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Localization of Multiple Leak Sources Using Acoustic Emission Sensors Based on MUSIC Algorithm and Wavelet Packet Analysis

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Abstract*—Multiple leak sources may occur in a large pressure vessel that contains corrosive materials or has been in use for a long period of time. Although a variety of leak localization methods have been proposed in previous studies, they are capable of locating only a single leak source. Methods for simultaneous localization of multiple leak sources are desirable in practical applications. To address this issue, a novel method using acoustic emission (AE) sensors in conjunction with MUltiple SIgnal Classification (MUSIC) algorithm and wavelet packet analysis is proposed and experimentally assessed. High-frequency AE sensors are assembled into a linear array to acquire signals from multiple leak sources. Characteristics of the leak signals are analyzed in the frequency domain. Wavelet packet analysis is deployed to extract useful information about the signals from the frequency band of 50 kHz - 400 kHz. The MUSIC algorithm is applied to identify the directions of the leak sources through a space spectrum function. Leak sources are located based on the directions identified by the AE sensor array placed at different locations. The performance of the proposed method is evaluated through experimental tests on a stainless steel flat plate of 100 cm ×100 cm×0.4 cm. The results demonstrate that the method is capable of locating two leak holes. In addition, the localization accuracy depends on the leaking pressure. It is demonstrated that the two leak holes are located within two small areas, respectively, which are 25.12 cm^2 for leak hole 1 and 1.96 cm^2 for leak hole 2.

***Index Terms*—Acoustic emission, localization, multiple leak sources, MUSIC, wavelet packet**

I. Introduction

LARGE PRESSURE vessels are widely used in a range of industrial processes such as carbon capture and storage (CCS) [1], natural gas transportation [2, 3] and fuel supply systems [4]. Most of the vessels used in industry are filled with fluid or gas materials that are of high temperature, high pressure, inflammable, explosive or poisonous. Once leakage occurs, the leaked substance can lead to severe accidents which endanger human lives and the environment [5]. Leakage is a potential hazard from almost all large vessels in industry.

Leak localization has been studied for decades. Several methods have been proposed, including soap screening, negative pressure wave, optical fiber sensing and infrared imaging [6]. Most of the previous studies were conducted under the condition that there was only a single leak source in the area of interest. However, multiple leak sources in a large vessel are common, especially if the vessel contains corrosive substance or has been in use for a long period of time. To date there have been very limited studies of localization of multiple leak sources. In the field of leak localization of water distribution network, Soldevila *et al.* [7, 8] presented a method using pressure sensors and Bayesian classifiers. The leak sources with a posterior probability above a specified threshold were selected as candidates. Zan *et al.* [9] used joint time frequency analysis of pressure fluctuations for the localization of multiple leak sources. However, hundreds of sensors were required for a large distribution network since leak sources were assumed to appear only on the nodes of the network. This type of system is of high capital cost and labour-intensive during system installation and maintenance. Zhao and Yang [10] conducted the diagnosis and localization of multiple leak sources in a gas pressure vessel through infrared imaging. The advantage of this technique is that interference of leak signals from different leak sources can be avoided. However, this method is adversely affected by the shape of the surface area. If the surface area is irregular, the technique will underperform. In the field of leak localization, acoustic emission (AE) techniques have been successfully applied to locate a single leak source. However, when multiple leak sources exist at the same time, the localization problem becomes more complex because the leak signals interfere with each other. Under such cases conventional methods such as triangulation [11], hyperbola [12], and beamforming [13] provide inaccurate or even erroneous results. The interference of AE waves produces a superimposed signal at the sensor location, which may differ completely from the individual signal. Boya *et al.* [14] combined AE sensing and blind signal separation techniques to recover the signals from multiple sources. The localization was realized through the measurement of time difference of arrival. However, waveform distortion due to dispersion is inevitable in the propagation process of acoustic waves [15]. This is

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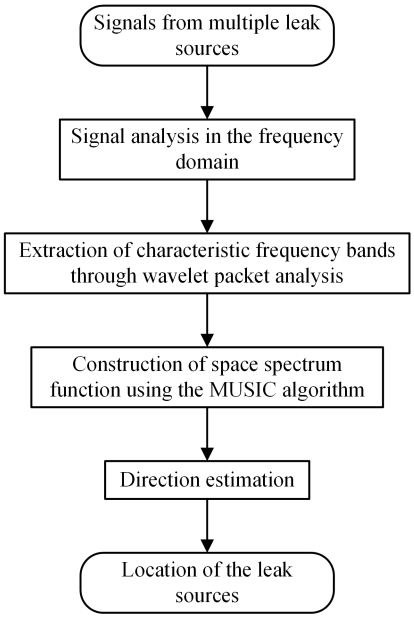


Fig. 1. Key steps in the localization method.

particular true for high-frequency signals, which severely affects the localization accuracy.

This study aims to develop a method for simultaneous localization of multiple leak sources through a combination of AE sensors, MUltiple SIgnal Classification (MUSIC) algorithm and wavelet packet analysis. In comparison with other methods, the AE method has advantages of high sensitivity, non-invasiveness, high location accuracy and good adaptability [16]. Unlike conventional methods such as triangulation [11], hyperbola [12], and beamforming [13] based on the time delay of the sensors, the localization method proposed in this paper utilizes the orthogonality between the signal and noise subspaces. Additionally, narrow-band signals are used instead of the original signals to minimize signal distortion in the conventional methods due to frequency dispersion. AE signals are generated when a pressure vessel is leaking. The air-structure coupling between the high-speed jet of a gaseous or liquid medium and the vessel wall near leak sources generates stress waves [17], which spread along the vessel wall. In this paper, an AE sensor array is used to obtain the leak signals from multiple leak sources. Since a small, plane area on a large pressure vessel can be regarded as a flat-surface structure, this study focuses on the detection of the leak sources in a flat-surface structure. It should be noted that only four AE sensors are required when there are two leak sources in this study, which implies a significant reduction of cost compared to other techniques for the same application [10]. In consideration of the broadband nature of the AE signals, wavelet packet analysis is used as a tool to extract useful narrowband information from the signals. Then a space spectrum function is defined based on the MUSIC algorithm to identify the directions of the leak sources. Leak sources are finally located by fusing the information from the sensor array at three different locations.

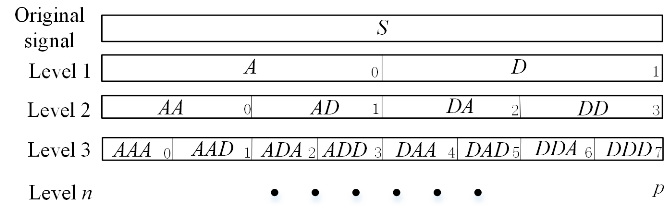


Fig. 2. N-level wavelet packet decomposition.

II. Methodology

Localization of a continuous leak is challenging because there is no noticeable starting feature and obvious sharp rising edges of the signal in the time domain. It is generally broadband in the frequency domain and cannot be directly utilized by the MUSIC algorithm. For this reason an effective tool for the extraction of a narrowband in the frequency domain is required. In the MUSIC algorithm, the independence of signals from background noise is used to construct a space spectrum function, on the basis of which the directions of multiple leak sources are identified. The positions of the leak sources are calculated when several directions are obtained. In summary, the localization process in this study includes several key steps, as shown in Fig. 1. Firstly, signals are analyzed in the frequency domain. Secondly, wavelet packet analysis is conducted to obtain the characteristic frequency bands. Thirdly, a space spectrum function is constructed based on the MUSIC algorithm. Fourthly, directions of the leak sources are obtained by searching the peaks of the space spectrum. Finally, localization of the leak sources is determined by multiple directions.

A. *Wavelet packet analysis*

The MUSIC algorithm is a method to estimate directions of narrowband signals. However, leak signal is broadband in the frequency domain. In this case, wavelet packet analysis is an effective tool. Coifman [18] introduced wavelet packet to extend the application of wavelet to signal processing. In traditional wavelet analysis, only the lower-frequency band is used for further decomposition. It has a low frequency resolution in the high-frequency band and a low time resolution in the low-frequency band. However, wavelet packet partitions both the high and low-frequency bands into smaller subspaces, which improves the resolution of the signal. For this reason, wavelet packet analysis finds more extensive applications [19, 20]. In view of its advantages, wavelet packet is applied in this study to extract the characteristic frequency bands from the AE signals. The target band can be easily obtained when a decomposition level and an appropriate wavelet packet node are set. Here, a n-level wavelet packet decomposition is illustrated in Fig. 2, where S indicates the original signal and A and D represent its low- and high-frequency bands, respectively. A pair of conjugate mirror filters are used to divide the frequency band. As a result, the signal is decomposed into two equal halves: low-frequency band (approximation coefficients) and high-frequency band (detail coefficients). Both the low- and high-frequency bands are used for further decomposition.

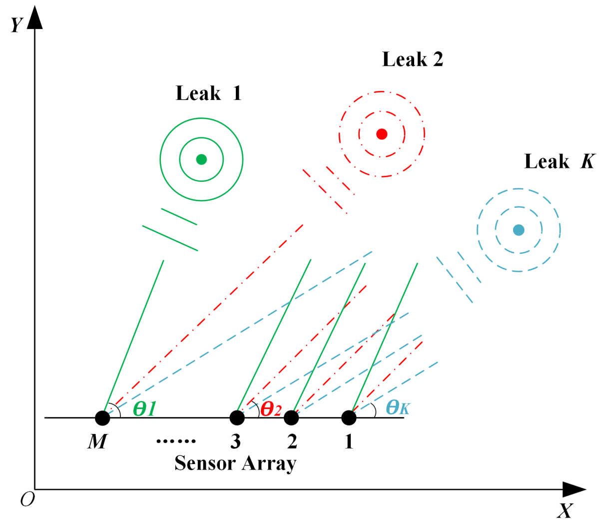


Fig. 3. Direction identification of multiple leak sources with a sensor array.

Taking a 3-level wavelet packet decomposition as an example, the decomposition principle is described as

$$S = AAA + AAD + ADA \\ + ADD + DAA + DAD + DDA + DDD \tag{1}$$

The decomposition is a balanced structure. Each subspace of the structure is indexed by its level n and subspace p. Based on a parent node (n, p), two new wavelet packet coefficients are determined as follows:

$$x_{n+1}^{2p}(k) = \sum_l h(l-2k)x_n^p(l) \tag{2}$$

$$x_{n+1}^{2p+1}(k) = \sum_l g(l-2k)x_n^p(l) \tag{3}$$

where x stands for the wavelet packet coefficients, h and g are low- and high-pass filters, respectively, which are also a pair of conjugate mirror filters, and k and l are the index numbers of the signals in the time domain.

B. MUSIC algorithm

When multiple leak sources exist at the same time, a method which can overcome mutual interference between each other is required in the localization process. The MUSIC algorithm was introduced by Schmidt [21] on an antenna array and can be used as a tool for direction identification. It has been widely used in communication and biomedical engineering and has achieved some successes in recent years [22, 23]. There have also been recent studies of this method for the localization of sound sources [24, 25]. However, limited research work has been undertaken for leak localization.

The direction identification of multiple leak sources with a linear sensor array is illustrated in Fig. 3. The AE sensors, numbered from 1 to M, are linearly arranged. Leak sources are in different directions from the sensor array.

When multiple leak sources exist, there is a time delay of each sensor due to wave-path difference. Different leak sources are in different directions of the array, which leads to different time delays. The output of sensor i ($0<i<M+1$) is obtained by

$$x_i(t) = \sum_{k=1}^{K} s_{k1}(t)e^{-j2\pi f\tau_{ki}} + n_i(t) \tag{4}$$

where s_{k1} and $n_i(t)$ represent the signal from leak source k received by the reference sensor and the noise of sensor i. f and τ_{ki} represent the frequency of the signal and the time delay. Then the output of the sensor array can be expressed as

$$X(t) = A(\theta)S(t) + N(t) \tag{5}$$

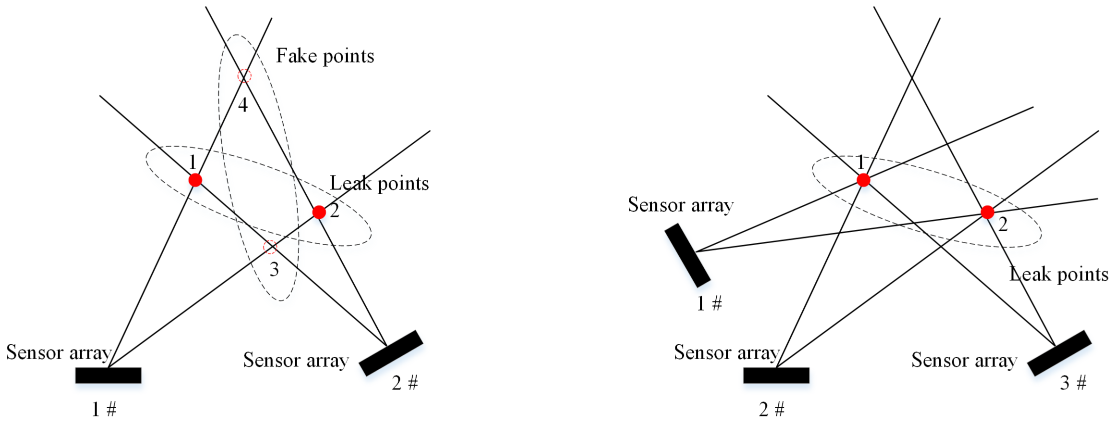
where $A(\theta)$ and $S(t)$ are the time delay matrix formed by K column vectors and the signals matrix of K reference sensors, respectively, and $N(t)$ the noise matrix. On the basis of the orthogonality of the time-delay matrix $a(\theta)$ based on direction scanning and the matrix V_N formed by ($M-K$) eigenvectors of covariance matrix of the array signal $X(t)$ [26], the space spectrum function is defined as

$$P(\theta) = \frac{1}{a^H(\theta)V_N V_N{}^H a(\theta)} = \frac{1}{\left\| V_N{}^H a(\theta) \right\|} \tag{6}$$

The denominator of (6) is zero when $a(\theta)$ and V_N are orthotropic. However, it is a small value in practice because of the noise. As a result, $P(\theta)$ has one peak or more. The directions corresponding to the peaks are the directions of the leak sources. In order to be more intuitive, the base-10 logarithm of $P(\theta)$ is used in the description of the experimental results (Section III. C).

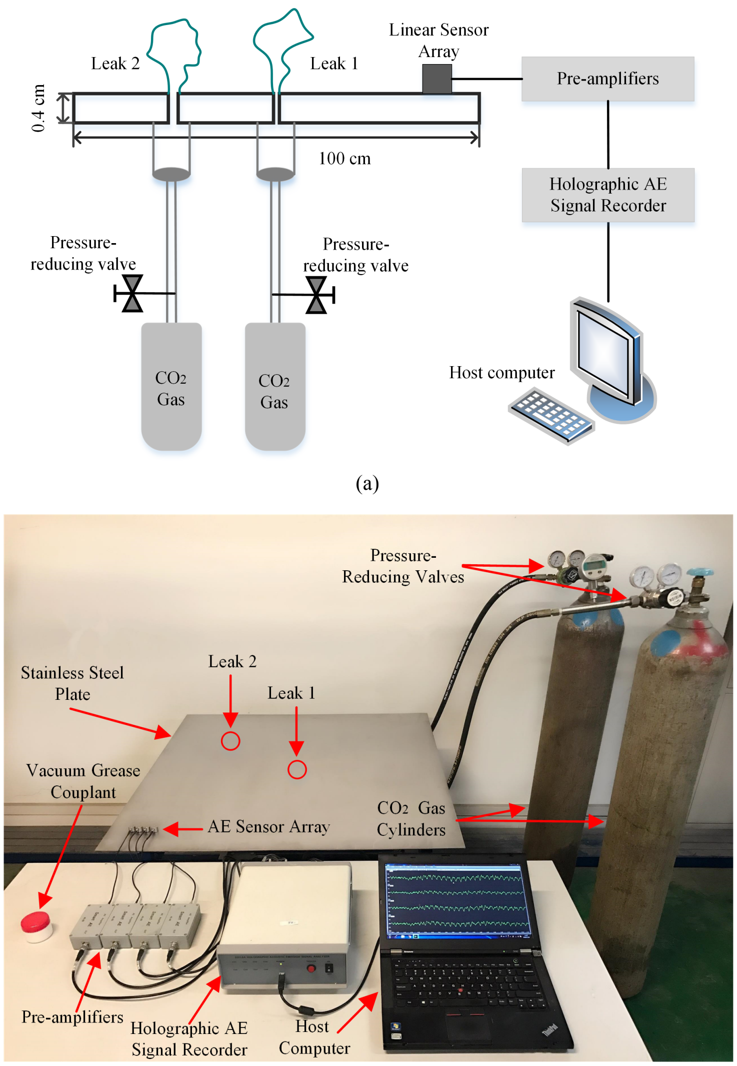
C. Localization

Directions of the leak sources are identified from the outputs of the AE sensor array using the MUSIC algorithm. If there is only one leak source, the sensor array should be used at least twice. However, when two leak sources or more exist, the sensor array should be used at least three times. In order to determine the locations of two leak sources or more, the sensor array should be placed at least at three different locations in sequential order to obtain the corresponding directions. The intersections of the identified directions are the locations of the leak sources. Fig. 4 (a) shows the fact that, when the sensor array is used only twice, localization cannot be realized. In this case, two directions are obtained through the sensor array at each location. Then two "fake points" and two "leak points" are obtained based on four directions. To identify the two fake points, the sensor array must be placed at an additional location for leak detection, as shown in Fig. 4 (b). When the three directions based on three different array locations intersect at one point, a leak source is then located. Based on this principle, localization of two or more sources is realized.



(a) (b)

Fig. 4. Localization using the array at two and three locations. (a) Two locations. (b) Three locations



(b)

Fig.5. Experimental set-up. (a) Schematic. (b) Photo.

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III. Experimental Results and Discussion

A. Experimental set-up

To evaluate the effectiveness of the proposed method for the localization of multiple leak sources, a series of experiments were carried out on a 304 stainless steel plate with dimensions of 100 cm × 100 cm × 0.4 cm. This type of structure is generally seen in large pressurized vessels.

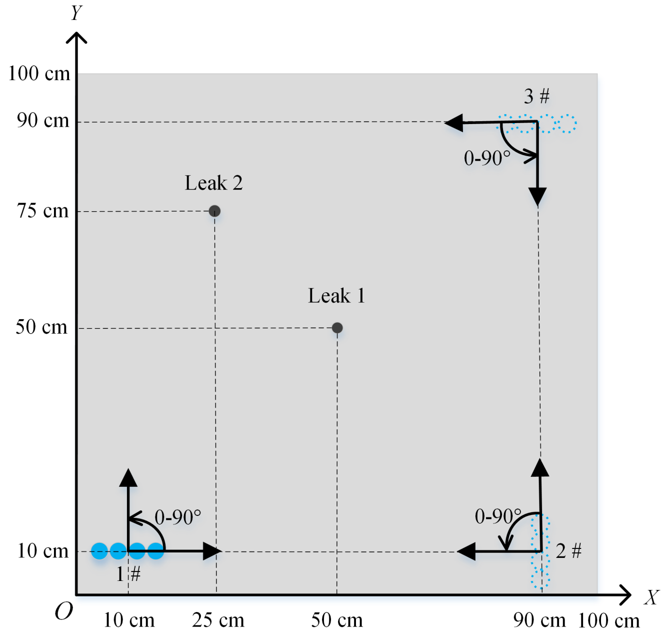

Fig. 6. Arrangement of the sensor array.

Fig. 7. Photo of the AE sensor RS-2A.

The experimental set-up is shown in Fig. 5. Two circular holes with diameters of 1 mm and 2 mm were drilled on the plate at locations of (50 cm, 50 cm) and (25 cm, 75 cm), respectively, with the origin defined at the bottom-left corner of the plate, as shown in Fig. 6. Two bottles of CO_2 gas were used at a constant pressure of 0.2 bar to create two continuous leak sources. The gas pressure was controlled by pressure-reducing valves.

As described above, the AE sensor array was placed at three different locations, labelled as locations 1#, 2#, and 3# on the plate, at the coordinates of (10 cm, 10 cm), (90 cm, 10 cm), and (90 cm, 90 cm), respectively, as shown in Fig. 6. Polar coordinates are defined for the array at each location, with the polar at the geometric center of the array. Direction from 0° to 90° was scanned at each location. The sensor array has four sensing elements with an equal spacing of 2 cm between a pair of adjacent elements. The sensors were attached to the plate using vacuum grease couplant.

The background noise such as machine vibration is usually below 100 kHz. In addition, leak acoustic signals distribute mainly under 400 kHz [27]. In this study, AE sensors (model

TABLE I

TECHNICAL SPECIFICATIONS OF THE AE SENSORS

Property	Value
Diameter	18.8 mm
Height	15.5 mm
Bandwidth	50 kHz - 400 kHz
Operating temperature	-20 °C - 200 °C

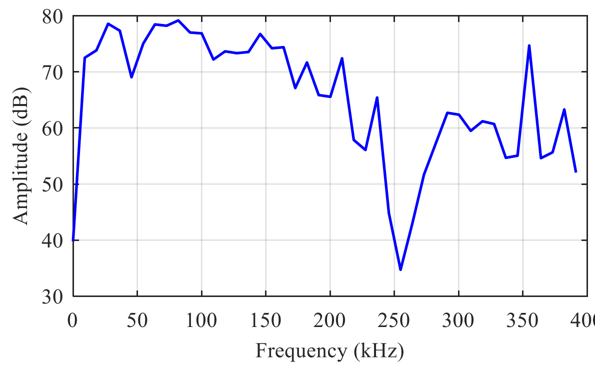

Fig. 8. Frequency response of the RS-2A sensor.

type RS-2A, Softland Co. Ltd) with a bandwidth of 50 - 400 kHz are used. The sensing element of the AE sensor (Fig. 7) is a piezoelectric film, which transforms displacement due to incoming acoustic waves to electric charge. The charge signal is then transformed into a voltage signal using a preamplifier. The technical specifications of the AE sensors are summarized in TABLE I whilst the typical frequency response characteristics are plotted in Fig. 8. There is no cross-talk among the sensors, because they are configured to work in a passive mode and do not disturb the propagation of the AE waves. The amplifiers used have a bandwidth of 10 kHz - 1 MHz and a gain of 40 dB. A holographic AE signal recorder (model type DA-8A, Softland Co. Ltd) was used to acquire the AE data at a sampling rate of 3 MHz.

B. Characteristics of the AE leak signals

Due to the fact that the sensors are close to each other (2 cm), the signals received from the sensors appear to be similar. Taking the signal from sensor 1 (for the sensor array, the sensors are numbered from small to large in the positive direction of the X or Y coordinate) at 1# as an example, the waveform of the signal and its corresponding power spectral density (PSD) are plotted in Fig. 9.

In the time domain, the signal is continuous and fluctuates between -40 mV and 40 mV. In the frequency domain, the signal contains frequencies with two main regions, with one in the high frequency band (156 kHz - 187 kHz) and the other in the low frequency band (63 kHz - 121 kHz). The frequency band of 156 kHz - 187 kHz is chosen as the characteristic frequency band because its amplitude is relatively high and this band is less adversely affected by ambient noise compared to the low-frequency band. It should be noted that the AE detection technique favors relatively high frequency for stainless-pressure vessels in practical applications in consideration of the factors of attenuation and signal-to-noise

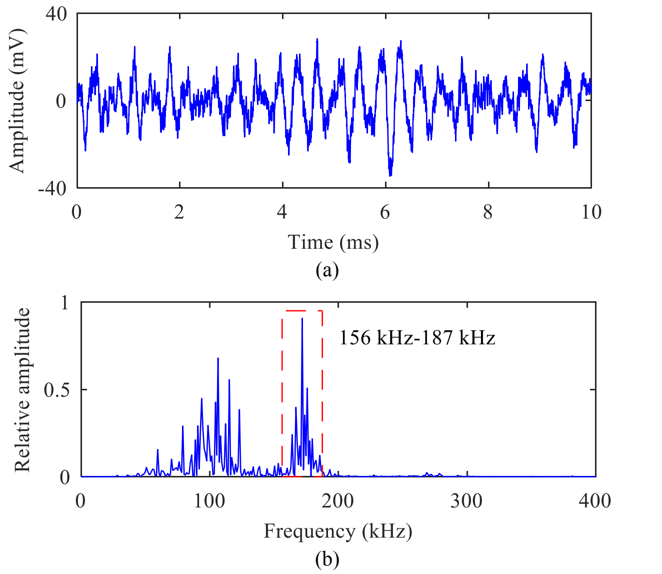

Fig. 9. Typical signal waveform and its corresponding PSD. (a) Time domain. (b) Frequency domain.

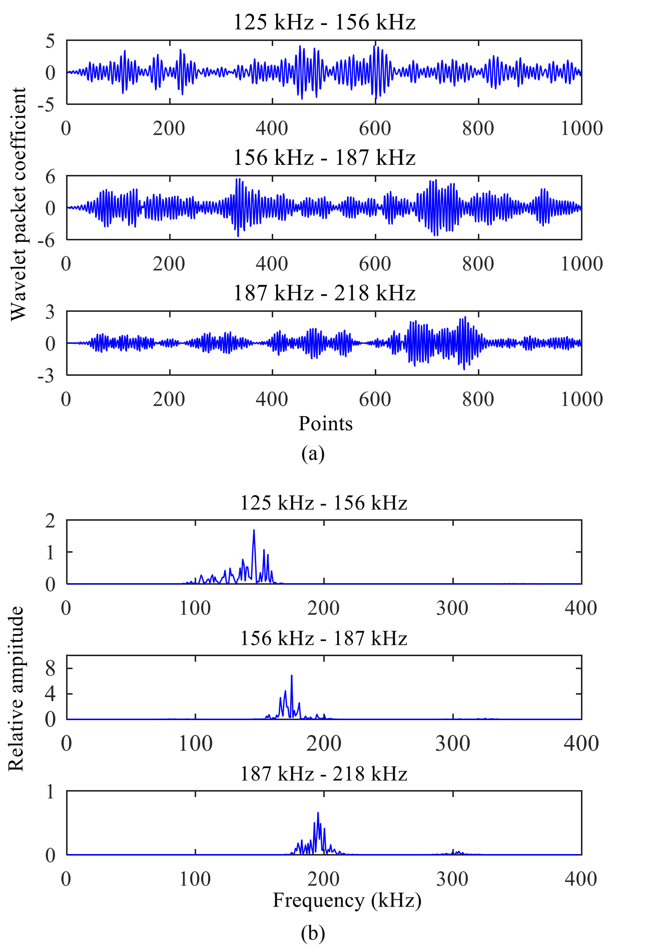

Fig. 10. Wavelet packet coefficient and PSD corresponding to several nodes. (a) Wavelet packet coefficient. (b) PSD.

ratio [28]. In addition, the energy distribution of this region is more centralized around 170 kHz compared to the lower one.

Wavelet packet analysis is adopted to decompose the original signals and extract the characteristic frequency bands.

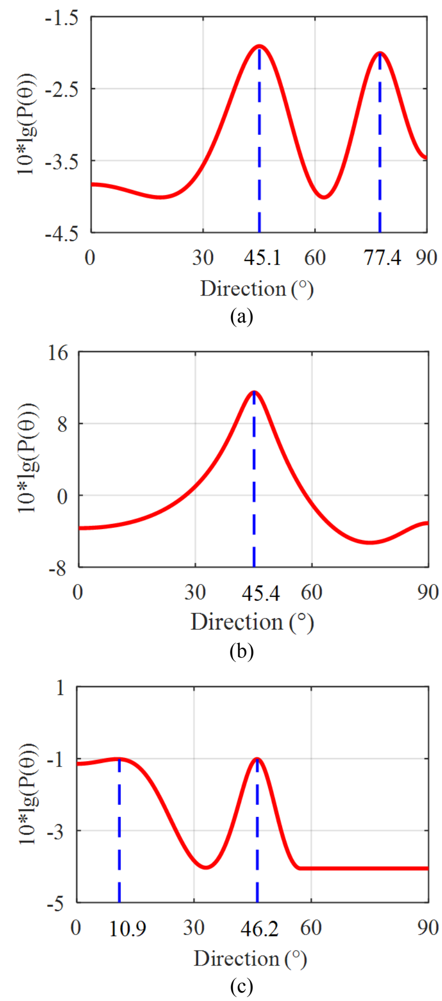

Fig. 11. Directional identification of the array at different locations 1#. (a) Location. (b) Location 2#. (c) Location 3#.

It is crucial to select an appropriate decomposition level so that the complete peak information is acquired. In addition, the decomposition level has to be a trade-off between the narrow band and the signal strength. In this study, the decomposition level is set to 4 according to the PSD and the sampling rate. The wavelet packet coefficient and the PSD corresponding to several wavelet packet nodes are shown in Fig. 10.

C. *Leak localization results and discussion*

The frequency band of 156 kHz - 187 kHz is chosen as the characteristic frequency band for purpose of leak localization. Similarly, this process is applied to all signals received from the AE sensors. The outputs of wavelet packet analysis are the inputs of the MUSIC algorithm. Directional identification of the sensor array at different locations is illustrated in Fig. 11.

For the sensor array at each location, the corresponding real directions of the leak holes are calculated from the simple geometrical relationship in the set-up. For the array at 1#, the identified directions of leak holes 1 and 2 are 45.1° and 77.8°, respectively, with the corresponding real directions of 45.0°and 77.0°, as shown in Fig. 11 (a). For the array at 2#, the identified directions of leak holes 1 and 2 are both 45.4°, respectively,

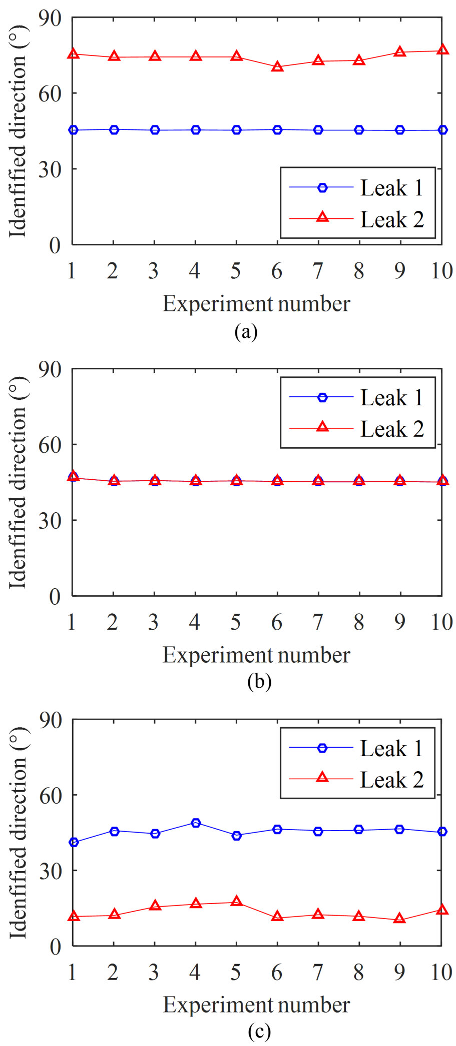

Fig. 12. Directional identification of the array at different locations. (a) Location 1#. (b) Location 2#. (c) Location 3#.

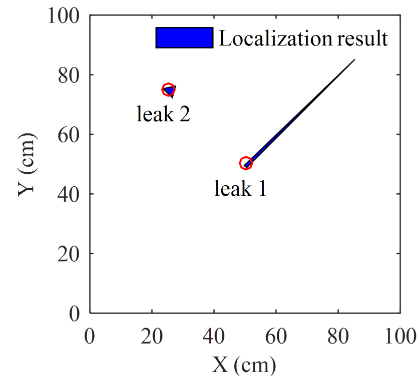

Fig. 13. Localization result.

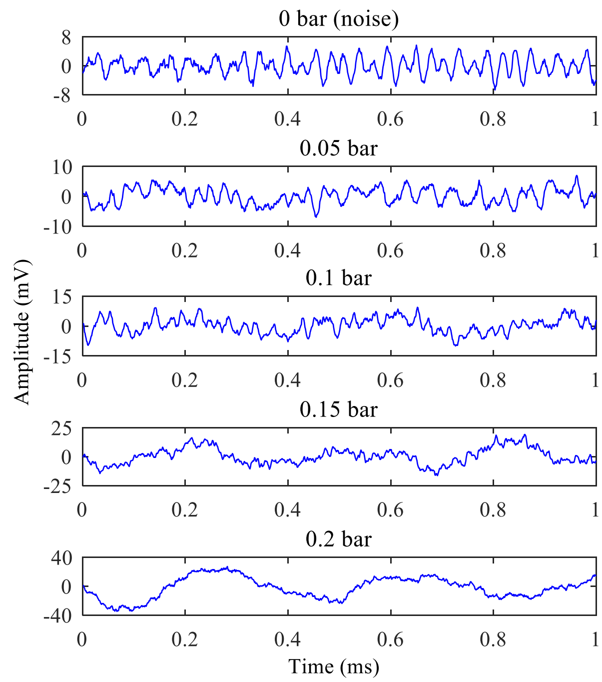

Fig. 14. AE signals corresponding to different leak pressures.

with the corresponding actual directions of both 45.0°, as shown in Fig. 11 (b). For the array at 3#, the identified directions of leak holes 1 and 2 are 42.2° and 13.9°, respectively, with the corresponding true directions of 45.0° and 13.0°, as shown in Fig. 11 (c). In order to assess the repeatability of the proposed method, experiments at each location were repeated for 10 times. The results are showed in Fig. 12. The standard deviation of the results for the three locations are: 0.1° for leak 1 and 1.7° for leak 2 at location 1#; 0.4° for leaks 1 and 2 at location 2#; 2.3° for leak 1 and 1.9° for leak 2 at location 3#.

It can be seen that the identified directions fluctuate around the real directions of the leak holes. This result indicates the effectiveness of the proposed method. Generally, if the identified directions are accurate, the final localization will be reliable. However, there is an extreme case that the sensor array and a leak hole happen to be in the same line. This case is taken into consideration in this study, as shown in Fig. 6. The final identified directions of leak holes 1 and 2 are calculated by averaging the repeated experimental results. Based on the directions identified by the sensor array at three different locations, the final localization result is plotted in Fig. 13. In comparison with the actual locations of the leak holes, the error in the localization is due to the ambient noise. It should be noted that the localization result of Leak hole 1 is large and narrow compared with that of leak hole 2. As mentioned before, that is because location 1#, location 3#, and the leak hole 1 are in the same line. In such a special case, a slight error in the identified direction leads to a significant error in the final localization result. Changing the location of the sensor array will effectively solve this problem.

In order to demonstrate the accuracy of the method proposed in this paper at different pressures, the pressure in the experiments was increased from 0 bar to 0.2 bar with an increment of 0.05 bar. The AE signals were recorded in each step. Taking the signal from sensor 1 as an example, waveforms of the signals are plotted in Fig. 14. It is evident that the magnitudes of the recorded signals increase with the pressure. Similarly, the experiments at each location were repeated for 10 times and the final localization results are plotted in Fig. 15.

When the leak pressure is 0.05 bar, the method provides

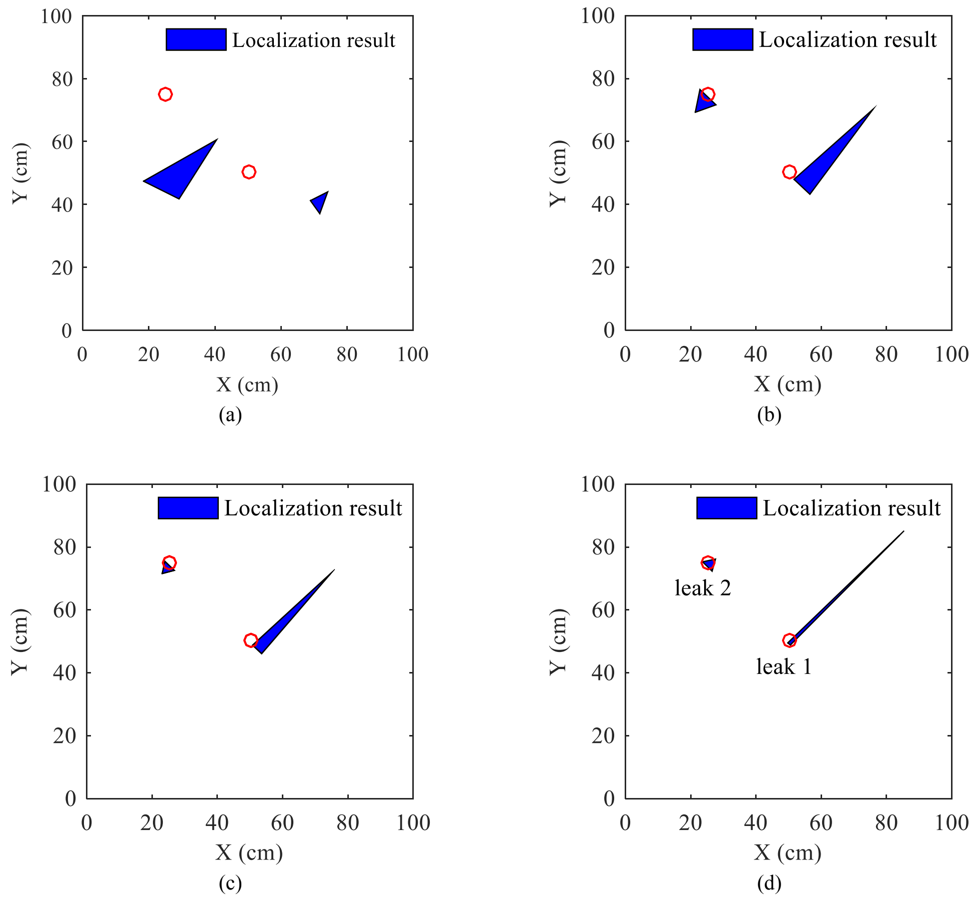

Fig. 15. Localization results corresponding to different leaking pressure. (a) 0.05 bar. (b) 0.1 bar. (c) 0.15 bar. (d) 0.2 bar.

erroneous or inaccurate results. When the pressure is greater than or equal to 0.1 bar, the method is capable of locating the positions of the two leak holes. The experimental results indicate that the localization accuracy depends on the leak pressure. Especially, when the leak pressure is as high as 0.2 bar, the leak holes can be located within two small areas of 25.12 cm^2 for leak 1 and 1.96 cm^2 for leak 2. Due to the limitations of the current experimental set-up, it was impossible to vary the distance between the two leak holes. However, through computer simulation with the leak pressure at 0.2 bar, it is found that, when the spacing between the two leak holes is less than 1.2 cm, the localization method is unable to distinguish them, i.e. the two leak sources would be regarded as a single one in terms of leak localization. This indicates, to some extent, the resolution of the proposed method for localizing multiple leaks.

The experimental conditions such as the size of the stainless steel plate and the number of the leak holes are fixed in this study. However, concurrent localization of three leak sources or more is realizable in principle. Because the method proposed is based on the orthogonality between the signal and noise subspaces, it is possible to locate any number of leak sources, as long as the number of sensors in the array is greater than that of leak sources. Additionally, the method can also be applied to storage units with curved geometries. In this case, the directions of the leak sources can be determined in the same way.

IV. Conclusions

In this paper, experimental investigations have been carried out with a combination of a linear AE sensor array, MUSIC algorithm and wavelet packet analysis for the localization of multiple leak sources on large pressure vessels. Experimental work was undertaken on a laboratory–scale test rig with the dimensions of 100 cm $\times$ 100 cm $\times$ 0.4 cm. The analysis of the acoustic leak signals in the frequency domain has indicated that the signals are within two main frequency bands: the lower frequency band from 63 kHz to 121 kHz and the higher frequency band from 156 kHz to 187 kHz. Wavelet packet analysis has been used to obtain the characteristic frequency band of 156 kHz to 187 kHz. Directions of the two leak holes are identified using the MUSIC algorithm. Positions of the two leak holes at the leaking pressure of 0.2 bar are finally obtained within two areas of 25.12 cm^2 for leak 1 and 1.96 cm^2 for leak 2. It is observed that the localization accuracy increases with the leak pressure. In summary, acoustic emission (AE) sensors in conjunction with the MUSIC algorithm and wavelet packet analysis have a good potential to locate multiple leak sources.

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