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Damage Detection by Applying Three-Dimensional Source Location of Acoustic Emission Technique

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ABSTRACT
Damage evaluation has become the recent event of research in conducting mechanical maintenance evaluation of engineering structures. Acoustic emission (AE) technique is regarded an invaluable nondestructive technique (NDT) tool in structural health assessment, especially in a dynamic mode. Source location routines are practicable in AE monitoring to recognize the existence of damage as well as damage mechanisms. Hsu-Nielsen (H-N) method has been used as a simulated source for AE source location applications. Time of arrival (TOA) is the basic phenomenon for the damage evaluation in the present technique. This paper presents an experimental validation of three-dimensional (3D) AE source location using time difference of arrival (TDOA) measurements from multiple sensor locations. At least four sensors are necessary for a 3D source location. However, in the present experiment, six sensors have been used to get a robust source location. Six piezoelectric sensors (model R15α with a frequency range 50-200 kHz), six preamplifiers (model 2/4/6), and an eight-channel AE acquisition board featured with AEwin software of Physical Acoustics Corporation have been used for data collection. 3D source location method has been applied to an iron specimen, and the evaluation output of proposed investigation has clarified in the present document.

Keywords: Acoustic emission, 3D Source location, Damage detection, biomedical application.

1. Introduction

Present importance in source identification as well as damage evaluation has become the increasing research interest among the researchers to assess the mechanical performance of engineering structures. Nondestructive Testing (NDT) is an engineering area that involves condition examination for material in related components damage situation identification and check faults, damages prolonging to the infrastructure's durability [1]. Conventionally, visual testing (VT), magnetic particle testing (MPT), etc. have been using to detect surface flaws, and radiography, ultrasonic testing (UT), etc. have been using to detect internal flaws. Regarding to that, AE monitoring is an important technique in nondestructive evaluation that can find both internal geometric defects and surface geometric defects. AE differs from other NDT techniques in a significant way that, at the very beginning of any tiny flaw, this technique identify damage features in running condition as well. In contrast, other NDT methods recognize the defect when it becomes matured [2].

AE refers to the generation of transient elastic waves (sonic and ultrasonic sound signals) generated due to the quick emission of elastic waves inside the subjects under stress. In damage monitoring and condition inspection of industrial structures, the AE technique has been broadly used for years as non-destructive testing (NDT) tool in many engineering applications [3]. This technique is identified as a valuable tool for finding the dynamical features in testing devises by enabling the damage values and damage occurring places inside the materials. In AE monitoring, damage localization indicates possibly an important monitoring item [4]. This primary aim in an AE testing is often to locate the source of essential stress wave emissions in AET. The related signal detection and analysis may provide useful information about the signal origination, thus it meaning about a discontinue-position inside the subject. Since the mentioned signal propagation may happen due to formations as well as progression of generating flaws, the source position is, therefore, a crucial primary tool in AE testing [5].

In order to classify the existence of damage as well as damage mechanisms, source location algorithms are helpful. Getting simulated signals in the proposed research, breaking of pencil lead tests are conducted which generate simulated AE signals as H-N (Hsu-Nielsen) source [6]. The generation of H-N signal as AE simulated source are widely used all over the world in AE experiments. This simulated source of acoustic emission was first produced by breaking the lead of pencil, and thus, it has been named as H-N source or as well-known technique named pencil-lead-break (PLB) tests.

The present research has been conducted on an iron cube to clarify the validity of damage localization technique in the proposed acoustic emission technique. The process has been elaborately emphasized in clarifying the further fields like biomedical as well. The time-of-arrival (TOA) is defines as a key feature in detection of signal-source in AE damage evaluation method. The traveling time necessary from the signal source to a signal acquisition sensor is termed as TOA. Again, the difference of TOA between two sensors is defined as time difference of arrival (TDOA). This paper presents a validation of three-dimensional (3D) AE source location using TDOA method and the evaluated experimental results are summarized the in the present paper as well.

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2. Theory of 3D source location

The time difference of arrival (TDOA) method is a frequently used technique for source localization [7–9]. According to the theory, the measurement of source position in 3-dimensions requires at least four sensors. However, for better accuracy of source position, it is advised to use more sensors than the least number of sensors, as more sensors contribute to a better geometry of the sensor array [10, 11].

The TDOA approach is applied in the present research as well. Six sensors are used in this approach to measure the position of the source in 3D. The coordinates of six sensors are mentioned as $S_1(x_1, y_1, z_1)$, $S_2(x_2, y_2, z_2)$, $S_3(x_3, y_3, z_3)$, $S_4(x_4, y_4, z_4)$, $S_5(x_5, y_5, z_5)$ and $S_6(x_6, y_6, z_6)$, where, $P(x_s, y_s, z_s)$ is assumed for an arbitrary AE source. The arbitrary sensor arrangements in 3D geometry are shown in Fig.1. The wave propagation medium is assumed as homogeneous, and the propagation speed is assumed as constant. Therefore, the equations governing the location of AE sources are expressed as follows [12]:

$$(x_1 - x_s)^2 + (y_1 - y_s)^2 + (z_1 - z_s)^2 = v^2 {t_0}^2 \quad (1)$$

$$(x_2 - x_s)^2 + (y_2 - y_s)^2 + (z_2 - z_s)^2 = v^2(t_0 + t_{12})^2 \quad (2)$$

$$(x_3 - x_s)^2 + (y_3 - y_s)^2 + (z_3 - z_s)^2 = v^2(t_0 + t_{13})^2 \quad (3)$$

$$(x_4 - x_s)^2 + (y_4 - y_s)^2 + (z_4 - z_s)^2 = v^2(t_0 + t_{14})^2 \quad (4)$$

$$(x_5 - x_s)^2 + (y_5 - y_s)^2 + (z_5 - z_s)^2 = v^2(t_0 + t_{15})^2 \quad (5)$$

$$(x_6 - x_s)^2 + (y_6 - y_s)^2 + (z_6 - z_s)^2 = v^2(t_0 + t_{16})^2 \quad (6)$$

where, t_0 is the AE wave propagation time from the source to the nearest sensor 1 (S_1). The TDOAs between sensor 1 and sensor 2, 3, 4, 5 and 6 are represented as t_{12}, t_{13}, t_{14}, t_{15} and t_{16} respectively. AE wave propagation velocity is represented as v. According to space geometry, Eqs. (1) – (6) represent spheres, each of which considers the respective sensor positions as its geometric center. The source point of the generated AE signals are identified from analyzing of above equations. The coordinate of this intersecting point is the coordinate of the source.

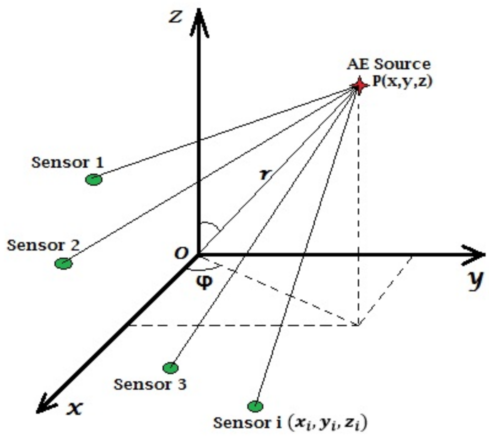
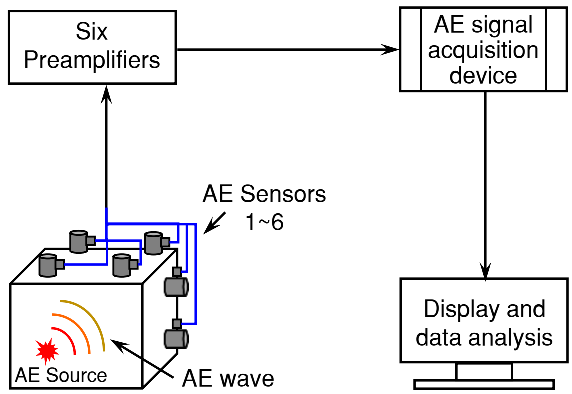


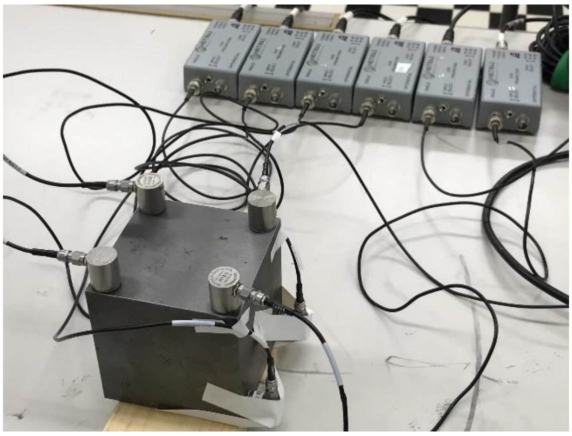
Fig.1 Schematics of sensor arrangements in 3-dimension.

3. Experimental methodology

Artificial AE events have been simulated based on the standards of the H-N method using pencil-lead breaks (PLB) on an iron cube having a dimension of 100 mm^3. The acquisition system of AE signals from the iron cube has been proposed according to the schematic view, as shown in Fig.2. Related apparatus that are necessary for the proposed experiment are shown in following figures (Fig. 2(a) and Fig. 2(b)). The acquisition system consists of six AE sensors (Physical Acoustics Corporation, model R15α, frequency 50-200 kHz) has been attached to the six corners of the iron cube, six preamplifiers (2/4/6 of Physical Acoustics Corporation) to provide 40 dB gain for each sensor, and an AE acquisition device (PC featured with AEwin software of Physical Acoustics Corporation) to control the signal acquisition and signal processing. All sensors are connected to the AE signal acquisition device through the respective preamplifiers.



(a)



(b)

Fig.2 Experimental apparatus and the operating setup; (a) experimental schematics, (b) sensor connections to each preamplifier.

A high vacuum silicone coupling gel (Shin-Etsu HIVAC-G, Shin-Etsu Chemical Co., Ltd.) is used between the sensing surface of the sensor and the contact place to the iron cube in order to remove any air gap. For the acquisition of AE signals, 1 MHz sampling frequency is used.

4. Experimental results and discussion

The 3D source location experiments have been performed on an iron cube by applying the AE experimental methodology, as mentioned above. The sensor arrangements as well as axis directions of six sensors (S1~S6), are shown in Fig.3. The coordinates of six sensors are presented in Table 1, where sensor 3 (S3) is considered as the reference sensor from which source location coordinates have been calculated. Three locations of AE sources have been considered randomly for the validation of the 3D source location method. A total of five PLB tests have been conducted at each location, and the trigger times (representing TOA) have been recorded by the spatially distributed six sensors. For each PLB, the source location is calculated, and averaging has been done by averaging results from five consecutive tests at each location. Finally, the average result has been compared with the actual location. The lead breaking place and the lead breaking conditions have been kept the same in all of these five consecutive tests at each location. The wave propagation speed used in this experiment is 5900 m/s. The coordinates of six sensors, their trigger times, and the mentioned wave speed have been used to calculate the locations of AE sources. All numerical results are summarized in Table 2, where the comparisons between actual and calculated source locations are also shown. The graphical representation of these results in a 3D plot is shown in Fig.4 as well. Results show that the calculated coordinates are very consistent with the actual coordinates.

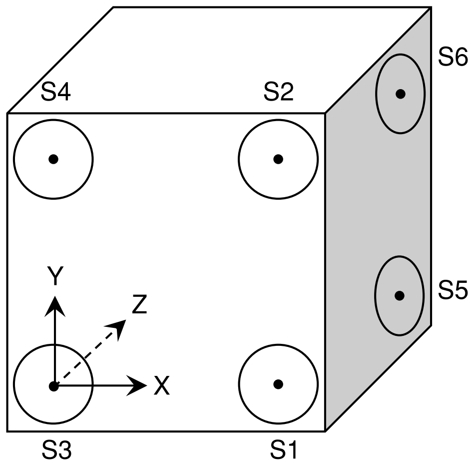


Fig.3 Schematics of sensor arrangements in a cubic setup for 3D source location.

Table 1 Coordinates of six AE sensors.

Sensor Number	Sensor Coordinates (mm)		
	X Coordinate	Y Coordinate	Z Coordinate
S1	80	0	0
S2	80	80	0
S3	0	0	0
S4	0	80	0
S5	90	0	90
S6	90	80	90

Table 2 Comparative results of AE source location between actual and calculated locations.

Location Number	Actual Location (mm)			Calculated Location (mm)		
	X	Y	Z	X	Y	Z
1	25	60	0	26.86	59.24	0.70
2	35	70	0	36.96	72.02	1.32
3	50	20	0	50.00	19.61	0.04

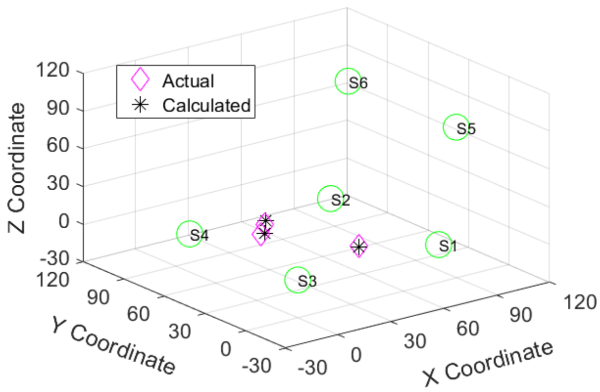


Fig.4 Actual and calculated locations of AE sources in 3D plot.

5. Biomedical application of 3D AE source location technique in knee damage detection

Having the advantage of nondestructive damage evaluation, recent interests have been focused on the application of the AE technique to the identification of the damage location in the osteoarthritic knee joint [13]. Osteoarthritis (OA) is the most common form of knee disease, which is caused by the articular cartilage damage inside the knee joint. Therefore, an initial investigation of damage detection in OA knee by 3D source location of AE technique has been conducted on an OA patient in the present research as well. Six AE sensors have been attached to the anatomical sites of the knee joint. Out of six sensors, three sensors are attached to the tibia bone, and three sensors are attached to the femur bone. For attaching AE sensors, a high elastic medical adhesive tape is used. To produce adequate AE signals in the knee joint, the frictional surfaces of the joint have been provided with ample stress through dynamic sit-stand-sit movements. In response to all sensors, the time of arrivals of AE signals at each sensor have been recorded

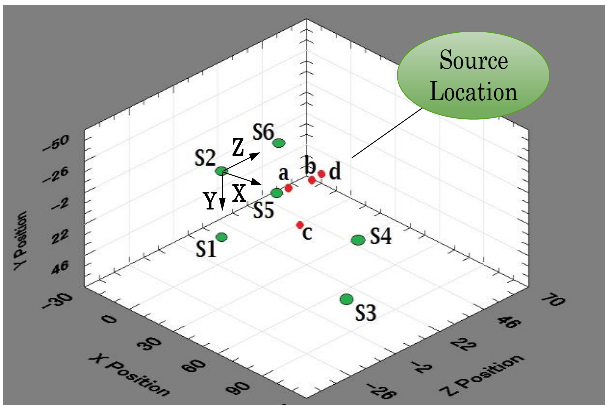


Fig.5 Sensor locations (S1-S6) for AE data acquisition and 3D source location from the damaged knee joint.

Table 3 Calculated coordinates of source locations in X, Y, Z dimensions from the knee joint experiment.

Sensor Number	Source Location Coordinates (mm)		
	X Coordinate	Y Coordinate	Z Coordinate
a	9.24	28.0	28.7
b	10.1	29.6	40.7
c	23.1	45.3	25.3
d	15.2	22.6	41.2

for each sit-stand-sit movements, and the location of the sources have been calculated. The experimental results of source location in 3D plot are shown in Fig.5. In this experiment, sensor 2 (S2) has been considered as the reference sensor from which source location coordinates are calculated. Four locations (numbered as a,b,c,d) have been calculated numerically and presented in Table 3. Out of four locations, three locations (a,b,d) have been found closer to the damaged area. However, one location (c) has been found deviated from the damaged area, which is considered as source location error due to the signal acquisition artifacts from the highly inhomogeneous knee joint.

6. Conclusions

In this research, acoustic emission technique has been applied as an experimental validation of three-dimensional (3D) AE source location using time difference of arrival (TDOA) measurements from multiple sensor locations for industrial as well as biomedical applications. 3D source location method has been applied to an iron specimen, and consistent results have been identified. The source location (damaged location) of the osteoarthritic knee has also been identified in three dimensions by applying the proposed AE experimental methodology. The majority of source locations have been found closer to the damaged area.
However, one of the source locations obtained in this experiment showed a deviated location from the damaged area. It is considered as the cause that the waveform of the AE wave might be changed during propagation as it passes through various layers such as bone, cartilage, muscle, skin, etc. This area will be considered as a future improvement in source location research in OA knee.

7. Acknowledgement

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