\Delta t_{13}}{\Delta t_{12}}\right) \tag{3}$$

In Eq. (3) one can see that the direction dependent velocity profile in the plate is not required to obtain θ_1. If three more sensors S_4, S_5 and S_6 are mounted near another corner of the plate as shown in Fig. 1 then the wave propagation direction θ_4 from the acoustic source to sensor S_4 can be obtained in the same manner from Δt_{45} and Δt_{46} from the following equation.

$$\theta_4 = \tan^{-1}\left(\frac{\Delta t_{46}}{\Delta t_{45}}\right) \tag{4}$$

From Eqs. (3) and (4), two straight lines with inclination angles θ_1 and θ_4 going through sensors S_1 and S_4, respectively are obtained. The intersection point of these two lines should be the acoustic source point.

2.1. Determination of time delay Δt_{ij}

It should be noted that the acoustic wave propagation direction (θ_1 and θ_4 in Fig. 1) and the acoustic source location A are obtained from the time delay Δt_{ij}. Therefore, it is necessary to measure it accurately.

Let the transient signals recorded by the i-th and the j-th sensors be expressed as arrays $\boldsymbol{I}(t) = [I_1, I_2, I_3, \ldots, I_n]$ and $\boldsymbol{J}(t) = [J_1, J_2, J_3, \ldots J_n]$, respectively. Here I_n and J_n represent the signal values at time t_n. Note that the time increment δt between two successive points in the transient signal is given by $\delta t = T/(N-1)$ where T is the total recorded time and N is the total number of points in the transient signal. These two arrays can be added and multiplied after giving a small time shift in one of the two arrays as shown below.

$$U(\Delta t) = \sum_{n=1}^{N-m}\left[|I_n + J_{n+m}|\right] \tag{5}$$

$$V(\Delta t) = \sum_{n=1}^{N-m}\left[|I_n + J_{n+m}|\right] \tag{6}$$

$$\Delta t = m \times \delta t \tag{7}$$

If $U(\Delta t)$ and $V(\Delta t)$ are plotted then they should reach their maximum values at $\Delta t = \Delta t_{ij}$ because then these two arrays are in phase. If two arrays in phase are added and all negative terms are made positive after addition by taking their magnitudes as shown in Eq. (5), then that value should be higher than for the same two arrays added when they are not in-phase, as long as there is some overlapping region for the two arrays. Same thing can be said for the two arrays when they are multiplied as shown in Eq. (6). Therefore, Δt_{ij} is equal to Δt of Eqs. (5) and (6) that gives maximum values of U and V. In this manner Δt_{ij} can be measured very accurately with precision equal to δt, the time increment of the recorded transient signal.

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