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A continuous gas leakage localization method based on an improved beamforming algorithm

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ABSTRACT

A continuous gas leakage localization method based on an improved beamforming algorithm is proposed and experimentally demonstrated. The ultrasonic signals excited by the leakage are collected by the contact-coupled piezoelectric ultrasonic sensor array, afterward, the time-space matrix of the leakage signal is calculated, and through analyzing the matrix, the position of the leakage hole can be obtained. The measured phase velocity is taken into account in the method to compensate the effect of frequency dispersion. Localization experiments were carried out on a flat plate and a stiffened plate, demonstrating that the proposed method can successfully locate the continuous gas leakage in both the near and far field cases. In addition, the experiment results indicate that frequency dispersion compensation can reduce the localization error efficiently. The method is demonstrated to achieve the mean errors of 3.74 mm and 8.59 mm, for an area of 1 m × 1 m on the flat and stiffened plates, respectively.

1. Introduction

Sealed pressurized gas vessels are very common in industrial field, such as gas storage tank, pressurized piping, aircraft and spacecraft. Since the vessel wall always bears under immense pressure, it will bring huge waste and loss of energy when the leakage occurs. Furthermore, if the internal storage is toxic and harmful gases, the leakage will threaten the personnel safety, and as for spacecraft and aircraft, the leakage will endanger the safety of astronauts. Therefore, quickly and accurately locating the gas leakage sources in sealed vessels is very necessary.

Acoustic emission (AE) testing is a promising method for pressurized vessel leakage detection, which has been widely used in leakage detection of pressure vessels, pipes and tanks [1]. Chou et al. [2] detected the damage in carbon fibre composite pressure vessels using the AE technique under the constant and cyclic internal gas pressure loading conditions. Mostafapour et al. [3] analyzed the continuous leakage signal in high pressure pipes using AE method and obtained the frequency characteristics of the leakage signal. Changhang et al. [4] improved the applicability of AE technique for long-range pipeline and proposed a novel leakage localization approach based on the multi-level framework. Sun et al. [5] proposed a small leakage feature extraction and recognition method in a natural gas pipeline based on local mean decomposition (LMD) envelope spectrum entropy and support vector machine (SVM). Kwon et al. [6] checked the structural defects of a repaired storage tank based on the AE activity indications. Wang et al. [7,8] proposed an auto recognition method of AE source distribution regions of tank bottom based on wavelet clustering and raised the accuracy of tank bottom corrosion evaluation.

The aforementioned AE testing applications mainly involves two types of signal processing: instantaneous and continuous. The former case includes the detection of crack growth, corrosion, and fracture, while the latter includes the leakage detection of pressurized piping, tank, aircraft and spacecraft. Continuous AE testing is much more challenging than the instantaneous one, as the continuous acoustic signal has no noticeable starting features in time domain and its propagation characteristics are more complicated due to the interference of reflected and refracted waves.

When the leakage occurs, gas flows out from the leakage hole forming an acoustic source [9]. The position of the leakage source can be located by dealing with the leakage acoustic signals. Acoustic localization methods are easy to implement with high localization speed [10]. The signal generated by the existing leakage is continuous ultrasonic broadband noise mixed with ambient noise [11,12]. Due to the air absorption and diffusion attenuation, the leakage detection using air-propagating waves is limited [13]. Since the attenuation of the acoustic signal in the structure is small, structure guided waves can be used for the leakage detection in large-scale projects [14,15].

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The thin plates and shells structures are widely used in sealed vessels of which acoustic signals generally propagate in the form of Lamb waves [16]. The multi-mode and dispersion phenomenon of the lamb waves have an ill effect on the positioning [17–19]. An et al. [20] proposed a novel Lamb wave line-sensing technique for crack detection based on the Lamb wave propagation rules. Reusser et al. [21–23] proposed an array based localization method for the orbiting spacecraft leakages. They calculated the intensity distribution of the wave number diagram (k-domain) of the collected signal in the specific frequency band to estimate the direction of the sound source. The method needs dense spatial sampling, thus it demands a large number of sensors (at least 64) to collect signals. Bian et al. [24] analyzed the impact of different modes to the leakage localization and found that A_0 mode plays a predominant role on the leakage positioning. In practice, different structures such as stiffener or step discontinuity are often adopted in the wall of the sealed vessels for the structural strength, which will decide the propagation of acoustic waves [25–27], thus affecting the leakage localization.

Based on the far filed acoustic model, a method was proposed by us to analyze the correlation of the time-space domain of continuous ultrasound to estimate the orientation of the leakage [28]. It obtained the location error within ±10 mm on a flat container wall, and achieved a mean location error of 16 mm on the container wall with integral stiffeners. However, the method will lose accuracy when the leakage is very close to the sensor array. The conventional delay-and-sum beamforming method has been extensively adopted in the acoustic measurements [29,30]. This paper proposes a method for localization of the continuous leakage source based on an improved beamforming algorithm compensating for the effect of frequency dispersion. The method can successfully locate the continuous gas leakage in both the near and far field cases. Experimental results indicate that this method can achieve a high accuracy of leakage localization with wide locating scope and without blind area.

2. Localization method

2.1. Algorithm theory

As most of large containers' surface can be regarded as plane structures, the only 2-D, cylindrical wave field is considered. Various modes and frequency dispersion exist when the acoustic waves propagate in the thin plate [31]. The algorithm is based on the beamforming algorithm improved by considering the frequency dispersion of the structure.

The basic principle of the detection method is illustrated in Fig. 1. A sensor array is adopted to collect the leakage acoustic signals, which concludes N numbers of sensor elements. Establish a plane right angle coordinate system, thus the coordinate of the sensor array is represented as $(x_i, y_i)(i = 1, 2, \ldots N)$. $A(x_A, y_A)$ is the scanning point, and $L(x_L, y_L)$ is the leakage source.

Assuming there are l modes propagating in the plate and denoted as $k = k_1, k_2, \ldots, k_l$. The leakage signals collected by the sensor array $\boldsymbol{P}(t)$ are the superposition of every existing mode:

$$\boldsymbol{P}(t) = \boldsymbol{P}_{k_1}(t) + \boldsymbol{P}_{k_2}(t) + \cdots + \boldsymbol{P}_{k_l}(t) \tag{1}$$

The signal in the k mode measured by the array $\boldsymbol{P}_k(t)$ is written in the following matrix form:

$$\boldsymbol{P}_k(t) = \begin{bmatrix} p_{1,k}(t) \\ p_{2,k}(t) \\ \vdots \\ p_{N,k}(t) \end{bmatrix} \tag{2}$$

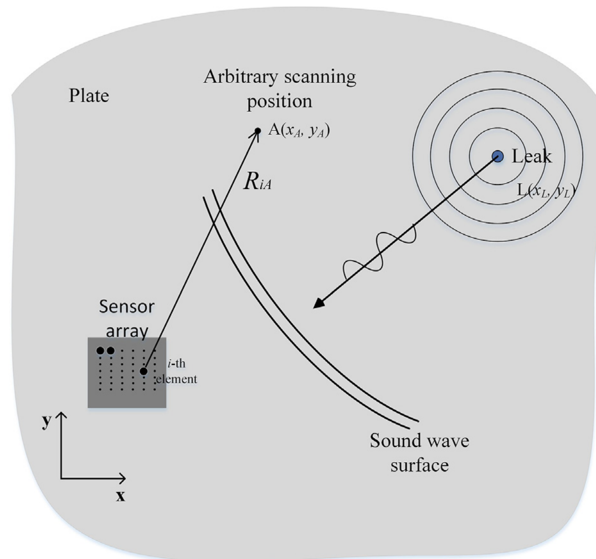

Fig. 1. Illustration of the detection method.

The signals received by the sensors are attenuated and phase delayed by the leakage source signal. Assuming the attenuated coefficient is marked as α_i and the leakage energy is concentrated in a certain frequency range (f_0, f_n), thus the signal collected by the i-th sensor in the k mode can be expressed as below:

$$p_{i,k}(t) = \int_{f_0}^{f_n} \alpha_i \cdot s_{k,f}(t) \cdot \exp\left[-j2\pi f \frac{R_{iL}}{c_k(f)}\right] df \tag{3}$$

In Eq. (3), $s_{k,f}(t)$ is the leakage source signal in the k mode and f frequency; R_{iL} is the distance between the leakage source and the i-th sensor, and its numerical coordinate is expressed as $R_{iL} = \sqrt{(x_L - x_i)^2 + (y_L - y_i)^2}$; $c_k(f)$ is the phase velocity of the acoustic wave in the k mode, which will be discussed in detail in Section 2.2.

In practice, the scanning point is introduced to obtain the location of the leakage. The energy intensity of the scanning point is obtained by the inverse time delay of the array signals. The time delay to the $p_{i,k}(t)$ at the scanning point $A(x_A, y_A)$ is

$$\Delta t_{i,k}(x_A, y_A, f) = \exp\left[2j\pi f \frac{R_{iA}}{c_k(f)}\right] \tag{4}$$

The time delay of the array can be written in the following matrix form:

$$\boldsymbol{T}_k(x_A, y_A, f) = [\Delta t_{1,k}(x_A, y_A, f), \Delta t_{2,k}(x_A, y_A, f), \ldots, \Delta t_{N,k}(x_A, y_A, f)] \tag{5}$$

The received signals are the superposition of multiple modes, thus the output energy at the scanning point is also their linear superposition. The total output energy of sensor array at the scanning point is defined as superposition of the modes $k = k_1, k_2, \ldots, k_l$:

$$\begin{aligned} E(x_A, y_A) &= E_{k_1}(x_A, y_A) + E_{k_2}(x_A, y_A) + \ldots + E_{k_l}(x_A, y_A) \\ &= \sum_{k=k_1}^{k_l} \int_{t_a}^{t_b} \int_{f_0}^{f_n} \boldsymbol{T}_k(x_A, y_A, f) \boldsymbol{P}_k(t, f) df dt \end{aligned} \tag{6}$$

Only A_0 and S_0 modes exist under the conditions we considered (the plate is less than 6 mm thick, and the signal frequency within the range 0–500 kHz). Moreover, the A_0 mode has a greater contribution to the localization results than the S_0 mode [27]. Thus, only the A_0 mode has to be considered, and Eq. (6) can be approximately written as: