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Pipeline Leak Detection Technology Based on Distributed Optical Fiber Acoustic Sensing System

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ABSTRACT Real-time monitoring of flammable and explosive gas pipeline networks is of great significance for ensuring the safety of life and property. Although the optical fiber sensing technology has achieved theoretical research results in the field of monitoring pipeline leakage recently, the practical applicability of theoretical results has not been noticed. This paper analyzes the research progress of pipeline leak detection technology based on optical fiber sensing technology firstly and proposes an algorithm for monitoring gas pipeline leakage based on distributed optical fiber acoustic sensing(DAS) system. The algorithm can obtain the time domain signal characteristics of pipeline leakage to identify leaks, locate the leak points through frequency domain. Experiments show that the algorithm can identify pipeline leakage and locate leaks, the Signal to noise ratio (SNR) and correlation coefficient can be increased to 18.28 and 0.75 respectively. The accuracy of identifying pipeline leakage and locating the pipeline leak points is effectively improved.

INDEX TERMS Pipeline leakage, DAS, time domain, frequency domain, identify pipeline leakage and locate leaks.

I. INTRODUCTION

As the laid gas pipeline facilities age, pipeline safety levels and regulatory requirements are increasing. Steady and reliable leak monitoring system has become the focus of domestic and foreign scholars. In the traditional pipeline leakage monitoring method, the stress wave method [1] is not suitable for increasingly complicated pipe networks because of the short monitoring distance; The negative pressure wave method [2] overcomes the limitation of the length of the pipeline, but it has poor monitoring effect on small leakage; Ultrasonic testing [3] requires expensive equipment and high requirements for pipelines, which cannot be monitored in real time. Among the software-based detection methods, the mass flow balance method [4] and the pressure gradient method [5] achieve real-time monitoring, but with a high false alarm rate, they have been hardly adopted. Supervisory Control and Data Acquisition (SCADA) system realizes online monitoring of pipeline leakage, but the system is large and the reliability is low.

In recent years, distributed optical fiber sensing technology has been applied to pipeline leakage monitoring. Compared with other technologies, optical fiber has many advantages. In 2001, Vogel *et al.* [6] used Raman scattering distributed optical fiber sensing technology to monitor oil and gas pipeline leakage, and realized the identification of leakage by monitoring the temperature change near the pipeline, but it was easily affected by the surrounding environment.; In 2012, Jia *et al.* [7] used Brillouin scattering distributed optical fiber sensing technology to monitor oil and gas pipeline leakage, and realized leakage identification by monitoring stress changes during pipeline leakage, eliminating the influence of environmental temperature, but only simulated the corresponding experiment. In 2004, Monica *et al.* [8] used distributed optical fiber sensing technology based on Rayleigh scattering to simulate pipeline leakage by monitoring fiber bending loss, but ignored the impact of pipeline vibration on the experiment. The online monitoring system based on the Brillouin optical time domain analyzer (BOTDA) realized the

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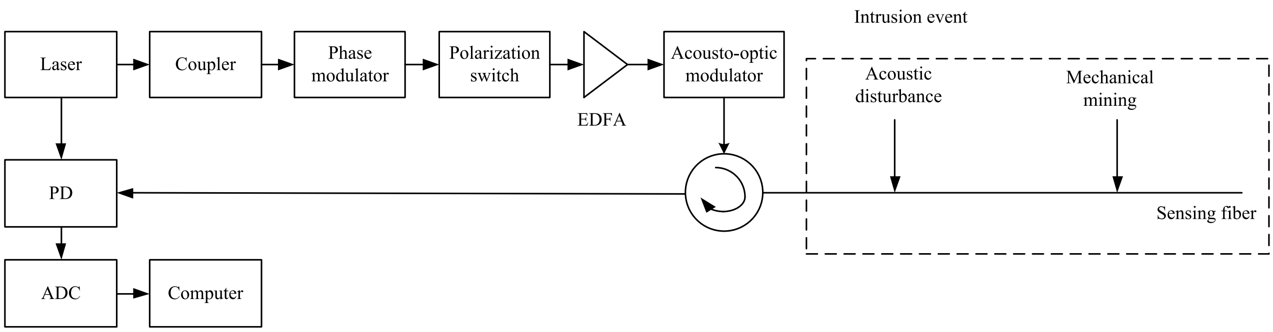


FIGURE 1. DAS system detection principle.

monitoring of pipeline leakage, but the system was complicated. In 2018, Stajanca *et al.* [9] used distributed optical fiber acoustic sensing (DAS) system based on Rayleigh scattering to monitor gas pipeline leakage. The optical fiber is directly spirally wound on the pipe wall to detect the vibration caused by the leakage. A method based on the DAS signal in the frequency domain is proposed to achieve the identification and location of the pipeline leakage. However, the experimental results are greatly influenced by external factors, the positioning accuracy is low, and the fiber consumption is huge. This paper uses the DAS systems based on Rayleigh scattering to monitor gas pipeline leakage. The fiber is freely suspended outside the pipeline to reduce the consumption of the fiber. It also proposes a leak detection algorithm based on wavelet transform and empirical mode decomposition (EMD) and a leak location algorithm based on frequency domain cumulative averaging. The basic principles of the DAS system are detailed in section 2, followed by technical solution in section 3. Section 4 proposes the signal processing method; Then the experimental results are analyzed in section 5. And give a summary at the end.

II. PRINCIPLES

The DAS system is a distributed fiber-optic acoustic sensing system based on coherent Rayleigh scattering. The detection principle is shown in Fig 1. The φ-OTDR technology is applied in the DAS system, and the optical time domain reflection technology lays a foundation for judging the location of the leak point. The output of the laser is modulated into a highly coherent light pulse and used as probe light, which enters the sensing fiber through the circulator. When an intrusion event occurs, the refractive index of the fiber at the invader point changes, causing a phase change of the backscattered Rayleigh light. Due to the interference effect, the intensity of the back-scattered Rayleigh scattering will change accordingly, and the detector detects the Rayleigh scattered light reflected from different positions of the fiber and extracts the weak disturbance signal [10], [11].

In the single-mode fiber, according to the one-dimensional impulse response model of the fiber back -rayleigh scattering, the incident laser is a rectangular pulse, and the amplitude $e(t)$ [12] of back-rayleigh scattering wave can be obtained by injecting the fiber at time $t = 0$.

$$e(t) = \sum_{i=1}^{N} a_i \, exp\left(-\frac{a}{2}\frac{c\tau_i}{n}\right) exp\left[j2\pi v(t-\tau_i)\right] rect\left(\frac{t-\tau_i}{w}\right) \tag{1}$$

where $\tau_i = \frac{2nl_i}{c}$, is the number of scattering centers, a_i is the amplitude of the i-th scattering wave, a is the attenuation coefficient, c is the speed of light, n is the refractive index, τ_i is the time delay of the i-th scattering wave, v is the frequency, w is the pulse width, and l_i is the length of the fiber from the i-th scattering center to the input.

The modulation frequency of AOM is f. After continuously injection of m pulses, the input of the detector will obtain a continuous backscatter Rayleighwave with a period of $T = \frac{1}{f}$ and its amplitude $e(t')$ is expressed as follows [12]:

$$e(t') = \sum_{k=1}^{m} \sum_{i=1}^{N} a_i \, exp\left(-\frac{a}{2}\frac{c\tau_i}{n}\right) \times exp\left[j2\pi v\left(t' - \frac{k}{f} - \tau_i\right)\right] rect\left(\frac{t' - \frac{k}{f} - \tau_i}{w}\right) \tag{2}$$

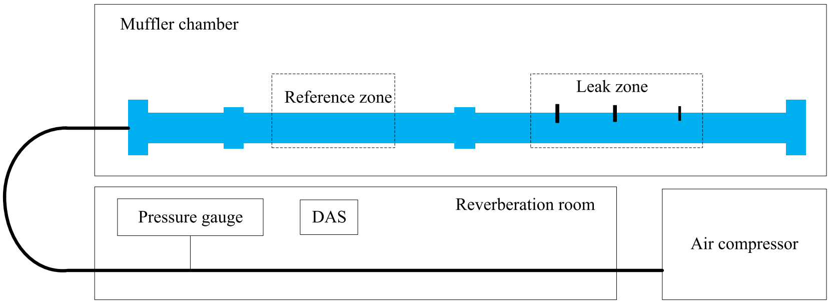
The light power is $p(t')$:

$$p(t') = |e(t')|^2 = p_a(t') + p_b(t') \tag{3}$$

where $p_a(t')$ represents the sum of the optical powers of each independent backscattering center, while $p_b(t')$ is the sum of the light power generated by the interference of the backscatter Rayleigh light, which has serrated ripples. When the saw tooth ripple is generated by $\cos 2\pi v(\tau_i - \tau_j)$, the phase difference between the two scattering wave is $\emptyset_{ij}$:

$$\emptyset_{ij} = \cos 2\pi v(\tau_i - \tau_j) = 4\pi vn(l_i - l_j) \tag{4}$$

Golacki *et al.* [13] have successfully applied the DAS system to detect acoustic perturbations. When the optical fiber is disturbed by the leakage sound of the pipeline, the refractive index of the intrusion point changes due to the elastic light effect, thereby causing a change in the phase difference between the two scattered waves of the interference and resulting in the change of the backscatter Rayleigh light intensity $p_b(t')$. By detecting the change of the Rayleigh light intensity before and after the disturbance, the detection and location of the pipeline leakage point can be realized.



(a) Schematic diagram of gas pipeline system

(b) Experimental pipeline and environment

(c) DAS sensing system

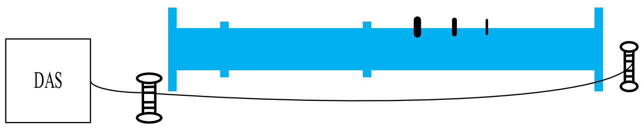
FIGURE 2. Experimental device.

III. TECHNICAL SOLUTION

A. GAS PIPELINE SYSTEM

The DAS system is used to detect gas pipeline leakage, and the tightly packed fiber is directly suspended outside the pipe wall. The experiment was carried out in a full muffler chamber with a background noise of less than 40 dB and a frequency below 1000 Hz. The linear pipe is located in the muffler chamber, and the DAS detection system is located in the reverberation room. The pipeline is composed of three steel pipe segments connected by flange, as shown in Fig 2. The total length of the pipeline is 12.9m and the diameter is 0.3m. The direct relaxation suspension sensing fiber on the outside of the pipeline is used for DAS detection.

The pipeline is divided into two parts: the reference zone and the leak detection zone. There is a simulated leak hole every 10cm in the leak detection zone, which is located directly above the pipe and has a hole diameter of 1mm, 3mm and 5mm respectively. Both ends of the pipe are sealed and closed. The controllable valve is connected to the inner end of the pipe through the hose, and finally connected to the air compressor through the pressure gauge. After the controllable valve is opened, the internal pressure of the pipe is pressurized by the air compressor.



(a) Schematic diagram of the application of the sensing fiber

(b) Experimental layout of the sensing fiber

FIGURE 3. Detailed picture of sensing fiber applications.

B. OPTICAL FIBER SENSING SYSTEM AND EXPERIMENTAL METHOD

The DAS sensing system uses a single-mode tight-package fiber as the probe fiber. As shown in Fig 3, the probe fiber is suspended on one side of the pipe, 0.05m away from the pipe wall; the fiber ring with 20m at both ends of the pipe is wrapped in the muffler cotton to eliminate the influence of other factors. The DAS system uses 50 ns laser pulse length and 20 KHz pulse frequency, and detects the length of fiber is 1000 m.

In the experiment, the leak hole size and the internal pressure of the pipe were combined and tested for each step.

For each combination test, the pressure in the pipe is first increased to a predetermined value of 0.1Mpa-0.7Mpa, and the leakage hole is opened after a short voltage stabilizing. Meanwhile, the DAS system is tested for 3 minutes, and the pressure will gradually decrease with the gas leaks.

IV. SIGNAL PROCESSING

A. LEAK DETECTION ALGORITHM BASED ON WAVELET TRANSFORM AND EMD

According to the characteristics of DAS signal x[n] at the time of pipeline leakage, the N-point signal collected in the second is added to the Hamming window to obtain the spectrum signal $x_t(k)$, and the power spectrum signals with the frequency between 20Hz and 5000Hz are accumulated and averaged:

$$x_t'(k) = \frac{1}{bin_2 - bin_1} \sum_{bin_1}^{bin_2} \frac{(\Delta t)^2}{T} |x_t(k)|^2, \quad k = 0, 1 \cdots, \frac{N}{2}; \quad t \in N^* \tag{5}$$

where $x_t'(k)$ is the time domain signal; $\Delta t = \frac{1}{f_s}$; f_s is the sampling rate, T is the sampling time; bin_1, bin_2 is the starting and ending position of the monitoring signal.

In order to remove the base noise, the local features of the signal are extracted, and the wavelet transform [14] is performed on $x_t'(k)$:

$$c_{j,k} = \sum_n c_{j-1,n} h_{n-2k} \quad k=(0,1,2,\cdots,N-1) \tag{6}$$

$$d_{j,k} = \sum_n c_{j-1,n} g_{n-2k} \quad k=(0,1,2,\cdots,N-1) \tag{7}$$

where $c_{0,k} = x_t'(k)$; $c_{j,k}$ is the scale factor; $d_{j,k}$ is the wavelet coefficient; h (e^{jw}), g $(e^{j(w-\pi)})$ is a pair of orthogonal mirror filter banks; j is the number of decomposition layers.

The corresponding coefficients of effective signals in wavelet domain are large, while the corresponding coefficients of noise are small. The corresponding coefficients of noise in the wavelet domain satisfy the distribution of Gaussian white noise. In order to better extract the weak DAS leakage signal characteristics, a minimax threshold is adopted to determine the threshold [15]:

$$\lambda = \begin{cases} 0.3936 + 0.1829 \left(\frac{\ln N}{\ln 2} \right), & N > 32 \\ 0, & N \le 32 \end{cases} \tag{8}$$

The wavelet coefficients containing the noise figure should be filtered to reduce the Gaussian noise figure. The wavelet coefficients achieved by the soft threshold method have overall continuity, and the signal will not bring extra oscillation:

$$w_{j,k} = \begin{cases} [sgn(d_{j,k})] (|d_{j,k}| - \lambda), & |d_{j,k}| \ge \lambda \\ 0, & |d_{j,k}| < \lambda \end{cases} \tag{9}$$

DAS signals processed by wavelet transform are obtained after reconstruction:

$$x''(t) = \sum_n c_{j,n} h_{n-2k} + \sum_n w_{j,n} g_{n-2k} \tag{10}$$

In order to further improve the SNR, the reconstructed DAS signal is processed by EMD [16]. The specific EMD steps of the one-dimensional signal are as follows:

(1)The upper and lower envelopes $e_{min}(t)$ and $e_{max}(t)$ are obtained by cubic spline interpolation for all the minimax points of $x''(t)$, and the upper and lower envelope mean $m(t)$;

(2) Determine whether $d(t)$ meets the condition according to the intrinsic mode function (IMF) condition, where $d(t) = x''(t) - m(t)$. If the IMF condition [17] is satisfied, $d(t) = c_i(t)$, otherwise the envelope of $d(t)$ is calculated;

(3)$IMF(t) = x''(t) - d$ (t). If $IMF(t)$ is monotonic, $IMF(t)$ is an approximate IMF component, otherwise the envelope of $IMF(t)$ is calculated.

The correlation analysis between the approximate IMF component IMF(t) and $x''(t)$. According to the correlation criterion, the components with correlation coefficient greater than 0.3 are superimposed and reconstructed to obtain the reconstructed signal $x'''(t)$ after EMD processing. That is, the final DAS reconstruction signal. According to the characteristics of the final DAS reconstructed signal, the signal SNR and detection accuracy can be effectively improved.

B. LEAK LOCATION ALGORITHM BASED ON FREQUENCY DOMAIN CUMULATIVE AVERAGING

The DAS sensing signal contains light intensity signals that are presented along two axes: the time axis and the spatial axis. According to the characteristics of the pipeline leakage signal $x[n]$, this paper proposes a leak location algorithm based on frequency domain cumulative averaging.

The N-point signal collected on the pipeline per meter is added to the Hamming window to obtain the spectrum signal $y(k)$, and the frequency domain signals of all the positions in the spectrum range from 20 Hz to 5000 Hz are subjected to cumulative averaging processing to obtain the overall frequency domain signal $y'(k)$:

$$y'(k) = \frac{1}{bin_2 - bin_1} \sum_{bin1}^{bin2} \sum_{n=0}^{N-1} e^{-i\frac{2\pi}{N}nk} x[n] \quad k = 0, 1, \ldots, N-1 \tag{11}$$

There is strong base noise in the overall frequency domain signal. Using (6) to (10), wavelet transform is used to improve SNR. The signal amplitude of the frequency of 20-5000 Hz on each sensing fiber is accumulated, so as to obtain the distribution curve of the position of the sensing fiber and the accumulated signal. According to the magnitude of the distribution curve and the location, the leak position of the pipeline can be determined.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. TIME DOMAIN RESULTS AND ANALYSIS

A leakage detection algorithm based on wavelet transform and EMD is used to process the monitoring signals. Fig 4 shows the original time domain signal when the leakage aperture is 1mm and the internal pressure is 0.1Mpa, 0.3Mpa, 0.7Mpa. The pipeline leakage occurs in the 5th, 11th, and

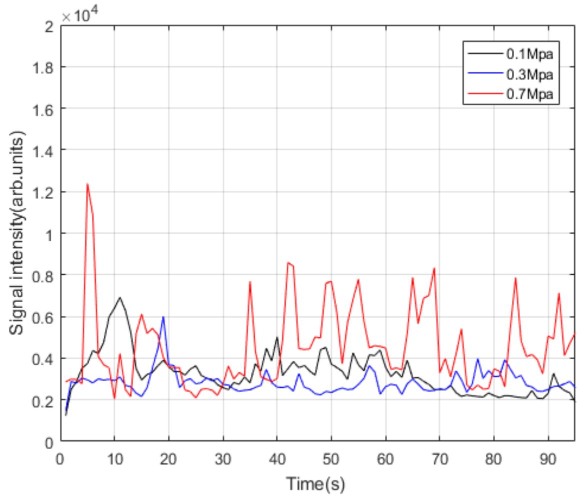


FIGURE 4. Time domain signal with a leakage aperture of 1 mm and a pressure of 0.1Mpa, 0.3Mpa, and 0.7Mpa.

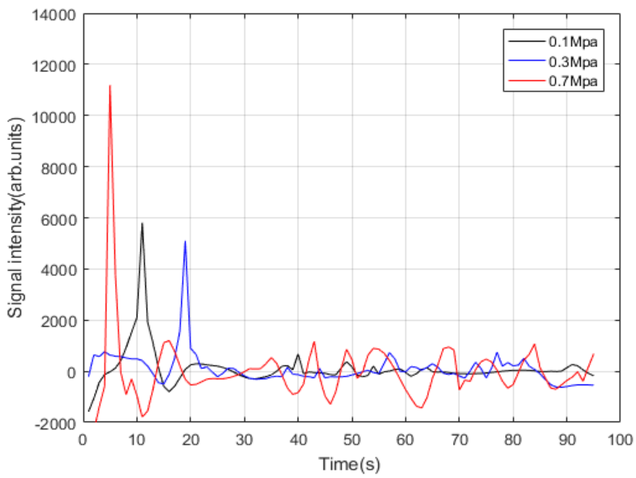


FIGURE 5. Reconstructed time domain signal with a leakage aperture of 1 mm and a pressure of 0.1Mpa.

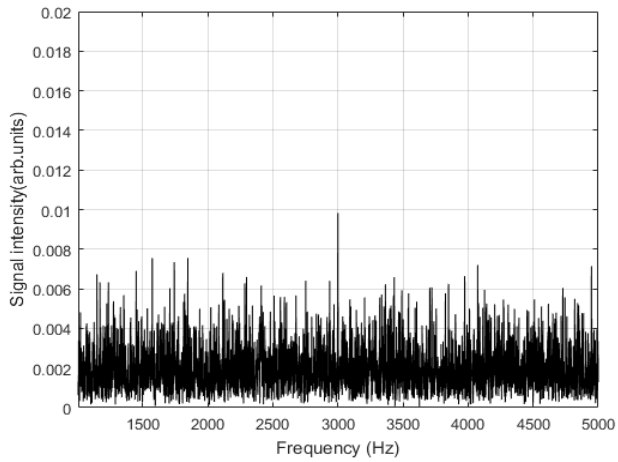
19th seconds respectively, making it difficult to distinguish the effective pipeline leakage signals.

The leakage detection algorithm based on wavelet transform and EMD was used to process the monitoring signal to obtain the reconstructed time domain signal. As shown in Fig 5, the pipeline leakage characteristic signal is obvious at the 5th, 11th, and 19th seconds.

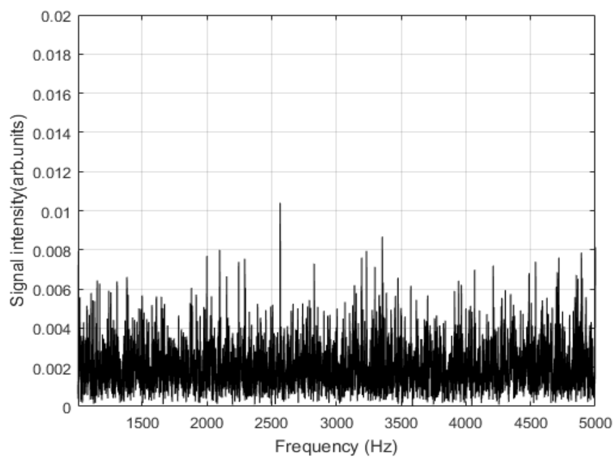
After the time domain signal reconstruction, the SNR is effectively improved, and the pipeline leakage characteristics are obvious. As shown in Table 1, the SNR of the original DAS signal after wavelet transform is 16.21. After wavelet transform and EMD processing, the SNR is increased to 18.28, and the correlation between the final reconstructed signal and the original DAS signal is increased to 0.75. The reconstructed signal features are substantially similar to the original signal characteristics. According to the characteristics of the reconstructed signal, setting the appropriate alarm threshold can determine whether the pipeline leaks, which effectively improve the detection accuracy.

TABLE 1. Comparison of SNR and correlation coefficient of original DAS signal processed by each algorithm.

Algorithm	wavelet transform	wavelet transform and EMD
SNR	16.21	18.28
Correlation coefficient	0.74	0.75



(a) Frequency domain signal with a leakage aperture of 1 mm and a pressure of 0.1Mpa in the tube



(b) Frequency domain signals with a leakage aperture of 1 mm and a pressure of 0.3Mpa in the tube

FIGURE 6. Frequency domain signals.

B. FREQUENCY DOMAIN RESULTS AND ANALYSIS

In the experiment, the pulse repetition frequency of 20 kHz was used for detection, and the number of sampling points was 4096. According to the Nyquist theorem, the maximum frequency of the DAS signal was 10 kHz. However, when the frequency is above 5000Hz, the DAS signal is almost submerged in the noise, which is caused by the inherent limitations of the DAS system measurement settings. Therefore, this paper mainly detects DAS signals below 5000Hz.

Fig 6 (a) and Fig 6 (b) show the original frequency domain signal when the leakage aperture is 1mm and the pressure

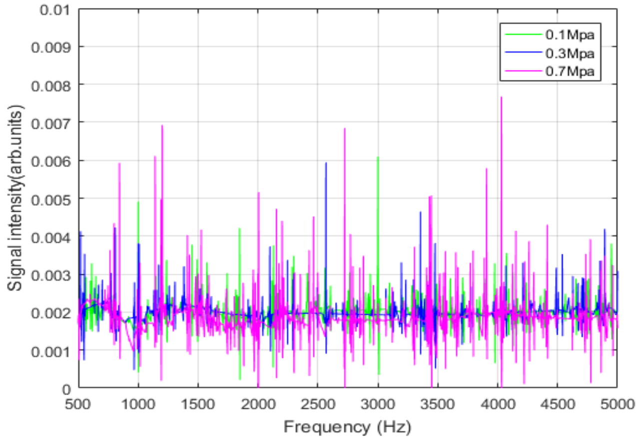


FIGURE 7. Reconstructed frequency domain signal of 1mm hole leakage under different tube internal pressures.

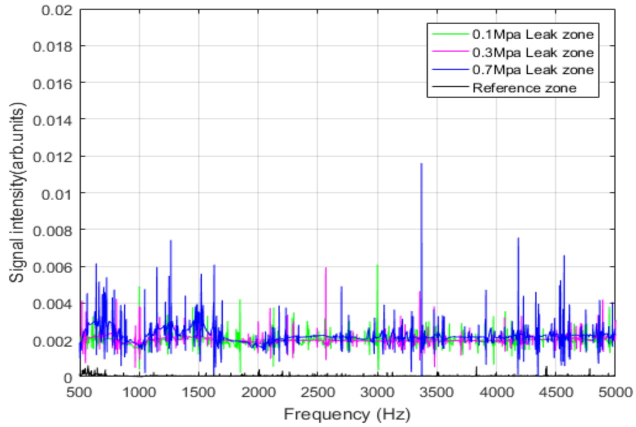


FIGURE 8. Reconstruction of frequency domain signals in different pipeline areas of 1mm hole leakage under different tube internal pressures.

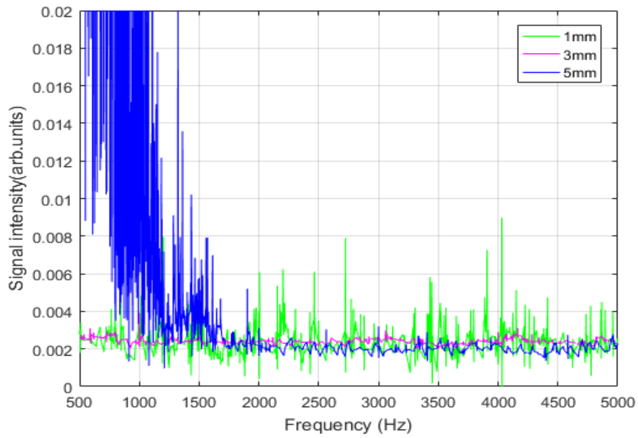


FIGURE 9. Reconstructed frequency domain signal when the pressure inside the tube is 0.7Mpa under different tube leakage apertures.

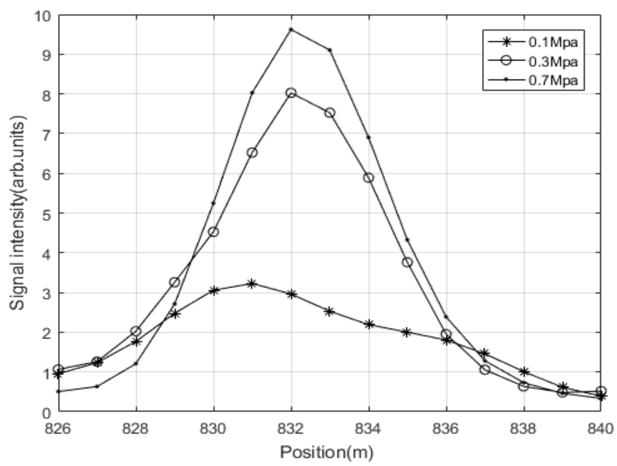


FIGURE 10. Distribution of leakage locations for different in-line pressures at 1 mm aperture after reconstitution.

inside the tube is 0.1Mpa and 0.3Mpa respectively. The DAS signal and noise are mixed with each other, making it difficult to distinguish the effective pipeline leakage signal, so the signal needs to be denoised.

In order to effectively identify the characteristic signals in the frequency domain when leakage occurs, noise reduction processing is performed according to (6) to (10) to obtain the signal in the frequency domain as shown in Fig 7, which effectively improving the SNR. As can be seen from the figure, when the frequency is greater than 4030 Hz, the peak value of the DAS signal is in a stable small fluctuation state. Therefore, the signal characteristics of the pipeline are mainly concentrated below 4030Hz when the 1mm hole and the pressure are 0.1mpa and 0.3mpa respectively. The overall trend of the frequency domain characteristic signal caused by the leakage remains stable, the characteristic signal of the lowest pressure (0.1MPa) is obvious. The new peak appears and the amplitude increased at the higher pressure (0.7Mpa), which is related to the increase of the internal pressure of the pipeline.

Pipeline leak detection is divided into two detection areas: the reference area and the leakage area. Fig 8 shows the DAS frequency domain signals in the two regions at the 1mm leak. In the reference zone, the DAS signal strength almost tends to be 0, while the DAS signal intensity is obvious in the leakage zone, that is, the frequency domain leakage characteristic is obvious. This indicates that the disturbance signal comes from the acoustic vibration generated by the leakage of the gas pipeline, and it can be determined whether a certain section of the pipeline is leaking.

Fig 9 shows the frequency domain signals of different apertures when the internal pressure of the pipeline is 0.7Mpa. Under constant pressure, the large leakage aperture stimulates the low-frequency acoustic vibration. When the leakage aperture is 5mm, the frequency characteristics of the leakage signal are mainly concentrated in 500Hz-1000Hz, while in the small leakage aperture, the frequency characteristics of the leakage signal are mainly concentrated in 2700Hz and 4000Hz.

So as to improve the accuracy of leak location, this paper uses a leak localization algorithm based on frequency domain cumulative average. Since the leakage signal is generally distributed between 500 Hz and 5000 Hz, DAS signals in this frequency range are averaged to obtain the location distribution map of pipeline leakage signals. Fig 10 shows the positioning diagram when the leakage aperture is 1mm and the pressure inside the pipe is 0.1Mpa, 0.3Mpa, 0.7Mpa respectively. The DAS signal strength reaches the maximum at about 832m, which is basically the same as the actual pipeline leakage hole. The DAS signal on both sides of the leak hole gradually decreases and tends to 0. This indicates that the DAS system can locate the pipeline leakage point, and the leak location algorithm based on the frequency domain accumulation average is helpful to improve the positioning accuracy.

VI. CONCLUSION

This paper presents a real-time monitoring method for gas pipelines based on DAS system. The method places the sensing fiber outside the pipe in a freely suspended manner to detect acoustic vibrations caused by leakage. a pipeline leak detection algorithm based on wavelet transform and EMD is proposed, which can obtain the time domain signal characteristics of pipeline leakage, and increase the SNR and correlation to 18.28 and 0.75 respectively, effectively improving the accuracy of leak detection. At the same time, the leak location algorithm based on frequency domain accumulation average is also proposed, which can realize the accurate location of pipeline leakage point. The field experiment results prove the effectiveness of the method, which lays a foundation for DAS system to monitor the leakage of gas pipeline in real time and locate the leakage point accurately. in practical engineering applications.

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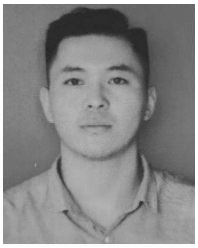

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