



Performance analysis of non-reflective boundary conditions on sound localization problem in an isotropic plate

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ABSTRACT

Acoustic source localization, considering the effect of reflected waves from geometrical features (such as holes, lugs and structural discontinuities) is still one of the most challenging areas in this field. In this paper, the effects of reflected waves from edges on source localization results are discussed. Most of the previous studies have ignored the reflected waves by selection of the test zone far from the test plate edges. The current approaches for considering reflected waves are based on using high Sampling Rate Data (SRD) which is unsuitable for practical applications.

This paper discusses how silicon dampers on edges affect the acoustic source localization on an isotropic plate using low SRD. In this approach, four silicon dampers are installed on a Plexiglas plate. The effect of each damper is experimentally tested on final prediction error. The experimental results reveal that the reduction of prediction error according to each damper highly depends on the impact and sensor location related to the damper's position.

1. Introduction

Acoustic emission (AE) has now become an important and effective part in Structural Health Monitoring (SHM) systems [1,2]. AE waves can be emitted by the damage mechanism itself such as the impact of foreign objects, crack formation, failure of structures, etc. [3,4]. Hence, the damage mechanism acts as an acoustic source propagating elastic waves through the structure which can be recorded by a group of sensors. Despite the fact that a lot of progress has been made on sound source localization, finding accurate location of the damage in reality by analyzing the data remains a challenging task. Several studies have proposed methods to solve this problem. Kundu [2] presented a comprehensive classification of these methods in two main groups according to whether the medium is isotropic or anisotropic.

Most of these methods reported in the literature are based on solving nonlinear equations [5], error function [6–9], Kalman filtering methods [10–13], time reversal methods [14–17], soft computing [18], Gaussian process [19], attenuation analysis [4], artificial training data [19,20], time-distance domain transformation [21] and shape of the wave front [3,22]. Three considerations that limit extension of acoustic source localization (ASL) in industrial are: (1) Knowing the plate properties in some techniques such as velocity profile in [3]; (2)

Structural complexities such as cavities and thickness changes, may cause changes in wave propagation path and velocity [23] and (3) reflected waves from the edge of plates cause the ASL result to be far from real [24].

During the last decade, the first two considerations have received significant attention. Therefore, various techniques have emerged to address these complications. According to previous research, solving these considerations in a real scenario is not easy due to high complexity and nonlinearity, especially the last one. Hence, researchers prefer to use assumptions in which there is no need to consider the effect of reflected waves from edges [25–27]. Among research studies on ASL considering reflected waves, one is popular presented by Nakatani et al. [28]. They improved the accuracy of the previous method presented by Kundu [26,27]. Nakatani et al. [28] method of modification considered the effect of reflected waves by replacing the recorded full time signal histories with only their initial parts. This can be explained in the following manner. The initial parts of each recorded signal (first dip and peak) were not affected significantly by the reflections from the plate edges. Although the assumption of free reflected recorded signal seems to be reasonable, the implementation of this technique needs high sampling data acquisition. The current available reported approaches for ASL due to reflected waves can be classified

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Nomenclature

<i>SHM</i>	structural health monitoring
<i>LkTD</i>	loci of k-tuple distances
<i>TDOA</i>	time difference of arrival
<i>AE</i>	acoustic emission
<i>ASL</i>	acoustic source localization
<i>SSD</i>	silicon strip dampers
<i>SRD</i>	sampling rate data

<i>t</i>	time
<i>C</i>	wave travel velocity
<i>d</i>	distance between sensors
<i>D</i>	distance between source to each sensors

Subscripts

P	acoustic source
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into two main classes as follows:

- (1) Considering reflected waves from plate edges by (i) Eliminating the part of signals affected by reflected waves [28]; (ii) Calculating all possible direction path and mode conversion of reflected waves from edges [29,30].
- (2) Assume the reflected waves can be ignored due to: (i) Selecting the test zone distance far from the plate edges (as much as possible) [1]; (ii) Installing Silicon Strip Dampers (SSD) on the plate edges [31,32].

Also, it should be noted that the mentioned techniques in (1) mostly have been applied on simple plates and used high SRD. Among ASL techniques that use edge reflections, two are extended to the plates with rivet-connected doublers, presented by Ebrahimkhanlou et al. [29,33].

Although ASL techniques for isotropic plates are well established in the literature, the effect of reflected waves especially in low SRD remains a challenging task which still needs to be solved. However, the localization accuracy in low SRD can certainly not be competitive with the high SRD, but it would be more efficient in a real world scenario. This paper discusses the effect of SSD installation on the ASL problem based on low SRD. The proposed method deals with how SSD affect the reflected waves and introduce a strategy for finding which edge is most effective in the final ASL result.

The main novelty of this paper is discussing the geometrical properties of dampers. The paper highlights the following two considerations:

- (1) Use of low sampling rate acoustic sensor.
- (2) Determining the effect of reflected waves from each edge for acoustic source localization problem in a simple plate.

The organization of the subsequent sections of the paper is as follows. Section 2 discusses the problem statement. Section 3 includes the experimental set-up used to validate the proposed method. Results and discussions are presented in Section 4 and finally concluding remarks are provided in Section 5.

2. Statement of problem

Investigation of how installing SSD on the plate edges will influence the reflected waves as well as the final ASL results, requires to know and consider that:

- 1- Acoustic source propagates Lamb waves through the plate structures, whether it is generated by an external or internal event [2].
- 2- These waves are made through constructive and destructive interferences also superposition of pressure waves (P-wave) and shear vertical waves (SV-wave) undergoing multiple reflections on the plate's lower and upper surfaces [34].

Hence, to study the reflected Lamb waves from the edges, it is needed to consider the reflection of pressure and shear vertical waves from the edges. Shen et al. [32] noted that the amplitude of reflected P-wave and SV-wave are strongly dependent on these waves incident angle. The results demonstrated that, the amplitude of reflected waves are decreased while the incident wave angle is small [32]. Shen et al. [32] discussed increment of reflected lamb wave (from plate boundary) absorption due to the increment of P and SV waves absorption (reflected from top and bottom plate surface near the edge) [31,32]. This can be explained as follows. If the incident wave angle is small (see Fig. 1(a)) the amplitude of reflected waves are massively decreased according to the Shen et al. [32] research results. Otherwise, silicon dampers at the top and bottom surface near the edge enforce decrease

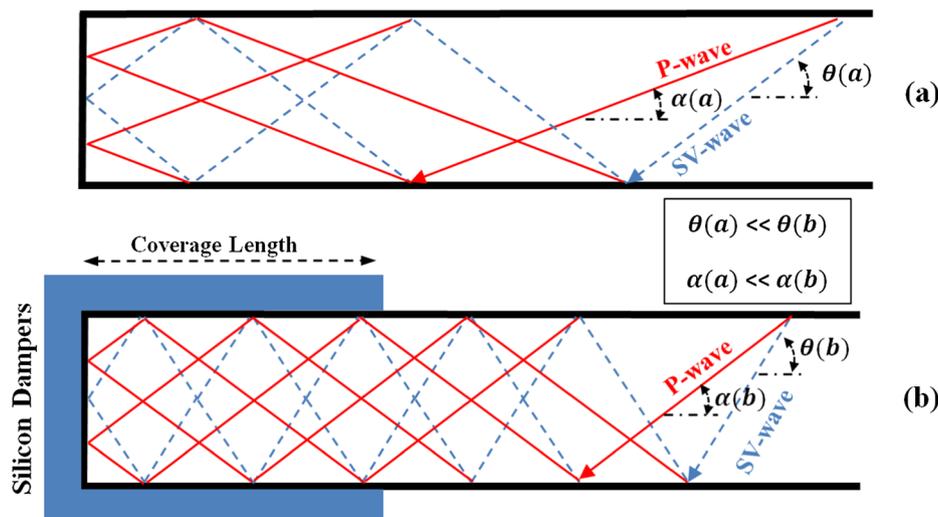


Fig. 1. Using SSD on top and bottom surfaces near the plate edge for absorption of lamb waves made by multiple reflections of P-wave and S-wave. Incident angles in (a) are much smaller than angles in (b).

of the amplitude of P and SV waves before reaching to the plate edge (see Fig. 1(b)). Hence, the combination of these effects causes the de-crementation of reflected Lamb waves from the edges.

3. Material and methods

3.1. Experimental set-up

An experiment is conducted on a Plexiglas plate (600 mm × 600 mm × 50 mm, weighing 0.4 Kg). The boundary conditions of the plate set to free–free–free–free by suspending the plate inside a framework (see Fig. 2). Unlike most previous research, since the effects of reflected waves were studied in this test, the whole test plate was considered as a test zone [1]. Four SSD were used in this experiment (with the thickness of 5 mm, weighing 0.07 Kg) shown in Fig. 3. The selections made were aimed to absorb reflected waves and simple structure [31]. An electret microphone and a pickup microphone in one cluster and a 2-channel sound card were used. A schematic description of the experimental setup is illustrated in Fig. 2. The experimental setup consists of:

- One simply free-free Plexiglas plate (weight and dimensions as given above).
- A two channel sound card (TASCOM US144MKII).
- Electret microphones with operating frequency range: 20–20000 Hz, weight: 0.8 gr, ϕ : 9.7 × 4.5 mm and signal to noise ratio of 60 dBA.
- A vibration pickup microphone (AKG c411, Austria) with an operating frequency range of 18–18000 Hz, weight: 18 gr.
- A Ping-Pong ball which is dropped from 6 cm height over the plate to generate acoustic waves.
- Four SSD.
- A framework for suspending the plate.
- A self-implemented analyzing framework.

The experimental tests were performed and repeated during five days at a temperature of 22 ± 3 °C. The sampling rate is set to be 44.1 kHz for all experiments in this article. One important mechanism of Lamb wave attenuation is known as leakage. Leakage or the effect of adjacent media describes the wave energy leakage into the adjacent medium [4,35]. The effect of leakage is ignored since the Plexiglas plate is attached to the corners of a framework by four similar springs and considered to be surrounded by air.

3.2. Experiments

This section introduces the effect of sound source localization on a Plexiglas plate while SSD is used.

To validate the proposed technique two experiments were carried out. The acoustic waves were generated from the impact of both, Ping-Pong ball and pencil lead-break in Experiment#1 and #2, respectively.

Experiment#1: In order to find how SSD affect the recorded signals, different arrangements of the SSD locations have been considered. Similar to the previous study [1] a Ping-Pong ball was dropped from a height of 6 cm over the plate to generate an acoustic wave, see Fig. 4. The recorded signals were calculated at sixteen possible dampers positions; see Fig. 5. Table 1 shows the corresponding position of SSD on the plate edges in each test. For simplification, the edges of the test plate are mentioned as “BC”, “AD”, “CD” and “AB” edges.

A number of assumptions were made regarding the mechanical parameters as follows: (a) All four springs have equal stiffness and (b) Excitation impact in all tests has equal intensity in both time and frequency domains.

Experiment#2: In order to find how this wave absorption on plate edges can affect the acoustic source localization, Experiment#2 is conducted on the suspended plate (see Fig. 6). The acoustic source was localized by implementing the Loci of k-Tuple Distances (LkTD) method, proposed by the authors in an earlier publication (The LkTD method is summarized in Appendix A) the experiment was conducted as Test#1: Suspending plate without dampers and Test #2: Installing SSD on suspended plate edges. As the dampers were effective on all four edges based on Experiment#1 result (see Section 4. Results and discussion), the dampers were used on all the edges in Test#2. Acoustic wave was generated by pencil lead breaks (Hsu–Nielsen source) [36] recorded by two electret microphones, see Fig. 6. The chosen pencil used 0.3 mm 2H leads and the lead was protruded 3 mm before breaking it on the plate [4]. As it was shown in previous studies [1,4] the LkTD method was not sensitive to both of wave generation methods (Ping-Pong ball drop and lead-break). So because of massive number of huge tests both methods were used.

The authors accept the fact that localization using low sampling rate can certainly not be competitive with localization using a high sampling rate [1]. However, when the application is restricted to using low sampling rates the method proposed in this paper, demonstrates a higher accuracy than other methods. It is really hard to specify cutoffs for low and high sampling data rates. The studies which are using

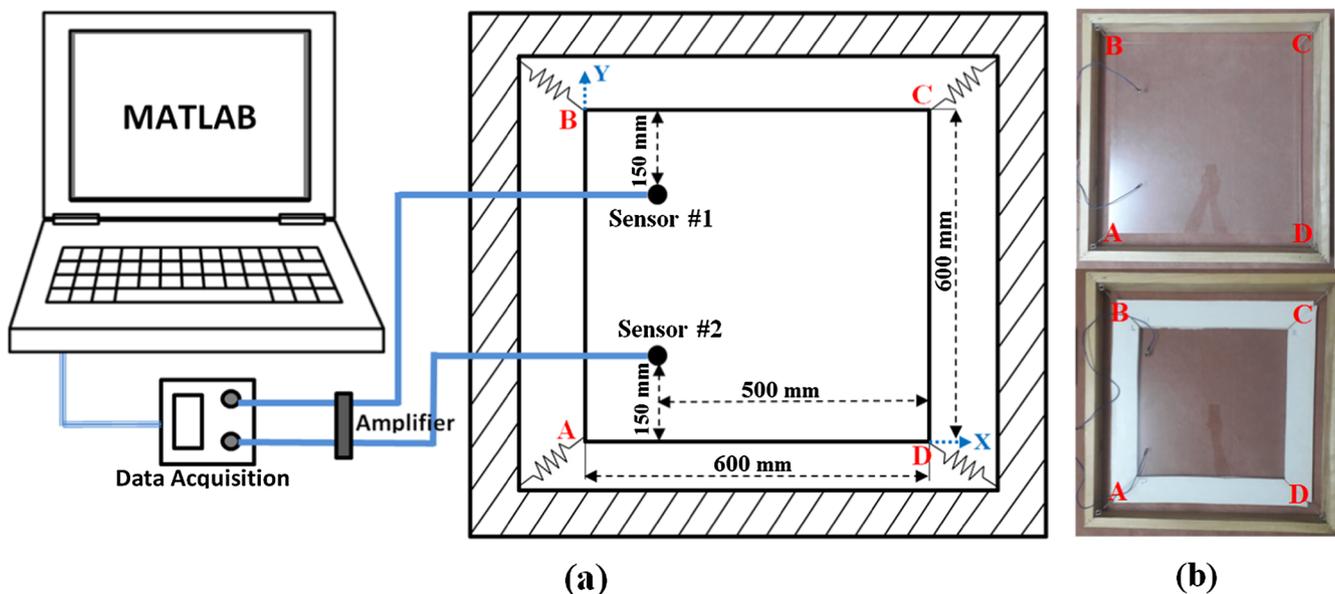


Fig. 2. Experimental set-up illustration in Experiment#2. (a) Locations of attached sensors (solid circles) and (b) The photographs of the Plexiglas plate.

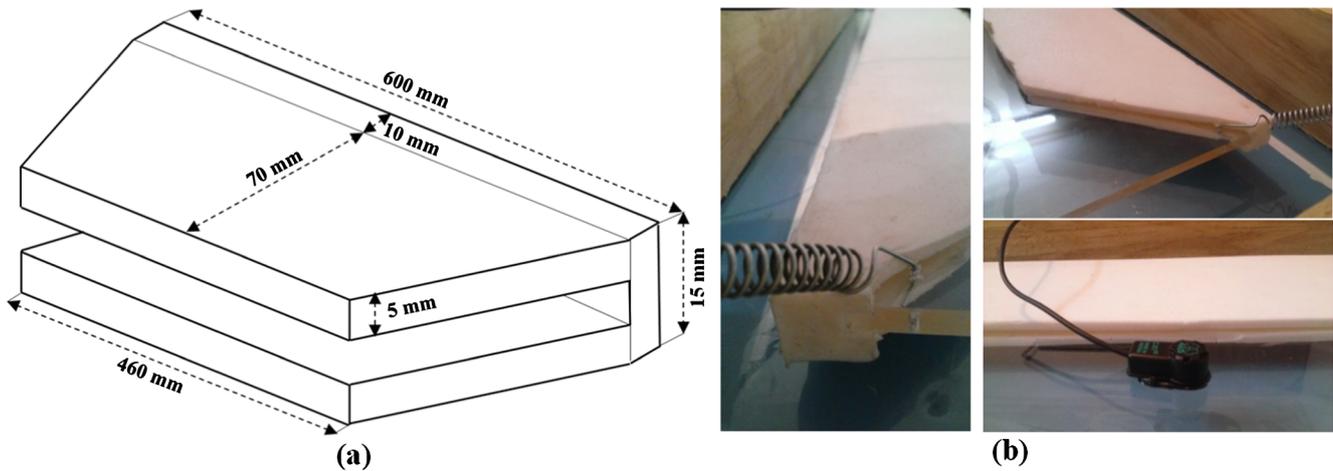


Fig. 3. Silicon Strip Damper properties. (a) Geometrical properties of SSD, (b) The photographs of SSD.

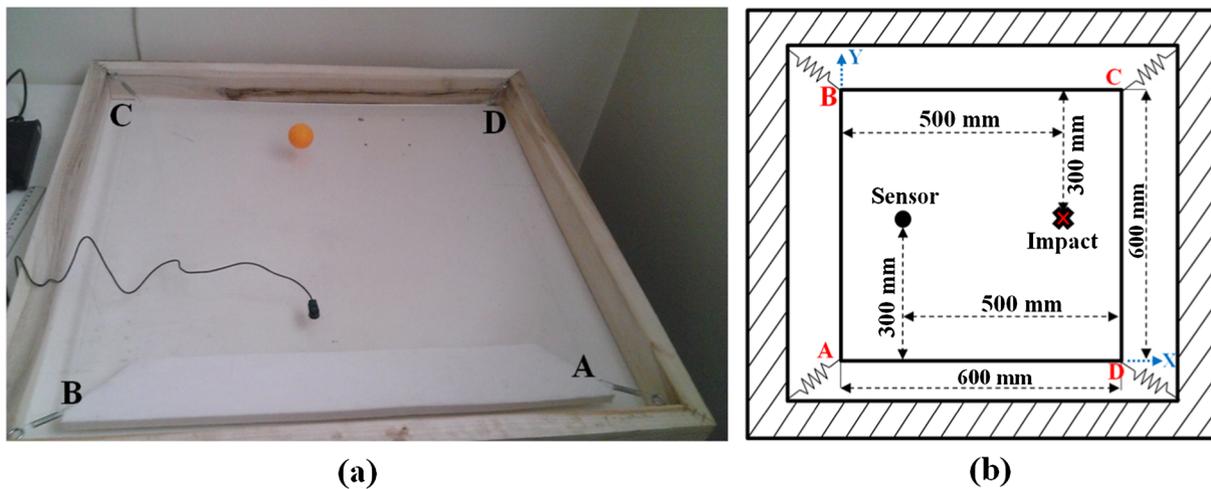


Fig. 4. Experimental set-up illustration in Experiment#1. (a) Locations of the attached sensor (solid circles) and acoustic source (X), (b) The photographs of the Plexiglas plate.

regular microphones instead of AE sensors with the sampling rate data is up to 44 kHz, known as “low SRD method”.

4. Results and discussion

The objective of this section is to report and discuss the results of the experiments explained in Section 3.2.

Experiment#1 Results: The acoustic waves generated by Ping-Pong ball was recorded by a vibration microphone. The energy of recorded signals (at sixteen possible dampers positions, Fig. 5) was calculated according to Eq. (1):

$$\text{Energy} = \int_{t_1}^{t_2} |v(t)|^2 dt \quad (1)$$

where $v(t)$ is the recorded signal. To evaluate the sensitivity of the proposed method to small variations, the experiment is repeated five times in all sixteen different dampers positions. Table 2 shows the corresponding signal energies.

The important question here is: how can make sure recorded signals contain the incident and the reflected Lamb waves, not the vibration waves? It can be explained in this manner. At low frequency experiments such as this study, Lamb waves have the same wave speed curves as vibration waves [34]. However, the propagated wave needs some distance before fully developing as the lamb waves, also it is only possible to observe vibrating mode shapes after (not before) the energy reaches the support position/boundaries. But it is completely

reasonable to call the waves, Lamb wave (or like Lamb wave). Since the group velocity dispersion curves are not used, it is reasonable to assume the captured waves are due to Lamb waves such as reported in similar experiments [4,37,38].

According to the results reported in Table 2, it is not easy to find how SSD position affects the signal energies. However, the considerable decreasing energy value in Test#16 in comparison with Test#1 clearly shows the effect of using dampers. In order to find, how position of SSD will influence the reflected waves from edges. The tests were classified into six main classes based on similarity of SSD numbers and usage as follows:

The incident and reflected waves from edges cause fluctuations in captured signals. The more reflected waves make more fluctuations. This can be explained as follows: The incident wave is assumed to be the same in all tests due to the identical properties (such as equality in medium and excitation impact). Hence, the assumption of relation between fluctuations and reflected waves seems to be reasonable. In order to discuss the effect of dampers, the captured signal in each class was compared with the first class, illustrated in Fig. 7. As the Figure shows using SSD in all classes reduce the reflected waves, but it is not easy to highlight the most effective ones. The important question to investigate is: Why the initial parts of signals are recommended to choose and how these parts are including reflected waves? This can be explained in the following manner. When low SRD is used, the initial parts of signals are contaminated with reflected waves as well as other parts. Also

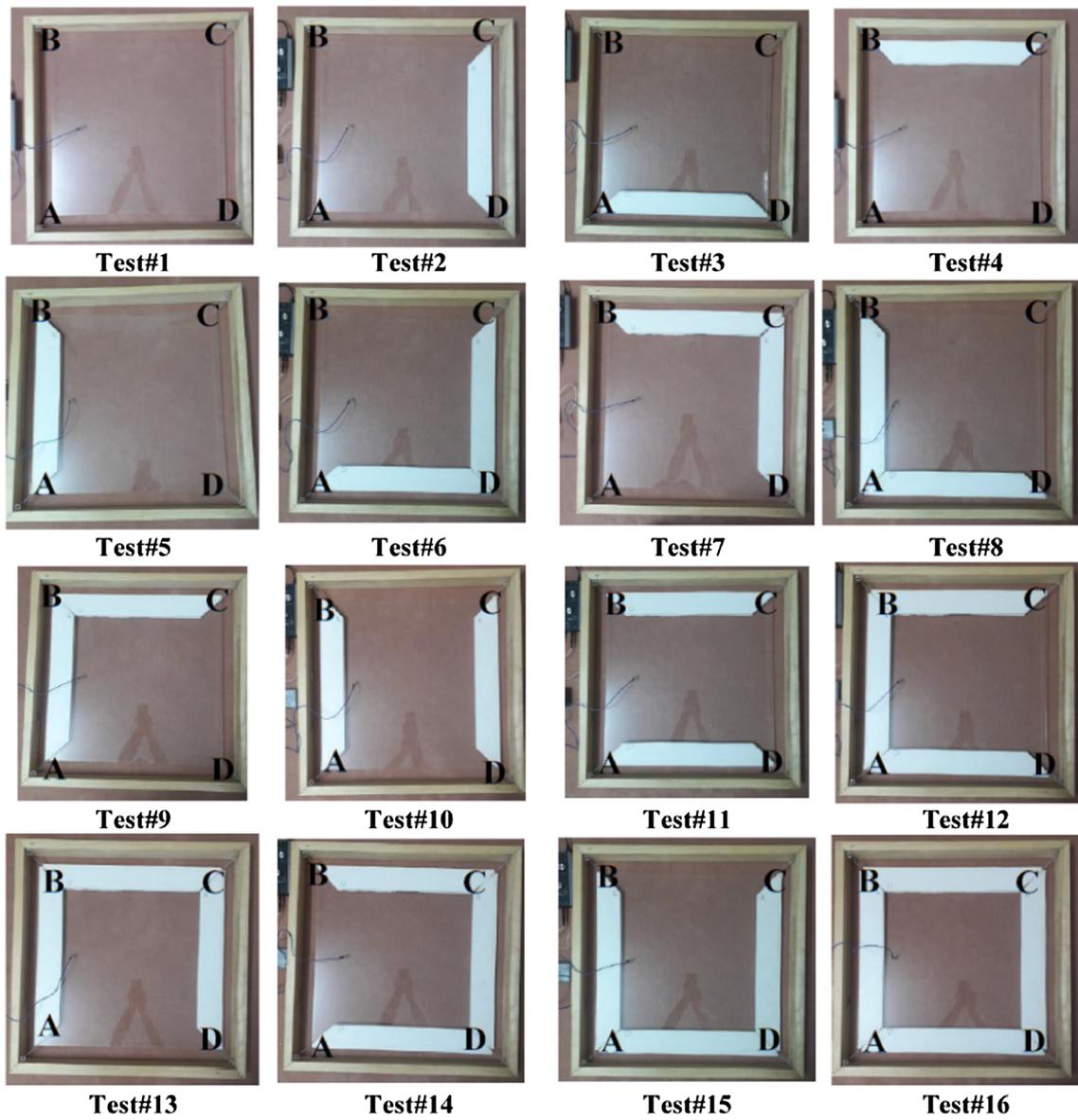


Fig. 5. Silicon strip dampers on plate edge according to Table 1.

Table 1

Position of silicon strip dampers (□: No, ■: Yes).

Test	Dampers location																		
	AB	CD	BC	AD		AB	CD	BC	AD		AB	CD	BC	AD		AB	CD	BC	AD
#1	□	□	□	□	#5	■	□	□	□	#9	■	□	■	□	#13	■	■	■	□
#2	□	■	□	□	#6	□	■	□	■	#10	■	■	□	□	#14	□	■	■	■
#3	□	□	□	■	#7	□	■	■	□	#11	□	□	■	■	#15	■	■	□	■
#4	□	□	■	□	#8	■	□	□	■	#12	■	□	■	■	#16	■	■	■	■

localizing the onset of the captured signal is more reliable than other parts. Fig. 7 shows, adding SSD in most classes causes a minor phase-shifting of the captured signal in time domain. The value of this phase shifting is different depending on the number and position of dampers. Therefore, class#6 is chosen to be used in Experiment#2 in order to absorb reflected waves and avoid phase-shifting.

Table 2 shows; there are 8 cases where each edge does not have SSD and 8 cases where each edge has SSD. The effect of using dampers on each edge for reduction of the reflected waves is reported in Table 3.

Table 3 shows the average energy of signals with or without using

SSD for each edge.

According to Table 3, adding SSD on all edges causes a reduction in reflected waves as it was expected. But it is not easy to highlight which damper is more effective. The “BC” and “AD” dampers have maximum and minimum succeed to absorb the reflected waves while the “CD” and “AB” dampers have almost the same performance. This can be explained in the following manner. Since the distance of the impact source from the “BC” edge is less than the “AD” edge, using dampers on “BC” edge is expected to be more effective than other edges. It is clear that by changing the location of impact and attached sensor, the

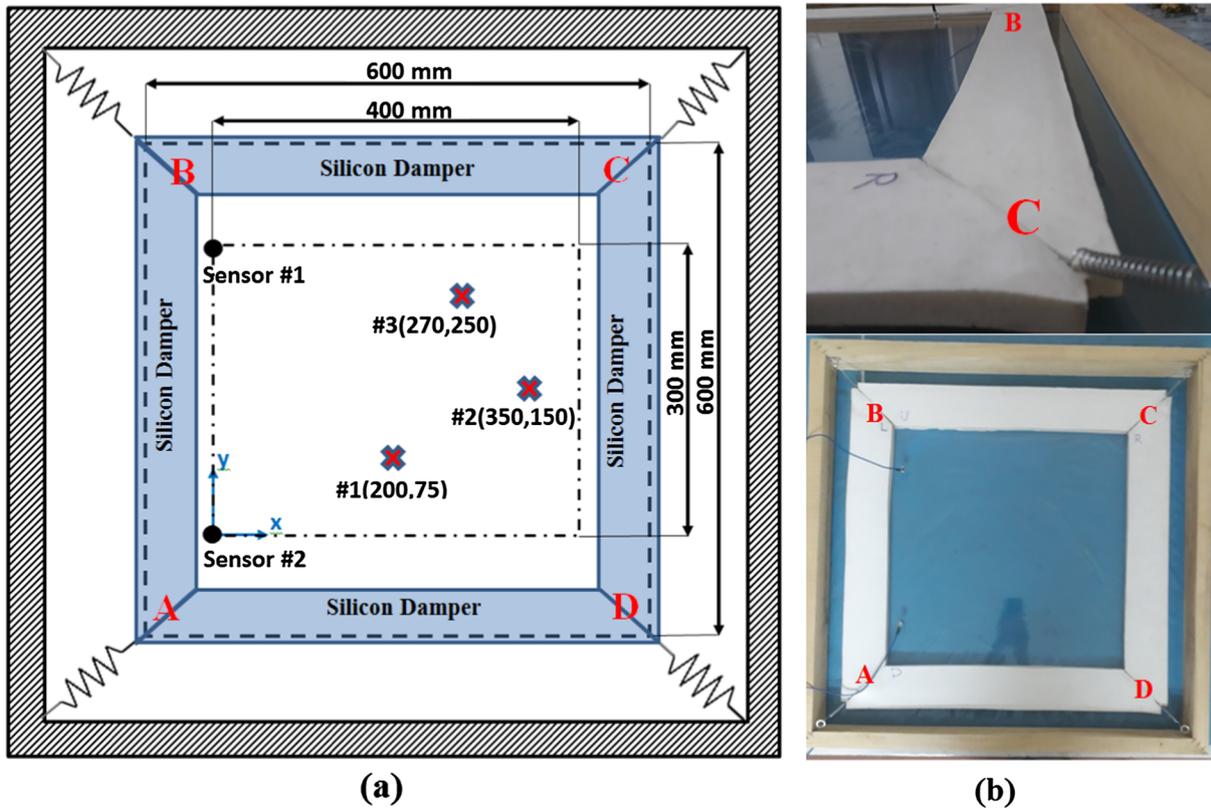


Fig. 6. (a) The locations of two sensors (solid circles) attached to the plate and the exact locations of the acoustic sources in the tests (X) plotted in Cartesian coordinates (dashed and dashed-dot lines are defined plate edges and test zone, respectively), (b) The photographs of the plate.

effectiveness of the dampers is expected to be changed.

Experiment#2 Results: The result of Experiment#1 shows that SSD can absorb the reflected waves. As the dampers were effective on all four edges based on Experiment#1 result (please see Section 4. Results and discussion), the dampers were used on all the edges in Test#2.

The locations of three acoustic sources shown by red crosses in Fig. 6 were found. The results of ASL with their corresponding error of localization (using Eq. (2)) are reported in Table 4.

$$Error = \sqrt{(x_{real} - x_{predicted})^2 + (y_{real} - y_{predicted})^2} \tag{2}$$

where (x_{real}, y_{real}) is the coordinate of real acoustic source location and

Table 2

Energy of captured signal. The experiments are repeated five times at sixteen possible damper positions.

Test number	Energy of signals ($v^2 \cdot s$)					Average	Standard deviation
	Iteration #1	Iteration #2	Iteration #3	Iteration #4	Iteration #5		
#1	0.0264	0.0246	0.0237	0.0268	0.0253	0.0254	0.0012708
#2	0.0213	0.0199	0.0174	0.0232	0.0211	0.0206	0.0021110
#3	0.0242	0.0221	0.0252	0.0226	0.0222	0.0233	0.0013616
#4	0.0183	0.0195	0.0195	0.0198	0.0188	0.0192	0.0006359
#5	0.0180	0.0200	0.0197	0.0189	0.0205	0.0194	0.0009643
#6	0.0185	0.0198	0.0202	0.0183	0.0184	0.0190	0.0008923
#7	0.0173	0.0169	0.0165	0.0164	0.0163	0.0167	0.0004025
#8	0.0180	0.0180	0.0186	0.0183	0.0191	0.0184	0.0004653
#9	0.0188	0.0192	0.0190	0.0188	0.0186	0.0189	0.0002273
#10	0.0158	0.0161	0.0152	0.0154	0.0146	0.0154	0.0005662
#11	0.0164	0.0170	0.0160	0.0166	0.0157	0.0163	0.0005133
#2	0.0155	0.0151	0.0143	0.0144	0.0149	0.0149	0.0004981
#13	0.0160	0.0154	0.0162	0.0154	0.0155	0.0157	0.0003743
#14	0.0142	0.0152	0.0154	0.0143	0.0143	0.0147	0.0005734
#15	0.0156	0.0162	0.0158	0.0180	0.0152	0.0162	0.0010937
#16	0.0217	0.0139	0.0136	0.0140	0.0138	0.0154	0.0035142

- (1). The first class contains only Test #1.
- (2). Class#2: Test #2, Test#3, Test#4 and Test#5.
- (3). Class#3: Test#6, Test#7, Test#8 and Test#9.
- (4). Class#4: Test#10 and Test#11.
- (5). Class#5: Test#12, Test#13, Test#14 and Test#15.
- (6). Class#6: Test#16.

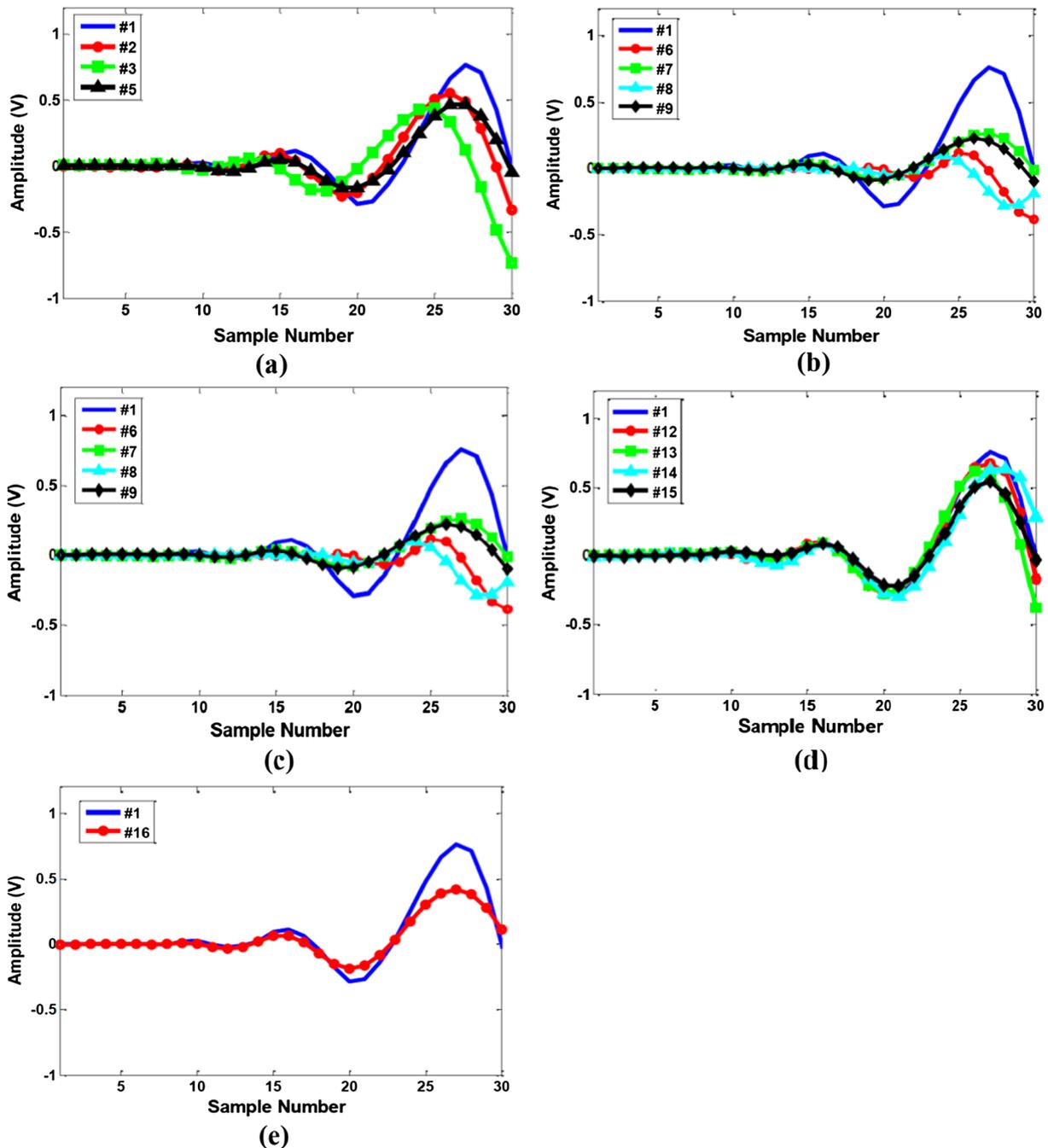


Fig 7. Comparison of first class captured signal (40 kHz) with other classes, (a) First and second, (b) First and third, (c) First and forth, (d) First and fifth and (e) First and last class. (For interpretation of the references to color in this Figure caption, the reader is referred to the web version of this paper).

Table 3
Average energy of captured signal for each edge.

Dampers Location	Energy of Signals ($v^2 \cdot s$)		Difference (Absorption)
	SSD Used	SSD Not Used	
AB	0.016780	0.019391	0.002611
CD	0.016706	0.019464	0.002758
BC	0.016460	0.019711	0.003251
AD	0.017265	0.018906	0.001641

Table 4
Locations of acoustic source and their corresponding errors.

Test points	Exact location (mm)	Predicted location			
		Test#1 (mm)	Error (mm)	Test#2 (mm)	Error (mm)
Impact #1	(200, 75)	(263, 31)	76.84	(258, 35)	70.45
Impact #2	(350, 150)	(396, 94)	72.47	(387, 203)	64.63
Impact #3	(270, 250)	(204, 197)	83.09	(212, 294)	72.80

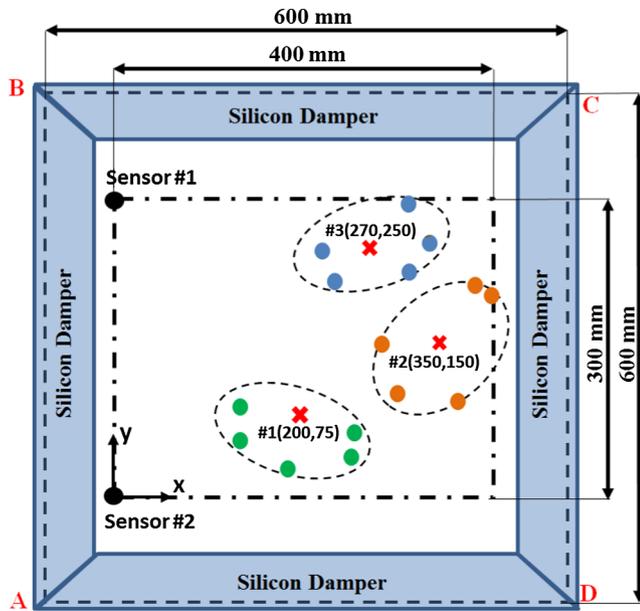


Fig. 8. Localization results of the test point in Fig. 6. The locations of the sensors and sources are shown by black circles and red crosses, respectively. Predicted acoustic source locations by the proposed method are shown by solid (blue, brown, green) circles, dashed and dashed-dot lines are defined plate edges and test zone, respectively. (For interpretation of the references to color in this Figure caption, the reader is referred to the web version of this paper).

$(x_{predicted}, y_{predicted})$ is the predicted location of acoustic source.

According to the Table 4, while the SSD is used (Test#2) the error value of ASL decreased significantly compared with Test#1. Average and maximum error in Test#1 are 77.46 and 83.09 mm, respectively, whereas in Test#2 these values are 69.29 and 72.80 mm, respectively.

To evaluate the sensitivity of the Test#2 to small variations, this test is repeated 5 times at three impact locations shown by red crosses in Fig. 6 and the final result are shown in Fig. 8. The corresponding errors are shown in Table 5.

The statistical analyses of the results are reported in Table 6. The average error and standard deviation of the Test#2 in fifteen iterations are 70.30 and 3.51 mm, respectively. The average uncertainties of test repetition are reported 1.57 mm (2.22%). According to Table 6, the maximum of repetition uncertainty for all three impact points is calculated to be less than 1.64 mm (2.27%) in the experiments. Although

Table 5
ASL errors. The experiments are repeated five times.

Test points	Exact location (mm)	Proposed method error (mm)				
		Iteration #1	Iteration #2	Iteration #3	Iteration #4	Iteration #5
Impact #1	(200, 75)	70.45	74.13	69.22	66.01	74.78
Impact #2	(350, 150)	64.63	65.61	63.11	71.09	68.89
Impact #3	(270, 250)	72.80	69.03	76.57	77.54	70.71

Table 6
The statistical analysis of the results reported in Table 5.

Test Points	Average (mm)	Standard deviation (mm)	Repetition uncertainty	
			Value (mm)	Percentage (%)
Impact #1	70.92	3.62	1.61	2.27
Impact #2	66.66	3.25	1.45	2.17
Impact #3	73.33	3.66	1.64	2.23
	Average = 70.30	Average = 3.51	Average = 1.57	Average = 2.22

the results show the robustness of the approach to the small variations, it is not perfectly preserved and more formal tests need to be carried out to verify this claim.

5. Conclusion

In this paper, the effects of reflected waves from the edge of an isotropic plate are discussed on plate source localization, using two acoustical low SRD sensors. The proposed method in this study is developed in two steps. First, the effects of SSD on reflected waves are analyzed due to corresponding signal energies. Moreover, in this step, the most effective damper among four dampers regarding, succeed to absorb maximum reflected waves is highlighted considering the sensor and impact positions. Second, the effects of SRD are discussed on sound source localization in a plate. To validate the proposed technique, an experimental set-up was conducted on a suspended Plexiglas plate using low sampling acoustical sensors. The results showed the effectiveness of the proposed technique in low SRD. The effects of mechanical and geometrical properties of these dampers are currently under investigation by the authors. The main contributions of this study can be known as the extension of acoustic emission localization implementation in a real world scenario. In this article, all the experiments are conducted based on low SRD. The authors accept the fact that using low sampling rate data has influenced the result of localization [1]. However, when the application is restricted to using low sampling rates the method proposed in this paper, demonstrates higher accuracy than the other methods. Therefore, it makes it difficult to perfectly analyze the reflected waves from the edges, although the results show the improvement. In summary, looking positively achievements of this study shows that:

- (1) The effects of reflected waves are decreased by using SSD.
- (2) The technique justifies industrial use of low SRD.

In return high lighting short comes:

- (1) Lamb wave reflection due to abrupt change in damper viscosity at plate surfaces near the plate boundary (known as impedance mismatch) is ignored.
- (2) The reliability of the approach in anisotropic plate is under question.
- (3) Use of SSD may not be applicable to all real scenarios.

Appendix A. Loci of k-Tuple distances method (LkTD) [1]

The Loci of k-Tuple Distances (LkTD) method is based on time-frequency properties. In this method, all of the points with common properties are classified as line patterns. So, any single point on each line can represent all the others which can be employed to detect the location of the source of impact. Consider the signals recorded by sensor #1 and sensor #2 are shown in Fig. 9, at time T_1 and T_2 known as clock times [2]. The calculation of time difference of arrival (TDOA), t_i , is possible according to Eq. (3) [2]:

$$t_{12} = t_1 - t_2 = T_1 - T_2 = T_{12} \quad (3)$$

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. (4), while C is the velocity of the wave travelling in the plate.

$$|\sqrt{(x_1 - x_p)^2 + (y_1 - y_p)^2} - \sqrt{(x_2 - x_p)^2 + (y_2 - y_p)^2}| = Ct_{12} \quad (4)$$

Estimation of TDOA in this method is based on the frequency properties of the signal. TDOA estimation is comprised of the following steps:

- Upsampling the recorded signals with integer interpolation factor $L = 5$.
- Spectrum analysis is applied to the above filtered signals.
- Estimation of t_{TDOA} is done by implementing cross correlation to the spectrum signals.

The impact is applied at point (x_p, y_p) , the distances from sensor #1 and #2 are d_1 and d_2 (see Fig. 9) and their ratio is called $k = d_1/d_2$. The locus of the impact points having the same constant k is a circle according to the following equations:

$$k = d_1/d_2 = \frac{\sqrt{x_p^2 + y_p^2}}{\sqrt{(x_p - D)^2 + y_p^2}}$$

$$x_p^2 + \frac{k^2 D^2}{k^2 - 1} - \frac{2k^2 D x_p}{k^2 - 1} + y_p^2 = 0, \quad k \neq 1$$

$$(x_p - \frac{k^2 D}{k^2 - 1})^2 + y_p^2 = \frac{k^2 D^2}{(k^2 - 1)^2}, \quad k \neq 1$$

$$(x_p - a)^2 + y_p^2 = R^2, \quad a = \frac{k^2 D}{k^2 - 1}, \quad R = \frac{kD}{k^2 - 1}, \quad k \neq 1 \quad (5)$$

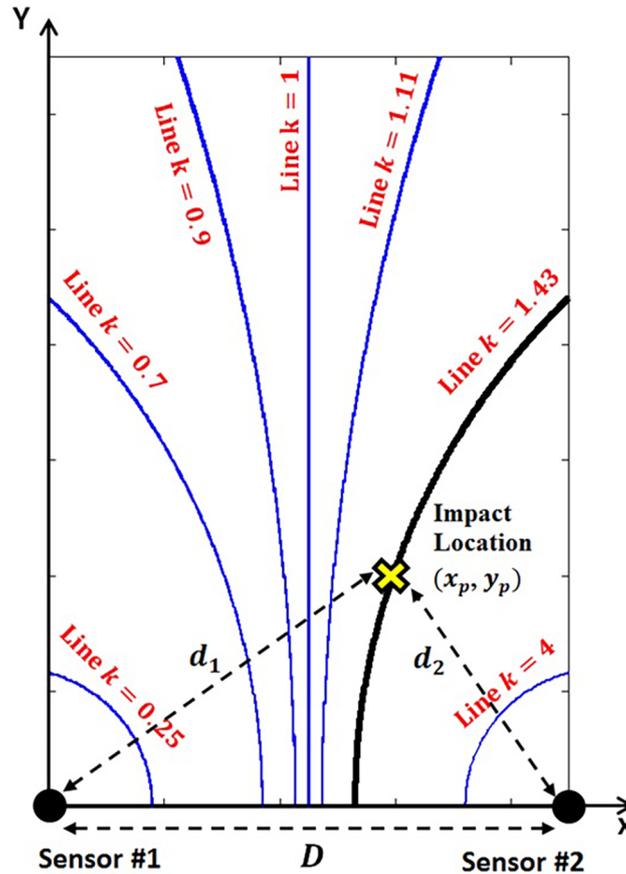


Fig. 9. Acoustic source and the two sensors locations (impact location is shown for $k = 1.43$ as an example) [1].

If $k = 1$, the locus will be a line with the equation $x = D/2$. Fifteen secondary points and their corresponding curved lines were used in this study. The unknown variables, x_p and y_p can be obtained by solving Eqs. (4) and (5) using Newton's iterative method. More information in this matter can be obtained from [1].

References

- [1] S.A.H. Sabzevari, M. Moavenian, Locating the acoustic source in thin glass plate using low sampling rate data, *Ultrasonics* 70 (2016) 1–11.
- [2] T. Kundu, Acoustic source localization, *Ultrasonics* 54 (1) (2014) 25–38.
- [3] N. Sen, T. Kundu, A new wave front shape-based approach for acoustic source localization in an anisotropic plate without knowing its material properties, *Ultrasonics* 87 (2018) 20–32 2018/07/01/.
- [4] S.A.H. Sabzevari, M. Moavenian, Sound localization in an anisotropic plate using electret microphones, *Ultrasonics* 73 (2017) 114–124.
- [5] M. Meo, G. Zumpano, M. Piggott, G. Marengo, Impact identification on a sandwich plate from wave propagation responses, *Compos. Struct.* 71 (3) (2005) 302–306.
- [6] T. Kundu, S. Das, S.A. Martin, K.V. Jata, Locating point of impact in anisotropic fiber reinforced composite plates, *Ultrasonics* 48 (3) (2008) 193–201.
- [7] T. Kundu, S. Das, K.V. Jata, Point of impact prediction in isotropic and anisotropic plates from the acoustic emission data, *J. Acoustic. Soc. Am.* 122 (4) (2007) 2057–2066.
- [8] T. Hajzargerbashi, T. Kundu, S. Bland, An improved algorithm for detecting point of impact in anisotropic inhomogeneous plates, *Ultrasonics* 51 (3) (2011) 317–324.
- [9] M. Koabaz, T. Hajzargerbashi, T. Kundu, M. Deschamps, Locating the acoustic source in an anisotropic plate, *Struct. Health Monitor.* 11 (3) (2011) 315–323.
- [10] E.D. Niri, A. Farhidzadeh, S. Salamone, Adaptive unscented Kalman Filter (UKF) for acoustic emission (AE) source localization in noisy environment, *Proc., Int. Soc. Opt. Photon.* (2013) 869513–869518-13.
- [11] E.D. Niri, A. Farhidzadeh, S. Salamone, Adaptive multisensor data fusion for acoustic emission source localization in noisy environment, *Struct. Health Monitor.* 12 (1) (2013) 59–77.
- [12] E.D. Niri, S. Salamone, A probabilistic framework for acoustic emission source localization in plate-like structures, *Smart Mater. Struct.* 21 (3) (2012) 035009.
- [13] E.D. Niri, S. Salamone, P. Singla, Acoustic emission (AE) source localization using extended Kalman filter (EKF), *Proc., Int. Soc. Opt. Photon.* (2012) 834804–834815.
- [14] F. Ciampa, M. Meo, Impact detection in anisotropic materials using a time reversal approach, *Struct. Health Monitor.* 11 (1) (2012) 43–49.
- [15] R. Ernst, F. Zwimpfer, J. Dual, One sensor acoustic emission localization in plates, *Ultrasonics* 64 (1) (2016) 139–150.
- [16] J.K. Agrahari, S. Kapuria, A refined Lamb wave time-reversal method with enhanced sensitivity for damage detection in isotropic plates, *J. Intell. Mater. Syst. Struct.* (2015) 1045389X15590269.
- [17] B. Park, H. Sohn, S.E. Olson, M.P. DeSimio, K.S. Brown, M.M. Derriso, Impact localization in complex structures using laser-based time reversal, *Struct. Health Monitor.* (2012) 1475921712449508.
- [18] J. LeClerc, K. Worden, W. Staszewski, J. Haywood, Impact detection in an aircraft composite panel—a neural-network approach, *J. Sound Vibration* 299 (3) (2007) 672–682.
- [19] J. Hensman, R. Mills, S.G. Pierce, K. Worden, M. Eaton, Locating acoustic emission sources in complex structures using Gaussian processes, *Mech. Syst. Signal Process.* 24 (1) (2010) 211–223.
- [20] M.G. Baxter, R. Pullin, K.M. Holford, S.L. Evans, Delta T source location for acoustic emission, *Mech. Syst. Signal Process.* 21 (3) (2007) 1512–1520 4.
- [21] K. Grabowski, M. Gawronski, I. Baran, W. Szychalski, W.J. Staszewski, T. Uhl, T. Kundu, P. Packo, Time-distance domain transformation for Acoustic Emission source localization in thin metallic plates, *Ultrasonics* 68 (2016) 142–149.
- [22] W.H. Park, P. Packo, T. Kundu, Acoustic source localization in an anisotropic plate without knowing its material properties: a new approach, *Proc., Int. Soc. Opt. Photon.* (2017) 98050J–98050J-11.
- [23] S. Al-Jumaili, M. Pearson, K. Holford, M. Eaton, R. Pullin, Fast and reliable acoustic emission source location technique in complex structures, *Mech. Syst. Signal Process.* (2016).
- [24] T. Kundu, X. Yang, H. Nakatani, N. Takeda, A two-step hybrid technique for accurately localizing acoustic source in anisotropic structures without knowing their material properties, *Ultrasonics* 56 (2015) 271–278.
- [25] F. Ciampa, M. Meo, A new algorithm for acoustic emission localization and flexural group velocity determination in anisotropic structures, *Compos. Part A: Appl. Sci. Manuf.* 41 (12) (2010) 1777–1786.
- [26] T. Kundu, A new technique for acoustic source localization in an anisotropic plate without knowing its material properties, 6th European Workshop on Structural Health Monitoring, 2012, pp. 3–6.
- [27] T. Kundu, H. Nakatani, N. Takeda, Acoustic source localization in anisotropic plates, *Ultrasonics* 52 (6) (2012) 740–746.
- [28] H. Nakatani, T. Kundu, N. Takeda, Improving accuracy of acoustic source localization in anisotropic plates, *Ultrasonics* 54 (7) (2014) 1776–1788.
- [29] A. Ebrahimkhanlou, S. Salamone, Single-sensor acoustic emission source localization in plate-like structures using deep learning, *Aerospace* 5 (2) (2018) 50.
- [30] A. Ebrahimkhanlou, B. Dubuc, S. Salamone, Damage localization in metallic plate structures using edge-reflected lamb waves, *Smart Mater. Struct.* 25 (8) (2016) 085035.
- [31] S.M.H. Hosseini, A. Kharaghani, C. Kirsch, U. Gabbert, Numerical simulation of Lamb wave propagation in metallic foam sandwich structures: a parametric study, *Compos. Struct.* 97 (2013) 387–400.
- [32] Y. Shen, V. Giurgiutiu, Effective non-reflective boundary for Lamb waves: Theory, finite element implementation, and applications, *Wave Motion* 58 (2015) 22–41.
- [33] A. Ebrahimkhanlou, S. Salamone, Single-sensor acoustic emission source localization in plate-like structures: a deep learning approach, *Proc., Int. Soc. Opt. Photon.* (2018) 106001O.
- [34] V. Giurgiutiu, *Structural health monitoring: with piezoelectric wafer active sensors*, Academic Press, 2007.
- [35] Z. Fan, W. Jiang, M. Cai, W.M. Wright, The effects of air gap reflections during air-coupled leaky Lamb wave inspection of thin plates, *Ultrasonics* (2015).
- [36] M.R. Gorman, W.H. Prosser, AE source orientation by plate wave analysis (1991).
- [37] M. Shehadeh, J. Steel, R. Reuben, Acoustic emission source location for steel pipe and pipeline applications: the role of arrival time estimation, *Proc. Inst. Mech. Eng., Part E: J. Process Mech. Eng.* 220 (2) (2006) 121–133.
- [38] R. Kuwahara, H. Ojima, T. Matsuo, H. Cho, Development of acoustic emission waveform simulation technique utilizing a sensor response and finite-difference time-domain method, *J. Solid Mech. Mater. Eng.* 7 (2) (2013) 176–186.