The Acoustic Emission Source Localization in the Pipeline Network with consideration of Radial Position of Defect

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Abstract. Pipeline as one important mode of transportation, its safety is a very critical public concern. The acoustic emission (AE) played a very important role in pipeline safety inspection and monitoring due to its many advantages. Moreover, AE is capable of localizing the defects in complex geometry in a real time, which is one of the most significant merits of this technique. For the localization algorithm, the 1D or 2D localization is most commonly used in AE measurement. The pipeline has been simplified as “axial line” without consideration of radial direction; however, in large-diameter pipelines, if the radial or circumferential direction across the certain position was ignored, it can cause the negative impact on the accuracy of the AE localization of pipeline defects. Therefore, this study explores the influence of radial position of the defects associated with the pipeline diameter on AE localization. Six typical pipe schedules were selected and modelled by COMSOL Multiphysics5.5 software. The tone burst wave and pencil lead break was used as the artificial AE source. The numerical model has been validated experimentally. By parametric study, it has been concluded that with the increase of diameter, the wave propagation path cannot be simply considered as the straight line anymore. Otherwise, the error of the localization will increase. Therefore, it is necessary to consider the influence of the radial position and real path of wave propagation for the precise localization of the defects in the large diameter-pipeline.

1. Introduction

With the development of urbanization, the pipeline transport becomes more and more important for delivering the liquid or gas from the market area to the consumption. For gas pipeline system, thousands of households were connected. In China, Just in 2020, China's newly built oil and gas pipelines will have a mileage of about 5081 kilometers, and the total mileage of oil and gas pipelines will reach 144,000 kilometers [1] by then. While bringing convenience to people, the risk of gas pipeline leakage surges, which may cause properties loss and casualties. Many disasters happen: the “6.13” gas explosion accident in Hubei Province on June 13, 2021 caused 25 deaths, 138 injuries and a direct economic loss of 53,954,100 yuan [2]. On October 31, 2021, the Associated Press reported a gas explosion in Puebla, Mexico, 54 houses were destroyed, and more than 2,000 people were evacuated. According to U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration statistics from 2001-2020, there were 695 serious pipeline incidents, resulting in 256 deaths and 1,142 injuries [3]. Therefore, the safety monitoring of pipeline leakage is essential for public safety.

In order to ensure the safety of the pipeline system, there are many monitoring and inspection methods for pipelines. For example, Manual inspection [4], which is the traditional monitoring method,
is less efficient. Negative pressure wave technology [5] is a mature monitoring and detection method, but it only caused a non-continuous signal; therefore, the requirements for identifying the signal is highly restrict so that it cannot detect small leaks. Fiber optic sensing technology [6] is long-distance and real-time online monitoring method; but accuracy is more demanding on the use environment; and also, it is difficult to reflect the real-time status of the pipeline because of noise. Acoustic emission occupies a very important position in pipeline leakage monitoring due to its high sensitivity, strong practicability, real-time monitoring, and capability of localization. Therefore, many researchers contribute their effort on this technique to increase its detectability and applicability. Kosel et al. [7] applied a cross-correlation method combined with an appropriate band-pass filter to locate gas pipeline leaks. Osama et al. [8] studied the relationship between the acoustic emission signal of the leakage source in the plastic pipe and the leakage type, flow rate, attenuation rate, and wave speed with frequency. A method of using cross-correlation method to locate when the wave speed is known is proposed. Liu et al. [9] proposed a new method for oil and gas pipeline leak detection and location based on the law of acoustic emission propagation in oil and gas pipelines and the theoretical propagation model of acoustic waves in the pipeline. Though AE is suitable for leak detection and location of long-distance pipelines, few studies focused on improvement of localization mechanisms. Most of them still used either conventional 1D or 2D localization algorithm by simplifying the pipeline as “line”. Without considering the radial direction, in most cases, the localization results were acceptable due to the limitation of the dimension. But, some researchers already noticed that the simplification of wave propagation path as a line will introduce the error. Ozevin et al. [10] proposed a method of pipe network location based on sound waves propagating in a two-dimensional plane. This method considered the geometric connectivity to identify the path of leaking sound waves to the sensor to determine the time difference of arrival. Zhang et al.[11] introduce the sensor array to determine the location of the leak in the multidimensional space with consideration of radial and axial position of defects. It is different from the assumption that the pipelines are all leak locations in one-dimensional space in previous studies.

At present, many researches on pipeline leakage location and improvement of positioning accuracy are measuring the axial position defects of pipelines, and there are few studies on the influence of pipe diameter differences on pipeline positioning accuracy. Therefore, this study will investigate the influence of radial position of defects and diameter of the pipeline on the accuracy of AE source localization. The numerical and experimental study were conducted. It has been concluded that the radial direction influence associated with certain diameter cannot be ignored.

2. Methodology

Traditional pipeline positioning is mostly focused on the linear positioning of pipelines. It is assumed that the leakage signal propagates along a straight line [12], and the influence of the radial or phase direction on the positioning accuracy is not considered. The distance \( l \) from the sensor to the leak source during axial positioning is mainly calculated by the time of flight \( t \) of the leak source signal to the sensor and the signal speed \( V \), as follows

\[
l = Vt \tag{1}
\]

The actual working conditions of the pressure pipeline are mainly continuous acoustic emission signals, and it is difficult to directly measure the time of flight. Usually, the axial positioning is performed by calculating the flight time difference and signal speed of two adjacent sensors of the leakage source. The algorithm of acoustic leakage location [13] is shown below

\[
X = \frac{(L-V\Delta t)}{2} \tag{2}
\]

Where \( X \) is the distance from the leakage source to the first sensor that receives a signal, \( L \) is the distance between two sensors adjacent to the leakage source, \( V \) is the propagation speed of the signal in the medium, \( \Delta t \) is the acoustic flight time difference of two adjacent sensors AE-1 and AE-2, as
shown in figure 1(a) below. However, in a pipeline with a large pipe diameter, the assumption that the leakage signal propagates along a straight path is obviously not suitable. The flight time of signals excited by different defects along the circumference of the pipeline to the adjacent sensors is different. For example, as shown in figure 1(b), when the actual leakage position is 180° from the AE sensor in the circumferential angle θ, the assumed propagation path is L and the actual propagation path should be the curved line S along the curvature surface of the pipe. Therefore, the flight time of the elastic wave to the AE sensor is mistaken. Therefore, when performing high-precision positioning, the influence of the radial direction or pipe diameter cannot be ignored.

![Figure 1](image1.png)

**Figure 1.** Contrast Chart of sound wave propagation path. (a) Schematic diagram of one-dimensional algorithm positioning. (b) Schematic diagram of ultrasound wave propagation path.

According to the localization algorithm of equation (1), it is known that the factors that affect the positioning are the wave speed V and the flight time difference Δt between adjacent sensors. The difference in flight time may result in a difference in time of flight, which will eventually affect the accuracy of localization. Therefore, this study studied the influence of different pipe diameters on the flight time difference.

In order to understand the radial influence, this study proposed a combined numerical and experimental model of pipes with the same axial length and different pipe diameters. The experimental model was used to verify the numerical results. Moreover, the validate numerical model can be further extended. The effect of the pipe diameter on the flight time difference was determined by calculating the flight time difference of the leakage sound waves of different pipe diameters reaching two adjacent sensors. The two adjacent sensors are the same in axial distance and are arranged at different angles along the circumferential direction.

### 3. Numerical and Experimental Validation

**3.1. Numerical Model Description**

This study uses COMSOL Multiphysics5.5 software to establish a numerical model. The radial displacement of the leak point received by the sensor was used to simulate the response of sensor. According to the GB/T 21035 specification, 6 pipes schedules with different diameters are selected to establish a finite element model, the detailed dimension was listed in table 1. The length was 1m for all scenarios. The stainless-steel pipe was used, and the material properties were shown in the table 2.

| Schedule | Diameter (mm) | Wall Thickness (mm) |
|----------|---------------|---------------------|
| D32      | 32            | 2                   |
| D108     | 108           | 2                   |
| D244.5   | 244.5         | 5.16                |
| D559     | 559           | 5.16                |
| D854     | 854           | 12.7                |
| D1321    | 1321          | 30                  |
Table 2. The material properties.

| Basic material parameters | unit |
|---------------------------|------|
| density                   | 8000 kg/m³ |
| Poisson's ratio           | 0.34 |
| Young's modulus           | 1.9×10¹¹ Pa |

Through transient analysis, the elastic wave propagation process on the pipe surface wave is simulated. A free tetrahedral element was used. In order to achieve the sufficient resolution, the time step and mesh size is 0.83μs, respectively. A 5-cycle tone-burst signal with the frequency of 60kHz is used as the artificial AE source on the surface of the pipe, see in figure 2. The preset wave speed is 3000m/s.

The AE sensors and the location of the simulated acoustic emission source are shown in figure 3. Among them, the circumferential relative angle between the sensors AE0 and AE1 and the acoustic emission source is 0°. Position and angle of the other 4 sensors relative to AE1 (counter clockwise) are shown in section 1-1 in the figure.

3.2. Numerical Results
The influence of the pipe diameter on the time of flight is obtained by calculating the flight time difference between the acoustic emission source of different pipe diameters and each sensor. The time of flight is calculated by the threshold method, which was the most common method in the AE system, and the time when the signal exceeds the displacement threshold for the first time is defined as the time of flight. In this case, the threshold in this study is defined as 1/10 of the peak amplitude. The results of calculating the time of flight from the acoustic emission source to the AE1 to AE5 sensors and the flight time difference between the AE1 to AE5 sensors and the sensor AE0 are shown in figure 4.
Figure 4. (a) The flight time from the AE source to the AE1 to AE5 sensors (b) The corresponding flight time difference.

By calculating the time of flight, it can be seen that the influence of the pipe diameter on the time of flight is mainly reflected in the circumferential direction of the pipeline. The time of flight increases with the increase of the phase angle between the sensor and the prescribed acoustic emission source. The maximum time of flight happens when the maximum relative angle of 180° is reached, which also confirms that the straight-line assumption may introduce the error. If the diameter is within certain range, the error is acceptable. However, in the scenario with large diameter, the real propagation path should be considered. In this case, the simulation with a relative positioning error of 5%, this error is acceptable if the diameter is within the range of 108 mm, otherwise it will lead to a wrong positioning. It shows that it is very necessary to consider the influence of the pipe diameter in the precise location of the defects of the large diameter pipeline.

Taking into account the actual working conditions of the pipeline, the leakage often causes a continuous signal, so the defect location algorithm is usually based on the flight time difference, see in figure 4(b). The influence of different pipe diameters on the flight time difference has a similar trend. Therefore, even in the AE localization by continuous signal, the radial direction or the real path of wave propagation should also be considered.

We introduced the artificial AE source on the length of 0.5m away from AE0 with the phase angle of 0. Based on the conventional 1D localization algorithm, the AE0 was fixed in the position, while changing phase angle on the other end (AE1 to AE5), the localization results and relative errors were summarized in the Table 3. When the source-sensor phase angle is 0 degrees, the calculated localization is more accurate; while when the relative angle reaches 180° (relative highest differences in phase), the highest error is acquired. As the pipe diameter increases, the error becomes more obvious and unacceptable. Figure 5 shows the comparison of phase angle between different diameters. With the pipe diameter increases, the radial direction influence shows more significant effect on localization. Therefore, the use of traditional localization algorithms in different circumferential positions will inevitably bring errors, and the error will increase with the increase of the pipe diameter.

Table 3. Axial positioning length table of different pipe diameters with relative error(m).

| Angle | Diameter | D32 | D108 | D244.5 | D559 | D854 | D1321 |
|-------|----------|-----|------|--------|------|------|-------|
| 0°    |          | 0.5050 | 0.4900 | 0.4925 | 0.495 | 0.5050 | 0.5100 |
|       | (1%)     | (2%)  | (1.5%) | (1%)   | (1%)  | (2%)  |       |
| 45°   |          | 0.5350 | 0.5300 | 0.5050 | 0.5675 | 0.4300 | 0.5825 |
|       | (7%)     | (6%)  | (1%)   | (13.5%) | (14%) | (16.5%) |       |
| 90°   |          | 0.5675 | 0.6150 | 0.5250 | 0.6725 | 0.8075 | 0.9375 |
|       | (13.5%) | (23%) | (5%)   | (34.5%) | (61.5%) | (87.5%) |       |
| 180°  |          | 0.4825 | 0.6375 | 0.6250 | 0.8900 | 1.3900 | 1.8050 |
|       | (3.5%)  | (27.5%) | (23%) | (78%) | (178%) | (261%) |       |
| 270°  |          | 0.4850 | 0.5875 | 0.5425 | 0.6925 | 0.8275 | 0.9625 |
|       | (3%)    | (17.5%) | (8.5%) | (38.5%) | (65.5%) | (92.5%) |       |
3.3. Experimental Validation
In order to verify the numerical model and the proposed observation, the experiment was conducted. The diameter of the pipe is 114.3mm, the wall thickness is 4mm, and the length is 890mm. The experiment uses three R3α sensors with Tektronix MDO34 oscilloscope to record the signal as shown in figure 6. 0.5mm HB pencil lead breakage was used to the AE source.

As numerical simulation, the position of the PLB remains unchanged along the axial position of the pipe, only the circumferential position is changed. The angle change is consistent with the numerical modeling, taking 0°, 45°, 180° and 270°. The results of the axial positioning experiments are shown in figure 7. It can be concluded that as the relative angle in the circumferential direction increases, the positioning deviation also increases, which is consistent with the simulation results. It shows that in the precise location of pipeline defects, the difference of pipe diameter has an impact on the location accuracy.

4. Conclusions
The conclusions were drawn from the above discussion. In the defect location of large pipe diameter pipelines, the radial direction associated with pipe diameter has an influence on the localizing the defects. This effect increases with the increase of pipe diameter; and when the relative phase angle reached 180°, the error is highest. Therefore, the influence of radial direction and real path of wave propagation cannot be ignored for accurately localizing the defects of the pipeline with a large diameter.

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