



## Acoustic source localization in heterogeneous media

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### ABSTRACT

Acoustic source localization (ASL) or predicting the location of the acoustic source in a structure by analyzing the recorded signals at the receivers is of considerable interest for various applications. Recent research advances on this topic have been limited to homogeneous media. This paper presents a solution for acoustic source localization in a heterogeneous medium without knowing the properties of different materials constituting the heterogeneous structure.

In this paper new developments for acoustic source localization in an anisotropic plate is first reviewed briefly. Then an ASL technique is presented for localizing acoustic source in heterogeneous layered structures when the layer properties are not known. The proposed technique is verified experimentally and numerically. The experimental results were generated with a specimen having one interface while numerical results were generated for both two-layered medium with one interface and three-layered medium with two interfaces.

### 1. Introduction

The acoustic source localization technique plays an indispensable role in nondestructive testing (NDT) and structural health monitoring (SHM) applications [1]. Deformation and cracking of materials under stress can cause structural failure. Such crack formation can act as the acoustic emission source. An effective acoustic source localization technique can decrease the damage of the structure by taking remedial action to arrest the crack growth soon after its formation and location are detected. Thus ASL can help preventing catastrophic failure of structures.

Several acoustic source localization techniques have been proposed by various investigators over the last few decades [1–10,17]. Kundu et al. [11] proposed a technique based on the minimization of an objective function that includes the information on the time difference of arrival (TDOA) of waves and the direction-dependent velocity to locate the acoustic source. The need to know the velocity profile in an anisotropic plate was later avoided by Kundu [7] and Kundu et al. [12] by introducing a new technique that required six sensors placed in two “L” shaped sensor clusters. Yin et al. [13] modified that technique and proposed a localization technique using two “Z”-shaped sensor clusters that required a total of eight sensors but gave more reliable results. Park et al. [14] introduced a technique to localize the acoustic source in a highly anisotropic plate that generated rhombus and ellipse shaped wave fronts. Sen et al. [15,16] extended this concept and considered more non-circular shaped wave fronts. The wave front shape based source localization techniques proposed by Park et al. [14] and Sen et al. [15] avoid the assumption of straight-line wave propagation path

from the acoustic source to the sensor. Simone et al. [8] proposed a novel monitoring system which allows linearization of well-known nonlinear system of equations for the estimation of the impact location with the help of four receiving sensors. Ebrahimkhanlou and Salamone [9] proposed a single-sensor approach based on edge reflections in an isotropic plate and deep learning method of plate structures (2018).

Many heterogeneous materials are found naturally as well as in engineered structures, such as biological bodies, heterogeneous rock, underground sedimentation, airport runways, road pavements, functionally graded materials (FGM) etc. Compared to homogeneous solids in heterogeneous structures much fewer investigations have been carried out on acoustic source localizations. When the acoustic emission source and the receiving sensors are located in different media then the acoustic waves go through refraction at the interface, thus violating the assumption of the straight-line propagation path from the source to the receiver. Han et al. [18] investigated localization of acoustic sources for structural health monitoring of masonry bridge which is a heterogeneous material. Fluckiger et al. [19] presented a novel algorithm to accurately determine the location of an ultrasonic source inside a heterogeneous medium. Ebrahimkhanlou et al. [20] introduced a deep learning-based framework to localize and characterize acoustic emission (AE) sources in plate-like structures that have complex geometric features, such as doublers and rivet connections. Sedlak et al. [21] used first-arrival of extensional modes to estimate source locations in multi-layered plates with two-step AIC technique. Zhou et al. [22] adopted the iterative method to solve the nonlinear equations to locate the acoustic source in multilayered media using the refraction path method. They conducted an experimental study considering refraction in

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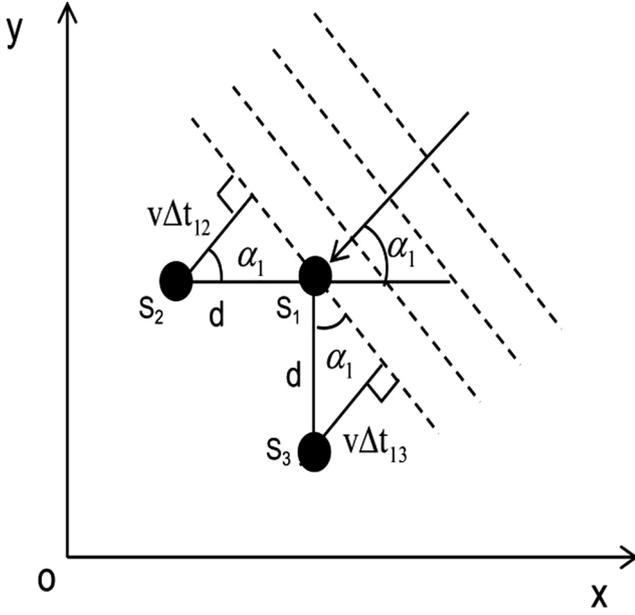


Fig. 1. The sensor cluster is placed on the surface of the plate to record the arriving wave signals.

different media by solving a function of actual arrival time and theoretical time [23]. To avoid cumbersome and time consuming iterative algorithm here a simple acoustic source localization technique based on Kundu's method [7,12] is proposed. This technique correctly predicts the direction of wave propagation through a sensor cluster and it does not require a priori knowledge of the plate material properties.

The proposed technique is applied to heterogeneous plates made of two or more different materials. With this new method the acoustic source is localized by properly considering the refraction phenomenon. The new technique is verified experimentally and by numerically modelling propagating waves from a point source in a heterogeneous structure. The acoustic source location is correctly predicted by applying the proposed technique on the numerically generated waves in two-layered and three-layered media.

## 2. Source localization in a homogeneous medium without knowing its material properties

Kundu [7] proposed a technique for acoustic source localization in an anisotropic plate with the help of only six receiving sensors that does

not need plate properties, it also avoids the need to solve a system of nonlinear equations. Kundu et al. [12] then experimentally verified this technique for plates made of both isotropic (requiring 4 sensors) and anisotropic materials (requiring 6 sensors). Ciampa et al. [24,25] also proposed a technique for source localization in anisotropic plates without knowing the plate properties. However, their technique required the solution of a system of nonlinear equations, and therefore was computationally more demanding. The technique proposed by Kundu [7] is briefly described here since it will be used for heterogeneous structure also. Kundu proposed an L-shaped sensor cluster composed of 3 sensors mounted orthogonally with a constant distance  $d$  from the middle sensor  $S_1$  to the end sensors  $S_2$  and  $S_3$  as shown in Fig. 1. The distance  $d$  should be much smaller than the distance between the acoustic source and the cluster to make the inclination angle from the acoustic source to the 3 sensors in the cluster approximately the same. For such configuration even for an anisotropic plate the wave speed from the acoustic source to the three sensors can be assumed to be the same. Let the coordinates of the acoustic source be  $(x_p, y_p)$ . The coordinates of sensors  $S_1$ ,  $S_2$  and  $S_3$  are  $(x_1, y_1)$ ,  $(x_2, y_2)$  and  $(x_3, y_3)$ , respectively. From Fig. 1 it is clear that  $x_1 = x_2 + d$ ,  $y_1 = y_2$ ,  $x_3 = x_1$  and  $y_3 = y_1 - d$ . A straight line drawn from the acoustic source to sensor  $S_1$  can be expressed as,

$$\tan \alpha_1 = \frac{(y_p - y_1)}{(x_p - x_1)} \quad (1)$$

After arriving at sensor  $S_1$  the time needed for the wave front to reach sensors  $S_2$  and  $S_3$  can be denoted as  $\Delta t_{12} = t_2 - t_1$  and  $\Delta t_{13} = t_3 - t_1$ , respectively. Clearly from Fig. 1 these two time delays can be expressed as,

$$\Delta t_{12} = \frac{d \cos \alpha_1}{v(\alpha_1)} \quad (2)$$

$$\Delta t_{13} = \frac{d \sin \alpha_1}{v(\alpha_1)} \quad (3)$$

where  $v(\alpha_1)$  is the wave velocity in the  $\alpha_1$  direction. From Eqs. (2) and (3) one can easily obtain,

$$\alpha_1 = \tan^{-1} \left( \frac{\Delta t_{13}}{\Delta t_{12}} \right) \quad (4)$$

From Eq. (2) one can also obtain the wave speed in the  $\alpha_1$  direction in the following manner,

$$v(\alpha_1) = \frac{d \cos \alpha_1}{\Delta t_{12}} = \frac{d \Delta t_{12}}{\Delta t_{12} \sqrt{(\Delta t_{12})^2 + (\Delta t_{13})^2}} = \frac{d}{\sqrt{(\Delta t_{12})^2 + (\Delta t_{13})^2}} \quad (5)$$

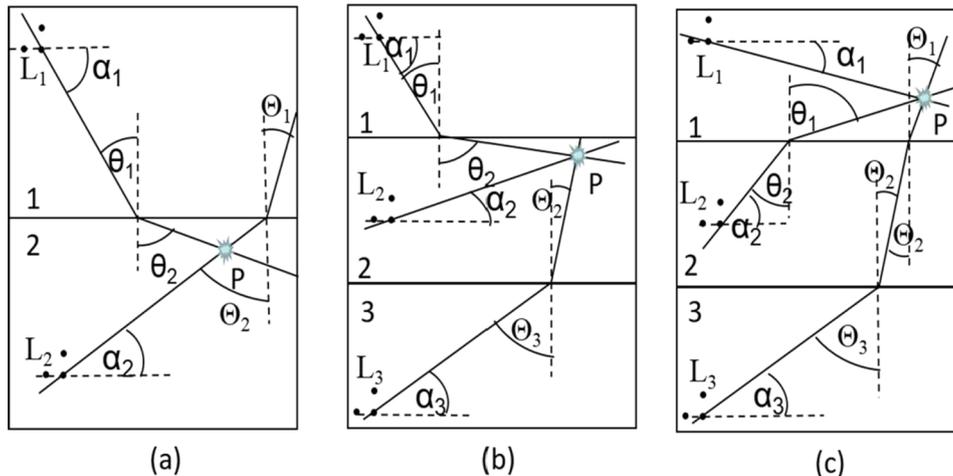


Fig. 2. Tracing the acoustic source location in 2-layered and 3-layered structures from L-shaped sensor clusters without knowing the material properties of individual layers.

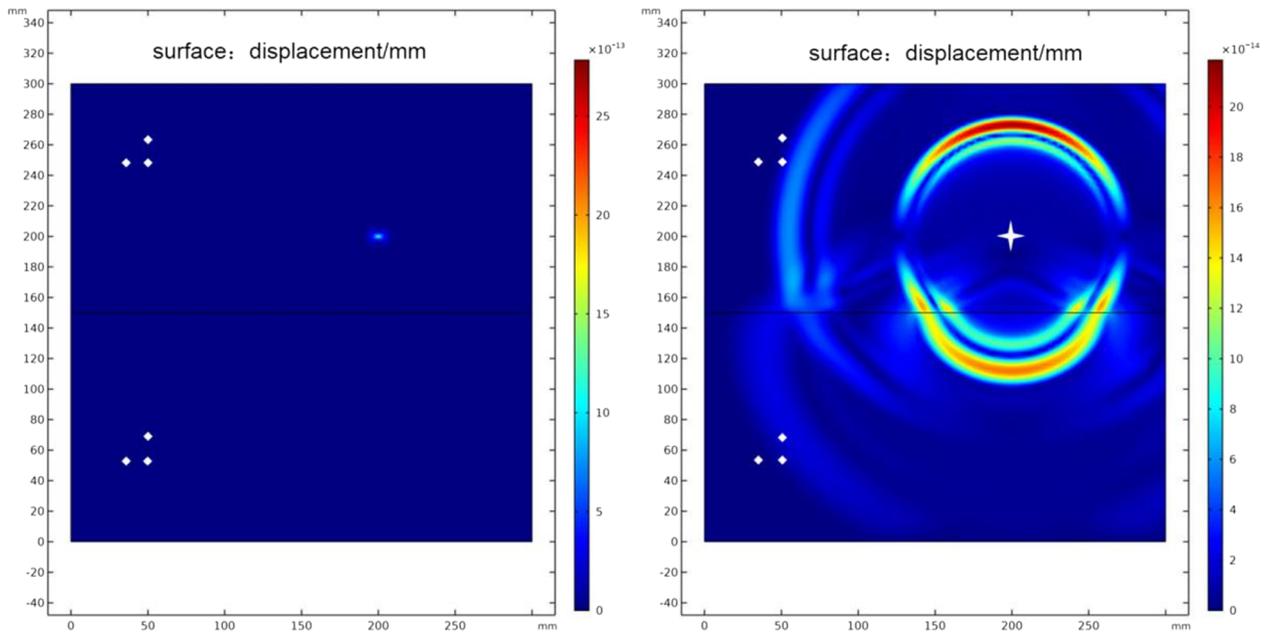


Fig. 3. The acoustic pressure surfaces showing the wave fronts at 2e-6s (left image) and 2.6e-5s (right image), after the excitation of the source located at (200, 200) mm. The source is shown as a star and the receivers are shown as white dots of rectangular shapes.

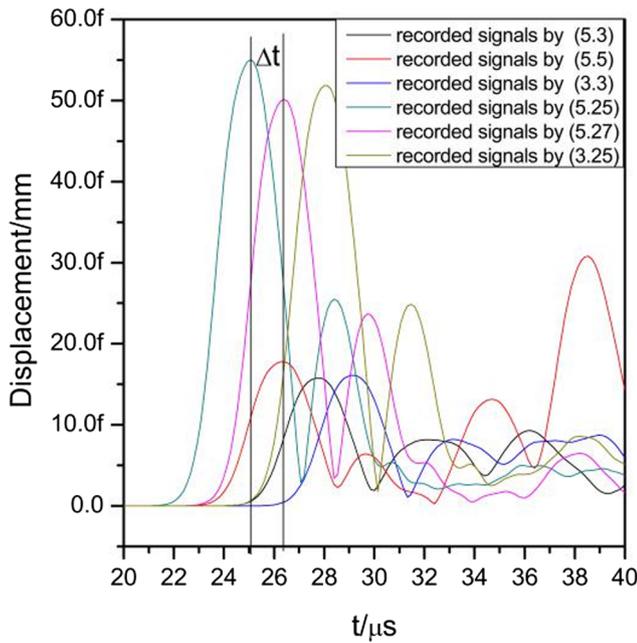


Fig. 4. Amplitudes of recorded signals by different sensors of two clusters. TDOA between any two sensors in a cluster is obtained by measuring the time shift  $\Delta t$  of a recognizable peak.

To localize the acoustic source two L-shaped sensor-clusters are placed at two different locations of the plate. Using Eq. (2) two inclination angles ( $\alpha_1$  and  $\alpha_2$ ) corresponding to the wave propagation directions at the two cluster positions are obtained. Intersection point of these two direction lines are designated as the acoustic source location.

### 3. Source localization in a heterogeneous medium

Zhou et al. [22,23] localized acoustic source in multi-layered plates using an iterative scheme to take into account the refraction phenomenon at the interfaces. Our objective is to localize the acoustic source in a heterogeneous structure without any iteration or *a priori* knowledge of

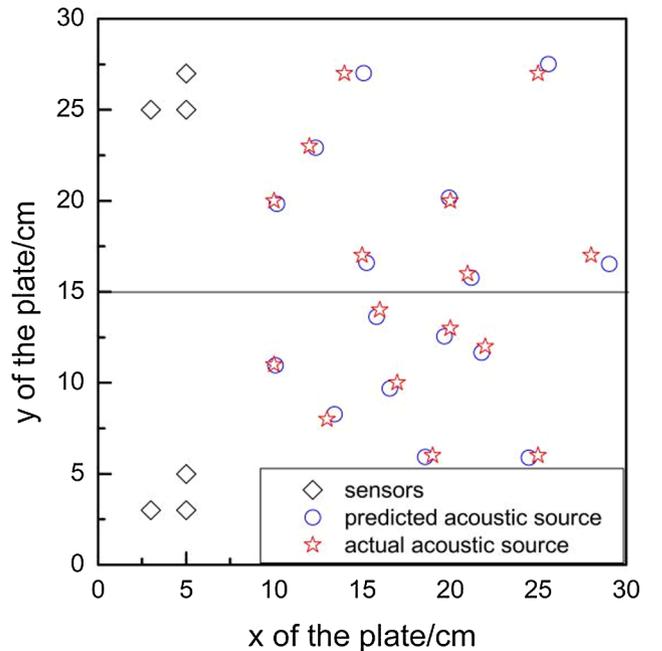


Fig. 5. Actual and predicted acoustic source locations obtained from the TDOA values in two sensor clusters. Predictions match reasonably well with the actual source locations for almost all cases.

the elastic properties of different materials constituting the structure. The proposed technique is illustrated in Fig. 2. Fig. 2(a) shows a structure made of 2 materials while Fig. 2(b) and (c) show three-layered structures made of three different materials. Let the acoustic source P be located in layer number 2, 2 and 1 in Fig. 2(a)–(c), respectively. One L-shaped sensor cluster ( $L_i$ ) is placed in every layer of the structure as shown in Fig. 2. Wave propagation directions through these clusters (angles  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$ ) can be obtained from Eq. (4) after knowing the time difference of arrivals  $\Delta t_{12} = t_2 - t_1$  and  $\Delta t_{13} = t_3 - t_1$ , for each sensor cluster. These lines obtained in this manner should intersect the interfaces without intersecting each other since they are drawn in different layers of the structure.

**Table 1**

True and predicted source locations for the 2-layered structure. Error is the distance between the predicted and the true source locations.

Exact source location (cm)	Predicted point considering refraction at the interface (cm)	Error considering refraction	Predicted point ignoring refraction at the interface (cm)	Error ignoring refraction
(10, 11)	(10.0736, 10.9548)	0.0864	(9.7024, 10.3729)	0.6941
(16, 14)	(15.8206, 13.6262)	0.4146	(15.4204, 13.2332)	0.9612
(20, 20)	(19.9508, 20.1708)	0.1777	(20.6748, 19.937)	0.6777
(12, 23)	(12.3627, 22.922)	0.3710	(12.4939, 22.8849)	0.5071
(20, 13)	(19.6691, 12.5449)	0.5626	(18.9947, 12.1061)	1.3452

After knowing the angles  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  the angles  $\theta_1$  in Fig. 2(a) and (b),  $\theta_2$  in Fig. 2(c) and  $\theta_3$  in Fig. 2(b) and (c) between the wave propagation directions and the normal to the interfaces are obtained. These angles can be obtained easily since  $\theta_j$  or  $\Theta_j = (90^\circ - \alpha_j)$ , where  $j = 1, 2$  or 3. For computing the angles of propagation on the other side of the interface -  $\theta_2$  and  $\Theta_1$  in Fig. 2(a),  $\theta_2$  and  $\Theta_2$  in Fig. 2(b),  $\theta_1$ ,  $\Theta_2$  and  $\Theta_1$  in Fig. 2(c) one needs to use Snell's law

$$\frac{\sin(\theta_1)}{v_1} = \frac{\sin(\theta_2)}{v_2} = \frac{\sin(\theta_3)}{v_3} \quad (6)$$

Wave speeds in individual layers are obtained from Eq. (5). It should be noted that from the time difference of arrival information those lines can intersect at only one point as shown in Fig. 2 when the wave propagation paths are drawn in individual layers and then extended to the neighboring layers following Snell's law. This intersecting point is the acoustic source location. To localize the acoustic source in this manner we do not need *a priori* knowledge of the material properties of individual layers but the positions of the interfaces (or the detailed geometry of the structure) are required to calculate the striking angles at

the interfaces. In the following numerical and experimental investigations the acoustic sources in heterogeneous media are localized following the steps described above.

### 3.1. Numerical simulation of wave propagation in heterogeneous media

The finite element simulation was carried out for verifying the proposed acoustic source localization technique in heterogeneous media. A two-dimensional finite element model of dimension  $300 \text{ mm} \times 300 \text{ mm} \times 7 \text{ mm}$  was created using COMSOL. The first heterogeneous structure is composed of two solids having the following properties (these properties are close to those of aluminum and carbon-epoxy composite solid):

Young's Modulus ( $E_1$ ) = 70e9[Pa]	Young's Modulus ( $E_2$ ) = 1.2e11[Pa]
Poisson's ratio ( $\sigma_1$ ) = 0.33	Poisson's ratio ( $\sigma_2$ ) = 0.31
Density ( $\rho_1$ ) = 2700 [kg/m <sup>3</sup> ]	Density ( $\rho_2$ ) = 1700 [kg/m <sup>3</sup> ]

The P- wave and S- wave velocities in each medium can be obtained

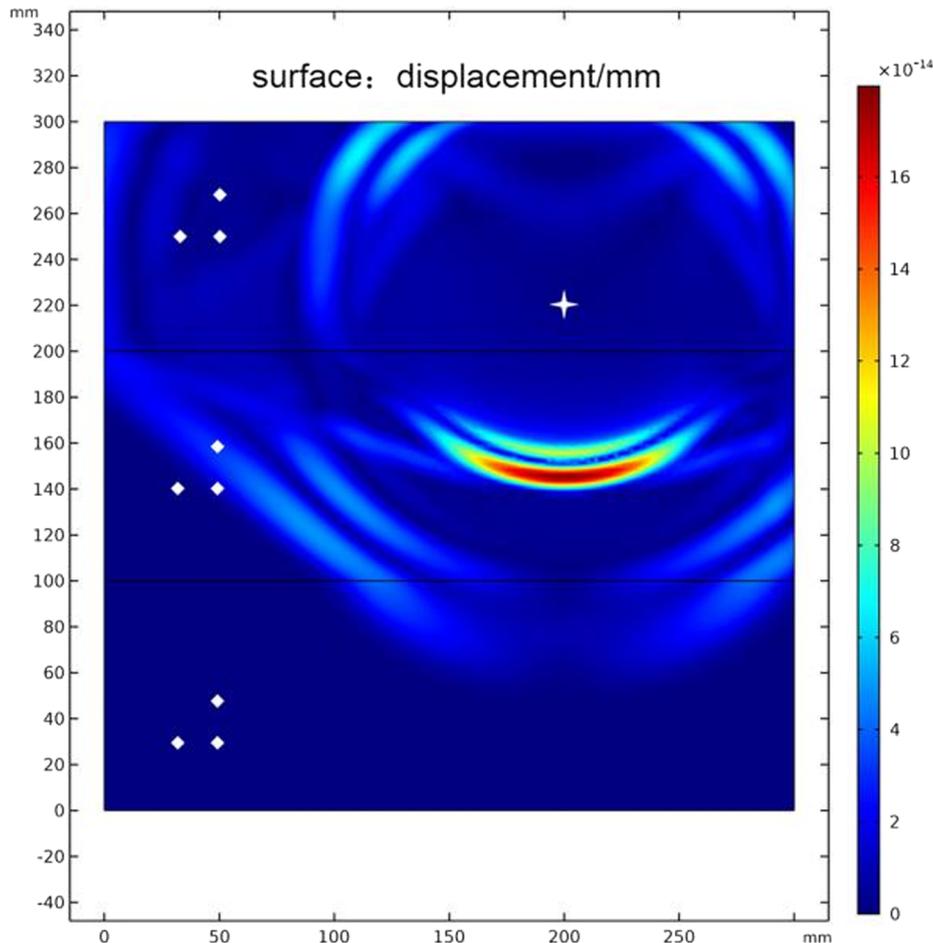


Fig. 6. COMSOL generated wave propagation snapshot at 2.4e-5s when the acoustic source is (200, 220) mm in a three-layered structure.

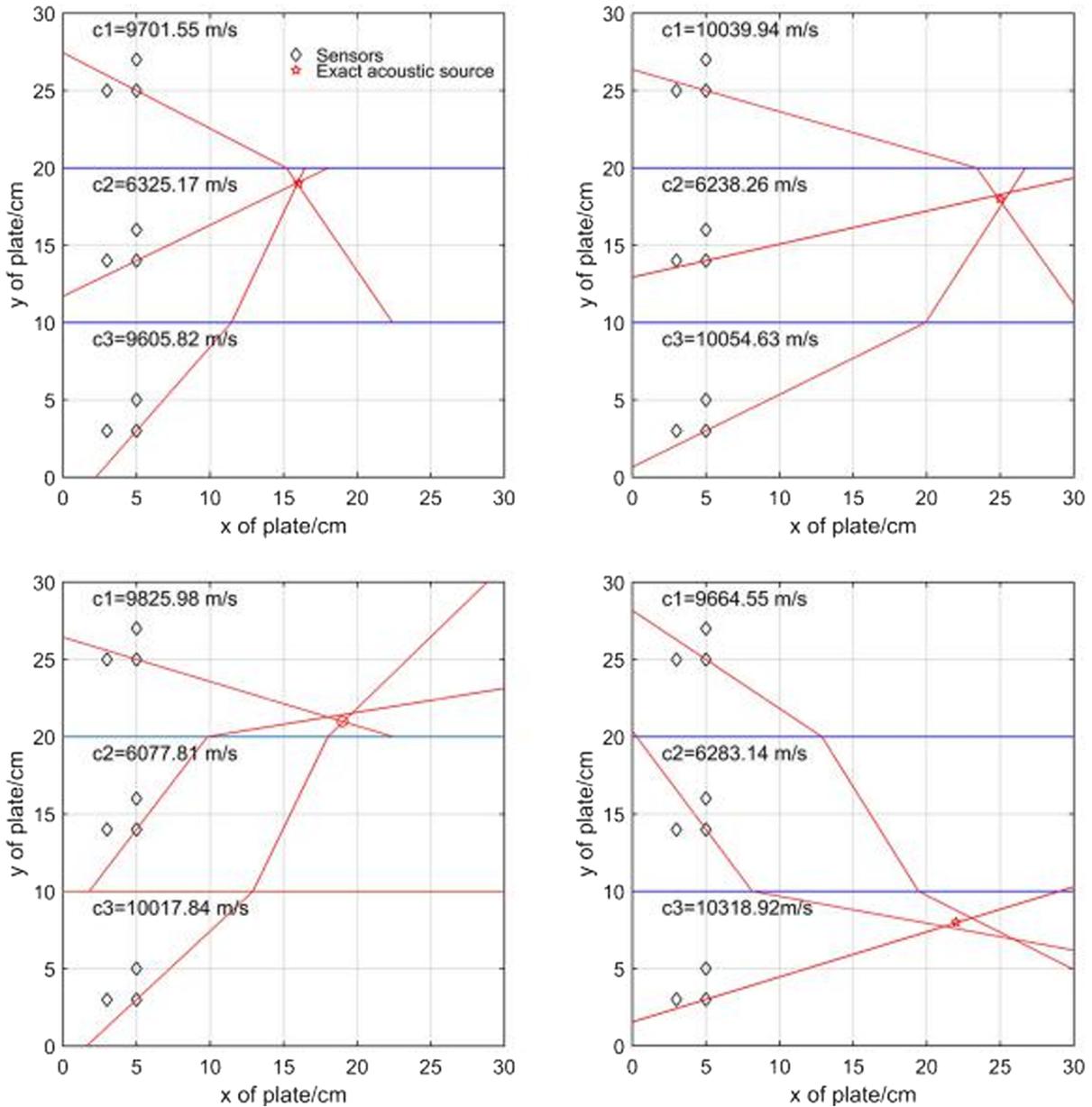


Fig. 7. Actual and predicted acoustic source locations obtained from the TDOA values recorded by the three sensor clusters in three layers. The intersection regions of 3 different lines drawn from the 3 sensor clusters are the predicted acoustic source locations. All 4 predictions match well with the true source locations. Wave speeds in each layer computed from Eq. (5) are shown in the figure. Note that the true values of the P-wave speeds are 6197.82 m/s for the middle layer and 9891.52 m/s for the top and bottom layers.

from the following equations

$$V_p = \sqrt{\frac{E}{\rho} \cdot \frac{1 - \sigma}{(1 - 2\sigma)(1 + \sigma)}} \quad (7)$$

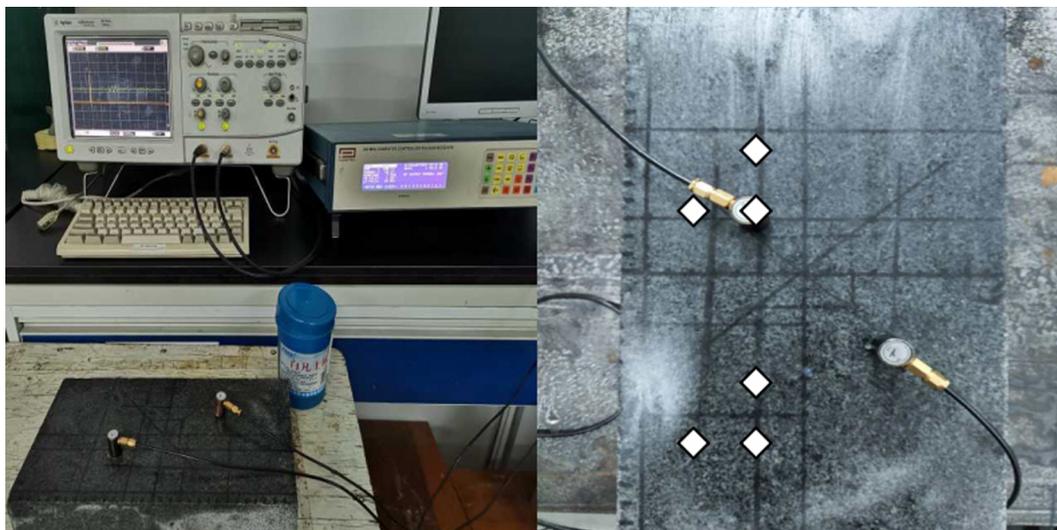
$$V_s = \sqrt{\frac{E}{\rho} \cdot \left( \frac{1}{2(1 + \sigma)} \right)} \quad (8)$$

A 150 kHz frequency signal was applied to the heterogeneous structure. The signal is chosen as a sine function. The excitation is applied to a line of length 0.01 mm. Since it is very small it can be regarded as a point source [26]. The initial excitation is given as a pressure in the z direction only in medium 1, as shown in Fig. 3. The bottom boundary is fixed while the other three boundaries are low reflection boundaries and avoid side wall reflection reaching the point of observation within the specified time. All plots show total displacement of the acoustic waves. The domain point probes are placed at the

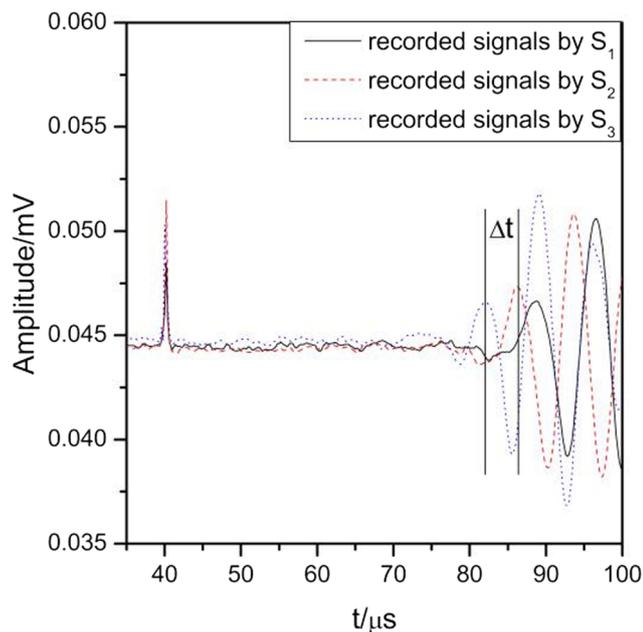
receiving sensor positions to record the total displacement as a function of time at the sensor positions. The mesh was generated automatically with triangular elements. Free meshing provided in COMSOL was used for the generation of mesh. The mesh was refined near the region of the excitation source. The element size is greater than 8 wavelengths. The number of elements is 33302. The Transient solver is applied. The computed results at different times show how the propagating wave front is reflected and refracted at the interface and boundaries. Different acoustic source locations (xp,yp) were considered for verifying the technique.

The amplitudes of the acoustic signals that propagate from the acoustic source to the sensors are recorded. The arriving times of the first wave at different sensors are different. The time differences can be obtained by comparing the corresponding peak positions, as shown in Fig. 4.

For the two layered structure the acoustic source is localized from



**Fig. 8.** Locations of two transducers attached to the rock plate – one transducer acting as the transmitter is placed in one location and the other transmitter acting as the receiver is placed in one of the six diamond marked positions. The experiment is repeated six times for the six different positions of the receiver marked by the diamond markers.



**Fig. 9.** Signals recorded by 3 different sensors in a cluster. The time difference  $\Delta t$  of signal arrivals at any two sensors in a cluster is obtained by measuring the time shift of a recognizable peak in the initial part of the time histories recorded by the two sensors.

the TDOA (time difference of arrival) values between the three sensors in two clusters as illustrated in Fig. 2(a). The final predictions and the actual source locations for various source positions are shown in Fig. 5.

Coordinate values of the actual and predicted source locations for six different source positions are listed in Table 1. The quantitative value of the error for a prediction is calculated from the distance between the actual acoustic source  $(x, y)$  and the predicted acoustic source  $(x_A, y_A)$

$$\text{error} = \sqrt{(x - x_A)^2 + (y - y_A)^2} \quad (9)$$

These error values (considering and ignoring refraction at the interface) are shown in Table 1 to get quantitative values of the error. These five source locations are randomly chosen from the fourteen source locations shown in Fig. 5.

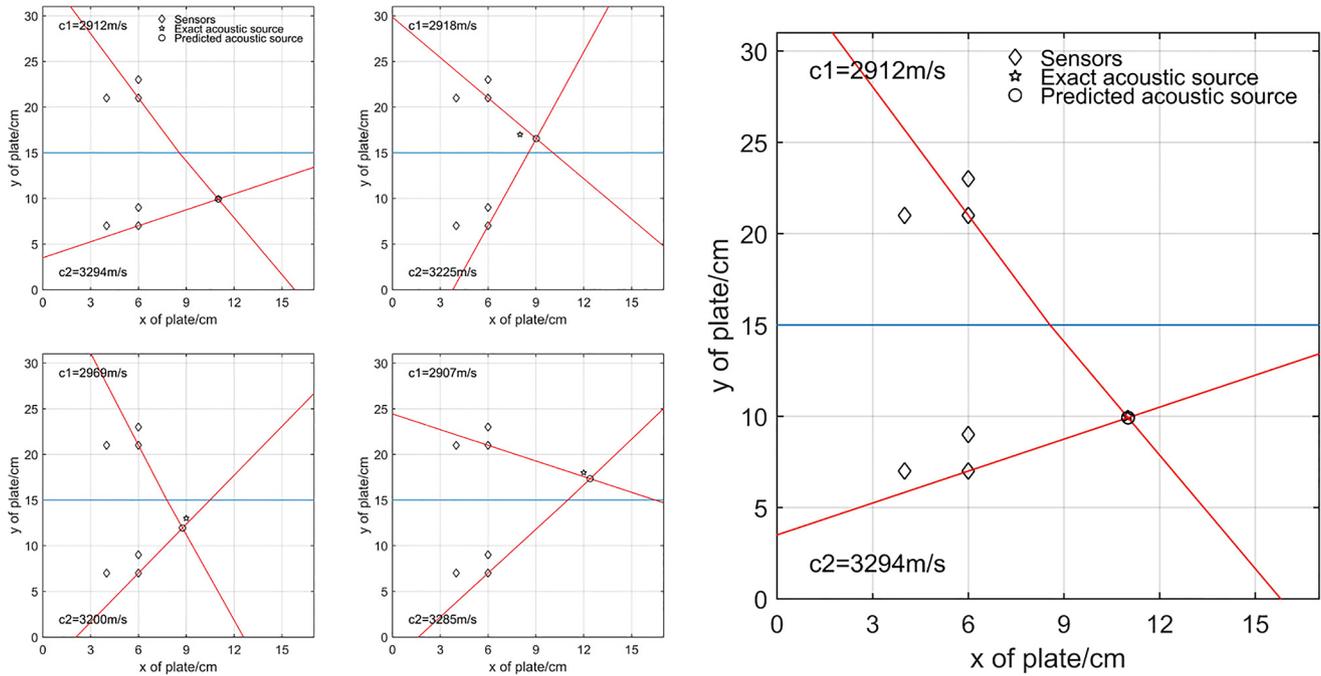
Then a three-layered structure of dimension  $300 \text{ mm} \times 300 \text{ mm}$  was modeled by COMSOL. The middle layer is medium 1 (having properties close to aluminum) while both top and bottom layers are medium 2 (having properties close to carbon fiber/epoxy) as mentioned earlier. A snap shot of the propagating waves at time  $t = 2.4e - 5 \text{ s}$  after the excitation of the source is shown in Fig. 6. The acoustic source is located at the top layer.

The predicted acoustic source locations for various source position in top and middle layers are shown in Fig. 7. Three lines from the three sensor clusters are obtained following the techniques illustrated in Fig. 2(b) and (c). For the 4 cases shown in Fig. 7 although often 3 lines did not intersect at a single point the three intersection points of these three lines are very close to the acoustic source locations confirming the reliability of the proposed technique.

### 3.2. Experimental investigation

A two layered heterogeneous plate was constructed from a porous natural rock plate and soaking half of the plate in water. Qu et al [27] showed that the acoustic wave velocity in some natural rock changes when it is saturated in water. Such a rock plate was chosen for this experiment. Half of the plate was soaked in the water for a long time until the wave velocity in the wet part of the rock plate reached a steady value. The water soaked part of the plate showed different acoustic properties than the dry plate and thus made the sample a heterogeneous plate. The experiment was conducted using an oscilloscope, a single channel ultrasonic emission unit and two 150 kHz ultrasonic transducers as shown in Fig. 8. In absence of a multi-channel oscilloscope (in the laboratory) this experiment had to be carried out in a more innovative way with the available simple devices listed above. Experimentally measured average guided wave speeds of the sample plate was  $c_1 = 2908 \text{ m/s}$  in the dry part and  $c_2 = 3204 \text{ m/s}$  in the water saturated part. The time difference of arrival of the first peaks at the 3 sensors in a cluster are shown in Fig. 9. The zero-axis is shifted vertically upward for a clearer view of the time history plots.  $\Delta t$  shown in this figure is the TDOA between sensors  $S_2$  and  $S_3$ .

First, locations of the six receiving sensors for two L-shaped cluster configurations are marked on a  $310 \text{ mm} \times 170 \text{ mm}$  sample plate of thickness 15 mm. One ultrasonic sensor acting as the transmitter is placed at a specific location on the plate while the other one acting as the receiver is placed in marked positions for  $S_1, S_2, S_3$  and  $S_4, S_5, S_6$  – one at a time. Travel time of the wave from the source to the individual



**Fig. 10.** Experimental results - the predicted source locations (intersection points of the two lines) and exact source locations (shown by the star markers) for 4 positions of the acoustic source (shown on the left). The experimentally obtained (using Eq. (5)) wave velocities  $c_1$  and  $c_2$  are also shown in the figure for every source location. The slight bending of the wave path due to refraction at the interface become more visible when a plot is magnified as shown in the right figure.

**Table 2**  
True and predicted source locations for a 2-layered structure.

Exact source location (cm)	Predicted point considering refraction at the interface (cm)	Error considering refraction	Predicted point ignoring refraction at the interface (cm)	Error ignoring refraction
(9, 12)	(8.7653, 11.9401)	0.2422	(8.7191, 11.8577)	0.3148
(9, 17)	(9.0197, 16.5516)	0.4488	(9.0227, 16.5472)	0.4533
(11, 10)	(11.0095, 9.9218)	0.0788	(10.7819, 9.7891)	0.3033
(12, 18)	(12.4002, 17.3388)	0.7729	(12.4431, 17.3143)	0.8164

receivers is recorded by repeating the experiment six times for six different positions of the receiver. Then the time differences of arrival  $\Delta t_{ij}$  for different sensor pairs ( $i$  and  $j$ ) are obtained simply by subtracting the wave arrival times to those sensor pairs.

The acoustic source was localized using the theory presented above. The velocity of dry part of the plate is  $c_1$  and that of the wet part is  $c_2$ . The calculated velocities obtained from Eq. (5) are shown in Fig. 10.

Final predicted results for four different source locations are shown in Table 2. Acoustic sources are localized by both considering and ignoring the heterogeneity. The error for each case is calculated from Eq. (9) and shown in the table. Note that for every case even for such small heterogeneity the error is reduced when the new algorithm for source localization in a heterogeneous structure is adopted.

#### 4. Concluding remarks

A new technique is proposed for source localization in heterogeneous structures. The new technique does not require any iterative scheme unlike some existing methods; it also does not need *a priori* knowledge of the material properties of the individual layers. However, the geometry of the structure – specifically the locations of the interfaces need to be known *a priori*. The proposed technique has been verified using numerically simulated wave propagation models in heterogeneous structures as well as experimentally. Predicted acoustic source locations in both numerical models and experimental results matched well with the true positions of the acoustic sources. Future work on acoustic source localization in heterogeneous structures may

involve thickness changes, connectors, rivets, etc.

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