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An underground pipeline leakage monitoring and precise positioning method based on multi-point signal compensation

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Abstract. Underground pipelines are an important infrastructure for cities and an important basis for ensuring the normal operation of urban production and life. As the earliest types of pipelines built in the urban underground pipe network, the water supply network and the heat pipe network of many cities have already experienced aging phenomena. Pipeline leakage and pipe burst accidents frequently occur, resulting in serious waste of water resources and greatly increasing operating costs [1]. At the same time, there are major security risks. Pipeline leak detection is an important task. There are many kinds of pipeline leakage detection methods [2], and the best one is the water leakage detection correlator, which can locate the location of the leakage point. However, the correlation instrument can not eliminate the environmental noise interference well during the leak detection process, and the positioning result sometimes has a large deviation. In order to solve this problem, an underground pipeline leakage monitoring and precise positioning method based on multi-point signal compensation is proposed. The method increases the third acquisition point of the noise signal, and compensates for the positioning deviation caused by the environmental noise through the signal of the third point, achieving accurate positioning of leak points.

1. Introduction

At present, pipeline leak detection methods at home and abroad are divided into two categories based on hardware and software. Hardware-based methods and techniques mainly include methods and techniques for acoustic emission, cable sensors, optical fibers, soil testing, ultrasonic flow measurement, steam measurement, and remote sensing. Software-based methods and techniques have mass (or volume) balance, real-time transient models, pressure point analysis, neural networks, statistical analysis, and more. These methods have higher false alarm rate and underreporting rate in practical applications [3]. The problem is that in the hardware signal acquisition process, the hardware parameter requirements are not clear enough, the sensors and acquisition systems used are uneven, and are not selected for the pipeline leakage monitoring requirements. In the aspect of algorithm processing, the ideal situation is often considered. Signal processing model is too singular. There is no particularly effective and widely applicable method for detecting pipeline leaks, especially for thermal pipeline leak monitoring. According to the sources of various errors in the leakage noise signal processing method, this paper makes a clear analysis of the leakage signal acquisition hardware and working mode, uses the cross-correlation method to locate the leak point, and applies the multi-point signal compensation method to

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correct the positioning result [4]. The leakage positioning accuracy is greatly improved, the false alarm rate and the underreporting rate of pipeline leakage detection are reduced, and the pipeline leakage refined management is realized.

2. Principle of correlation analysis positioning

When the pipeline leaks, it can generate sound pressure waves that are much higher than the normal underwater sound frequency and propagate along the pipeline. The vibration sensor is used to monitor the sound signal in the pipeline. The leak point positioning principle is that the leakage signal is measured by a vibration sensor placed at both ends of the pipe (the leak point is surrounded in the middle), and the time at which the leak sound propagates to the two sensors are different. Using the cross-correlation analysis of the two signals, the time difference between the leakage noise and the two sensors can be determined [5]. According to the time difference, the distance between the leak point and the two sensors can be calculated by the distance between the two sensors and the propagation speed of the sound wave in the tube. Under ideal conditions, there is only a water leakage sound signal in the pipeline, and the signals collected by the two sensors are sufficient to restore the leakage point position information. However, in the actual situation, the collected signal is doped with more environmental noise, which brings some errors to the positioning result [6]. The principle of multi-point signal compensation is that the signal acquired by an additional sensor is used to attenuate the effects of environmental noise and compensate for the leak location results.

3. Multi-point signal compensation method

Leakage monitoring and precise positioning methods are divided into three parts: signal acquisition rules, signal transmission requirements and signal processing algorithms. The main error sources should be controlled during signal acquisition. The errors have three types: data acquisition accuracy, acquisition time synchronization accuracy between different sensors, and analog-to-digital conversion module accuracy. The accuracy of data acquisition is that the acceleration error should be within 0.0000005g. Considering the stability, validity and availability of data acquisition, the requirements for the sensor are proposed:

Table 1. Requirement of sensor parameters

Parameter	Value
Resolution	0.0000005g
Sensitivity	50V/g
Range	0.1g
Impact resistance	100g
Resonant frequency	>8000Hz
Frequency Range	20-3000Hz
Temperature range	-30℃~+130℃
Vibration measurement direction	unidirectional
Output impedance	<20Ω
Acquisition frequency	10000Hz

The requirement for acquisition time synchronization is that the synchronization error should be less than 100μs. The source of this error requirement is as follows:

$$\Delta \mathrm{L} = \frac{1}{2} \cdot \mathrm{v}_n \cdot \Delta \mathrm{T}_d \approx 600 \times \Delta \mathrm{T}_d$$

Where v_n is the propagation speed of noise in the pipeline, generally about 1200m/s, T_d is the sensor synchronization error, △L is the positioning result error. When the sensor synchronization error is 100μs, the error caused to the final positioning result is about 6cm, which is an acceptable range, and 100μs time synchronization error is achievable.

The method of realizing time synchronization is that the host broadcasts a synchronous acquisition instruction through the wireless communication module, and each acquisition module collects signal immediately after receiving the instruction, as shown in Fig. 1.

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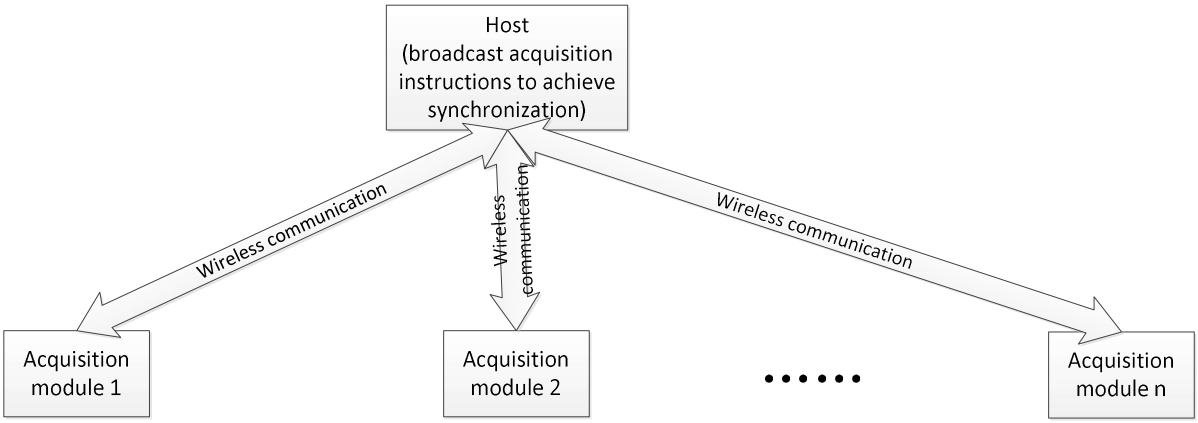

Figure 1. Synchronous acquisition implementation

The accuracy of the analog-to-digital conversion module should be at least 18 digits. The accuracy is derived as follows:

Among the sensor parameter requirements, the range is 0.1g and the resolution is 0.0000005g. Therefore, after digitization, the effective number of data is: 0.1/0.0000005=200000, and the module requirement for binary analog-to-digital conversion is $\log_2 200000 \approx 17.6$. From this, the accuracy of the analog-to-digital conversion module should be at least 18 bits.

The method of correlation analysis to locate leaks is as follows. x(t) and y(t) are the signals collected by sensor 1 and sensor 2 respectively. The calculation formula of cross-correlation function is:

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T y(t)x(t - \tau)dt = R_{yx}(-\tau)$$

In order to filter out the background noise in the signal, the signal is processed by frequency domain filtering. The key to this is the choice of the filter band and how to determine if the selected band is optimal. The concept of noise signal "signal-to-noise ratio" is proposed here. The signal-to-noise ratio SNR is the ratio of the maximum value of the cross-correlation function $R_{xy}(\tau)$ to the average value, i.e.

$$\mathrm{SNR} = \frac{MAX(R_{\mathrm{xy}}(\tau))}{AVG(R_{\mathrm{xy}}(\tau))}$$

When SNR takes the maximum value, τ is the time difference between the noise signal and the sensor 1 and the sensor 2, which is denoted as T_d. When the SNR maximum is greater than 6, it can be determined that there is a leak point. When the SNR maximum value is less than or equal to 6, it can be determined that no leakage has occurred. The calculation formula for the leakage point and sensor distance is as follows:

$$\mathrm{L} = 1/2(\mathrm{D} - (\mathrm{V} \times \mathrm{T_d}))$$

L is the distance between the leak point and the sensor 1, so that the position of the leak point can be determined. As shown in Fig. 2.

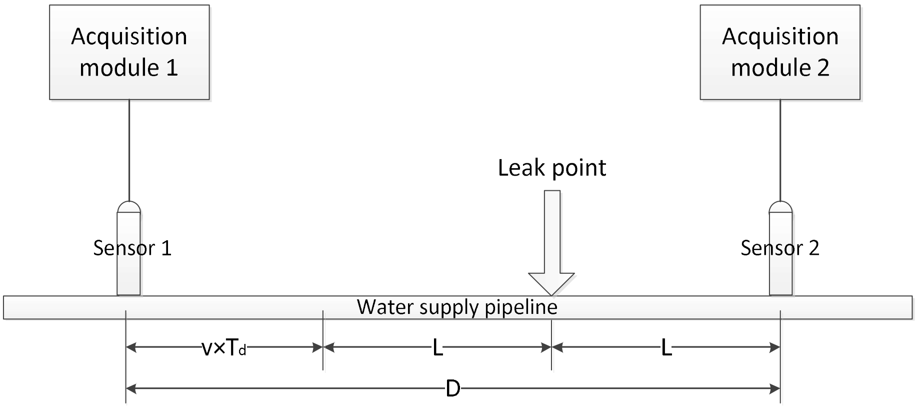

Figure 2. Related positioning principle

Finally, the location of the leak point is corrected by the multi-point compensation method. As shown in Fig. 3 signals are acquired at three points X, Y, and Z at the same time. After the signal acquisition is successful, the above method is used to determine the leakage point position interval. Assuming the leakage point is between X and Y, the Z point signal can be used to differentiate the X and Y signals. Let the signals of X, Y, and Z be x(t), y(t), and z(t) respectively. After the difference, the X and Y point signals are:

$x_0(\mathrm{t}) = \mathrm{x}(\mathrm{t}) - \mathrm{z}(\mathrm{t} - t_x)$, where t_x=(a+b)/v

$y_0(\mathrm{t}) = \mathrm{y}(\mathrm{t}) - \mathrm{z}\left(\mathrm{t} - t_y\right)$, where t_y=b/v, v is the speed at which the sound travels in the pipeline.

By using $x_0(t)$ and $y_0(t)$ instead of the acquired signal for positioning calculation, the error of the leak point location can be compensated.

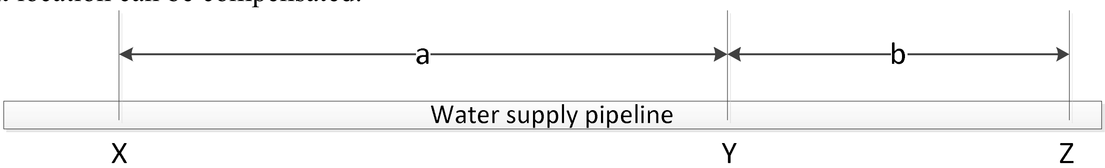

Figure 3. Multi-point compensation method

4. Experimental verification

In the actual urban underground pipe network, the four actual leakage points are detected by the method proposed in this paper. The positioning results without the multi-point compensation method are shown in Table 2.

Table 2. Positioning result

Index	Distance from point A (m)	Distance from point A (m)
1	162.3	89.7
2	113.9	134.1
3	54.9	133.1
4	211.5	93.5

After correction by the multi-point compensation method, the results are shown in Table 3.

Table 3. Corrected result

Index	Distance from point A (m)	Distance from point A (m)
1	163.0	89.0
2	113.1	134.9
3	54.2	133.8
4	212.2	92.8

By excavating the ground at the pipe network site, the actual locations of the leak point are determined, as shown in Table 4.

Table 4. Real leak location

Index	Distance from point A (m)	Distance from point A (m)
1	163.1	88.9
2	113.2	134.8
3	54.2	133.8
4	212.1	92.9

The positioning algorithm error and the corrected error comparison result are shown in Table 5:

Table 5. Error Analysis

Index	Related positioning error (m)	Error after compensation (m)
1	-0.8	-0.1
2	0.7	-0.1
3	0.7	0
4	-0.6	0.1

Through the error comparison, it can be concluded that the related positioning algorithm can effectively locate the leak point, but there is a large error. Through the multi-point compensation method, the positioning error can be greatly reduced.

5. Conclusion

For the current common pipe network leak detection method, the hardware parameters requirements are not clear, the signal acquisition rules are not specific, and the signal processing method is too single. In this paper, a method for monitoring and accurately locating underground pipeline leakage is proposed to solve that problem. The method proposes explicit hardware parameter requirements and specific signal acquisition rules, and precise positioning and correction method of leakage point based on multi-point signal compensation. The method greatly improves the leakage monitoring level and positioning accuracy, and is not only suitable for the water supply pipeline, but also effective for the thermal pipeline, and has good practicability.

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