Journal of Loss Prevention in the Process Industries 25 (2012) 90–102

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Experimental study on leak detection and location for gas pipeline based on acoustic method

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ARTICLE INFO

Article history:
Received 11 March 2011
Received in revised form
6 July 2011
Accepted 8 July 2011

Keywords:
Gas pipeline
Acoustic method
Signal recognition
Leak location

ABSTRACT

The leak of gas pipelines can be detected and located by the acoustic method. The technologies of recognizing and extracting wave characteristics are summarized in details in this paper, which is to distinguish leaking and disturbing signals from time and frequency domain. A high-pressure and long distance leak test loop is designed and established by similarity analysis with field transmission pipelines. The acoustic signals collected by sensors are de-noised by wavelet transform to eliminate the background noises, and time-frequency analysis is used to analyze the characteristics of frequency domain. The conclusion can be drawn that most acoustic signals are concentrated on the ranges of 0–100 Hz. The acoustic signal recognition and extraction methods are verified and compared with others and it proves that the disturbing signals can be efficiently removed by the analysis of time and frequency domain, while the new characteristics of the accumulative value difference, mean value difference and peak value difference of signals in adjacent intervals can detect the leak effectively and decrease the false alarm rate significantly. The formula for leak location is modified with consideration of the influences of temperature and pressure. The positioning accuracy can be significantly improved with relative error between 0.01% and 1.37%.

1. Introduction

Pipeline is a main energy-efficient means for natural gas transportation from fields to customs. As the total lengths of gas pipelines have increased significantly in recent years in China, pipeline leakages occur occasionally, which can cause huge economic losses and environmental pollution. So, it is important to find an efficient way to detect the leakage quickly and locate the leak position accurately.

Currently, some methods and systems for gas pipeline leak detection had been developed, such as methods based on mass/volume balance, static decision method, transient model method, distributed optical fiber and acoustic method, etc. Among these, acoustic method has been proven to be the most effective, true real-time and on-line leak detection method, which provides quick leak detection, high sensitivity, accurate leak location, and low false alarm rate.

Lots of studies have been done on acoustic method, especially on acoustic signal recognition. The acoustic wave (Watanabe, Matsukawa, Yukawa, Himmelblau, 1986) measured at two ends of the pipeline showed obvious sharp positive or negative pulse at a certain time, which can be used for leak location. Hunaidi and Chu (1999) investigated that the characteristics of frequency band distributions of acoustic signals in a water distribution pipe were determined by leak type, flow rate, pipe pressure, season, the determination of the attenuation rate, and the variation of propagation velocity. An equation of axisymmetric wave motion for a fluid-filled pipe (Muggleton, Brennan, & Pinnington, 2002) was developed, which can be applied for two different wave types (a fluid dominated wave and an axial shell wave). The expressions of a complicated wave number for each wave were also given. Afterward experiments (Muggleton, Brennana, & Linford, 2004) were conducted to validate those models. During the experiments, the wave number including both wave speed and wave attenuation were made on a water-filled pipe in vacuo and on a buried water-filled pipe. The conclusions showed that the elastic properties of the pipe wall were temperature dependent which may change considerably depending on the pipe environment, therefore the pipe conditions should be taken into account in calculating the expected wave speed to reduce the leak location errors. A modified method and device for leak location and detection (Yang & Recance, 2002) was provided. Pattern matching filter was used to reduce false alarm rate, increase sensitivity and improve the leak location detection accuracy. The device can detect a pressure wave generated

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doi:10.1016/j.jlp.2011.07.001

Nomenclatures

a_1	propagation velocity of acoustic wave in the section of pipeline $(0 \rightarrow x)$
a_2	propagation velocity of acoustic wave in the section of pipeline $(x \rightarrow L)$
$a[i]$	the i-th acoustic signal in the k-interval
c	propagation velocity of acoustic signal in medium
c_1	the average velocity of the fluid in the section of pipeline $(0 \rightarrow x)$
c_2	the average velocity of the fluid in the section of pipeline $(x \rightarrow L)$
j	the length of least square fitting data
k	the sequence number in a certain period of time
k_v	volume insulation index
K_i	least square fitting slope from x_i to $x_{(i+j)}$
$\overline{K}$	slope mean value
L	the distance between upstream and downstream sensors
M	the total number of the intervals in a period of test time
N	the total number of data points in the k-interval
p	the operation pressure of pipeline
P	the signal peak in the k-interval
q	function of acoustic signals
R	gas law constant, kJ/(kg K)
Δt	the time interval between upstream and downstream sensors received
t_1	the time of the arrival of the acoustic signal at upstream
t_2	the time of the arrival of the acoustic signal at downstream
T	the time period that acoustic wave spreads between the two adjacent sensors, $T = L/c$
T_0	temperature, K
x	the distance between the leak point and the upstream acoustic sensor
$x(n)$	the standard signal without de-noising
$\widehat{x}(n)$	the signal with de-noising
x_i	the i-th value of acoustic signal
$\overline{X}$	mean value of acoustic signal
z	compressibility factor

Greek letters

$r_{12}(\tau)$	value of cross-correlation function
τ	time, $\tau \in (-T/2, T/2)$
τ_0	the time when $r_{12}(\tau)$ reach to the maximum
ρ	the density of natural gas
σ	the root mean square value (RMS)

Abbreviations

meanAD	mean difference in adjacent interval
PD	peak value difference in adjacent intervals
PSD	power spectral density
RMS	root mean square value
sumA	accumulated value in each interval
sumAD	accumulated value difference in adjacent interval
sumADD	the difference of the accumulative value difference
SNR	signal to noise ratio

by a leak and discriminate against background noise and pressure disturbance generated by other non-leak sources. Liu, Li, Liu, and Li (2003) derived the dispersion equation of structure acoustic coupling system for fluid pipe from shell dynamic equation. The fluid pipe was surrounded by elastic media under axisymmetric motion. The attenuation characteristics of wave propagation in fluid-filled metal and PVC plastic pipes were studied. The leak detection of gas pipeline by acoustic method (Yang, Jing, and Gong, 2007) was studied and hardware circuit of acoustic data acquisition system was designed to do the tests. A leak detection method with sequential energy percentage based on the square of average interzone signal energy is proposed (Zheng & Lin, 2006). The

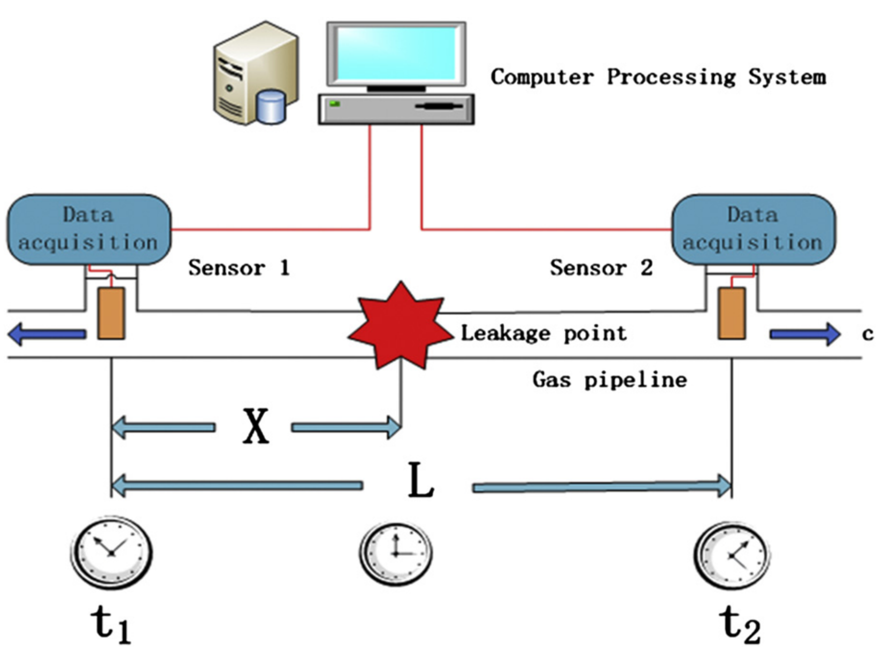

Fig. 1. Schematic diagram of acoustic leak detection system.

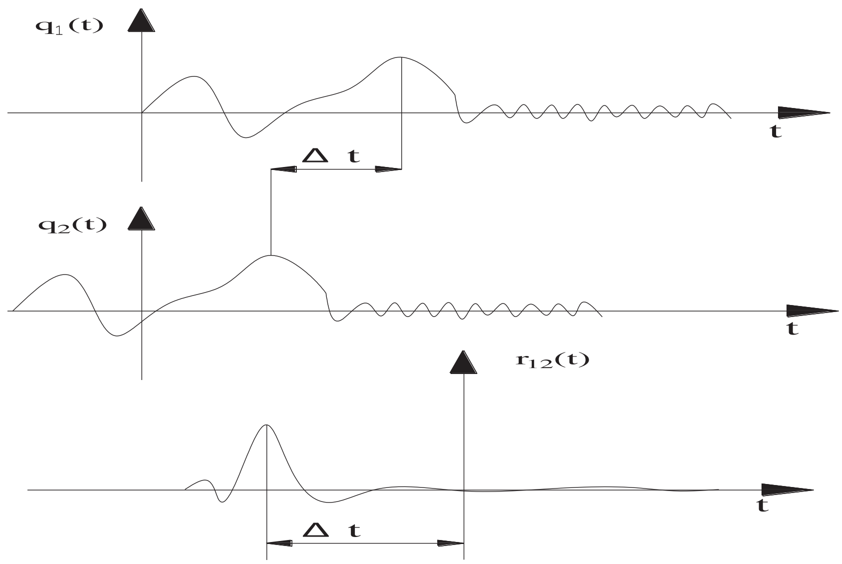

Fig. 2. Schematic diagram of cross-correlation position.

analysis results showed that the signal noise ratio of leak signal and the reliability of system were improved. Tolstoy, Horoshenkov, and Bin Ali (2009) used matched field processing (MFP) to check whether there had been changes such as new entrance of pipeline with respect to undisturbed fields measured earlier. Model of sound wave was not necessarily developed in the field and only the simple linear processor was applied with test data. The characteristics of dispersive acoustic wave (Kim & Lee, 2008) were identified through analysis of the cut-off frequency with time-frequency method experimentally and BEM (boundary element method) was developed as an experimental tool to analyze the leak signals in steel pipe. The results provided useful information for the selection

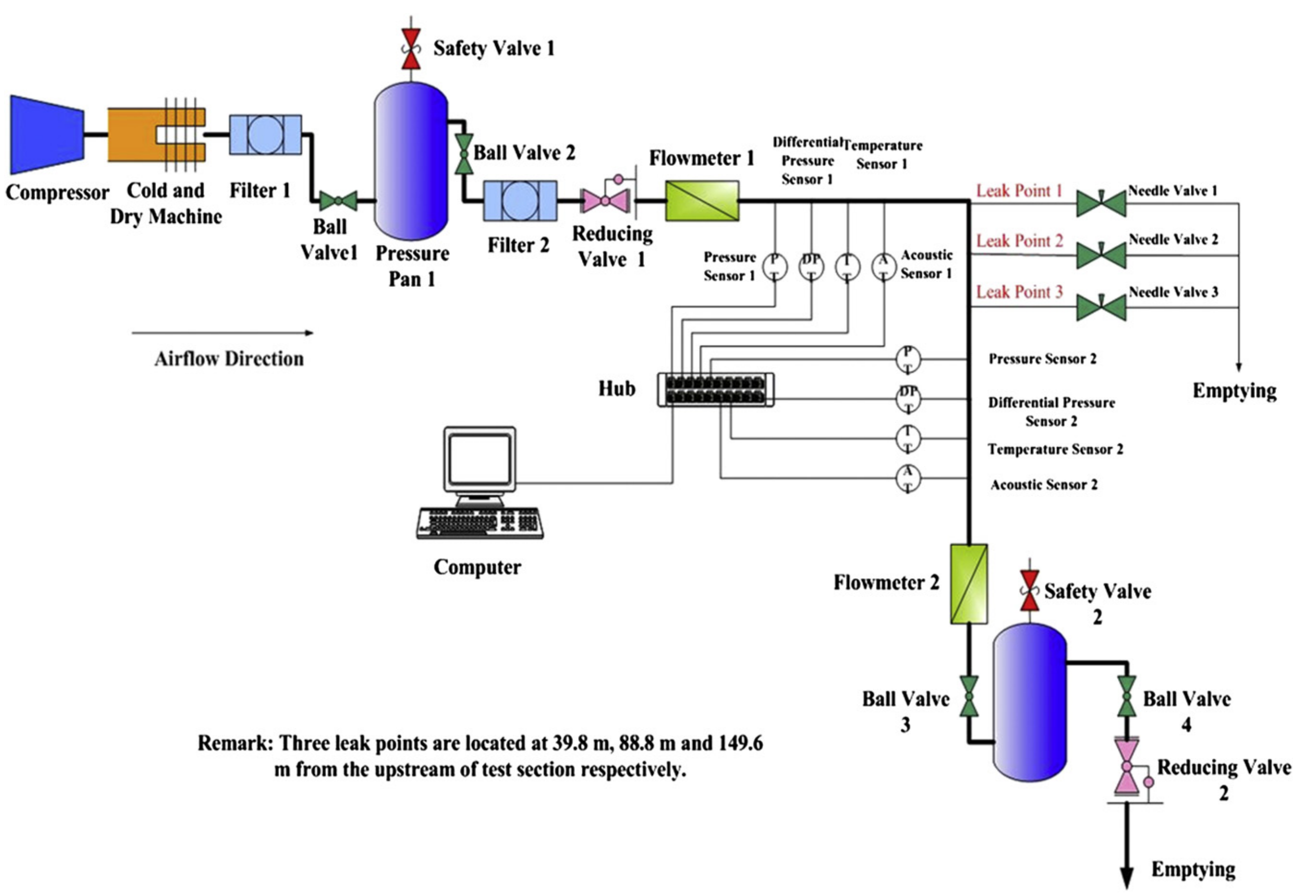

Fig. 3. High-pressure gas pipeline leak detection test loop.

Table 1
The distinction between leak signal and disturbing signals.

Signal type	Leak signal	Compressor signal	Valve signal	Knocking signal
Characteristics	Whole kurtosis	Waveform and amplitude, RMS, whole kurtosis	Correlation function, covariance function	Correlation function, covariance function
Statement	The whole kurtosis is maximum	Waveform is flattest, amplitude is 2.5–3.0 kPa, RMS presents increasing or decreasing trends, the whole kurtosis is minimum	Correlation function and covariance function is maximum	Correlation function and covariance function is minimum

of the filter bandwidth in the correlation method for the leakage detection.

The above studies focus on the processing of acoustic signal and extraction of acoustic signal characteristics, however, it ignores the influence of the external interference, which contains start-up and shut-down of compressor, valve switch, pipeline knocking, etc. Some characteristics of those disturbing signals are similar with those of leak signals. When an external interference occurs, it will lead to a false alarm. Therefore, this paper will make a distinction between leak signals and disturbing signals and choose the distinct features of leak signals to detect the leakage. A high-pressure pipeline leak detection and location system is designed and established by similarity analysis at field transmission lines. Lots of tests have been done to analyze characteristics of leak signal and disturbing signal. Time-frequency analysis of acoustic signal has been done and the characteristics of frequency domain are introduced in the paper. In order to locate the leak more accurately, the leak location formula is modified in consideration of temperature and pressure based on the correlation analysis.

2. Basic principles for acoustic leak detection and location of gas pipeline

2.1. Basic principle of acoustic leak detection

When a leak or rupture occurs, the pressure balance of the pipeline is interrupted and gas (or fluids) leak from the pipeline and acoustic waves are generated by the friction with the pipe wall. Meanwhile, acoustic signal along with the fluids propagates to upstream and downstream. The high-frequency component of acoustic signal attenuates quickly, while the low-frequency component can propagate for a long distance. Acoustic sensors installed at both ends of the pipeline receive the acoustic waves in the pipeline to determine whether a leak happens or not. Meanwhile, leak detection system can calculate and verify the leak location based on the acoustic propagation velocity and the time of arrival of acoustic signal at two adjacent acoustic sensors. When the pipeline is in good conditions, acoustic signals received by the acoustic sensors are treated as background noises. Once a leak occurs, both the acoustic leak signals and the background noises are received by the acoustic sensors and compared with the signature leak profiles in acoustic leak detection system. At the same time the system will send out leak alarms and the leak location will be determined.

There are three main classes of acoustic signals received in the field and laboratory: leak signals, background noises, disturbing signals. Background noises mainly refers to electromagnetic interference from the field and data acquisition system, which are inevitable, but could be reduced by de-noising method such as Wavelet Transform, Fourier Transform, etc. The disturbing signals refer to the start-up and shut-down of compressor, valve switch and pipeline knocking, etc. Some features of those disturbing signals are so similar with those of leak signal that they can lead to a false leak alarm. Wavelet Transform is used to de-noise the experimental data in this paper. The leak signals and disturbing signals are analyzed by characteristics of time domain and frequency domain. Finally, characteristics of acoustic signals will be extracted for leak detection.

2.2. Improvement of leak location method

Leak location is determined by the arrival time of the acoustic signals at two adjacent acoustic sensors as shown in Fig. 1. The algorithm for the acoustic leak location is shown as follows:

$$x = (L + c\Delta t)/2 \tag{1}$$

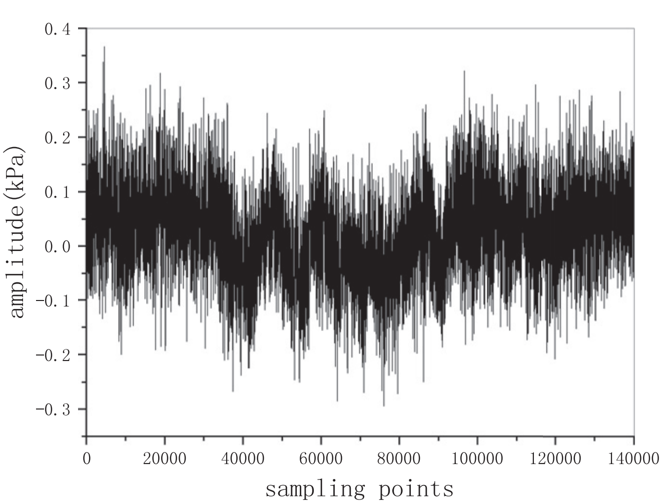

Fig. 4. Acoustic signal with noise.

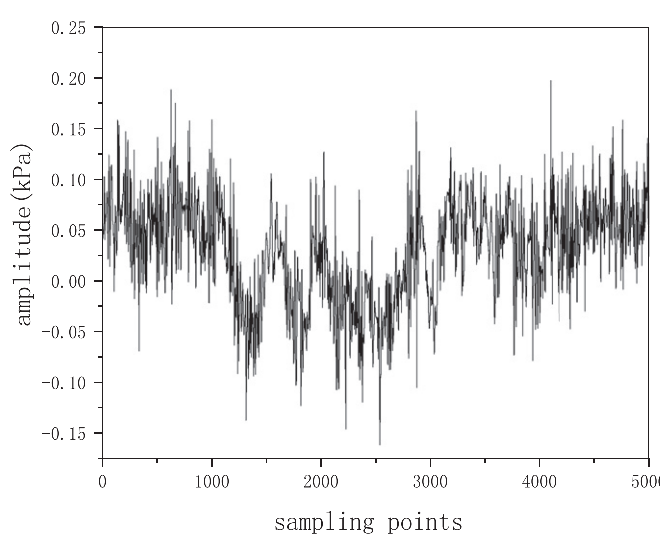

Fig. 5. Acoustic signal with de-noising.

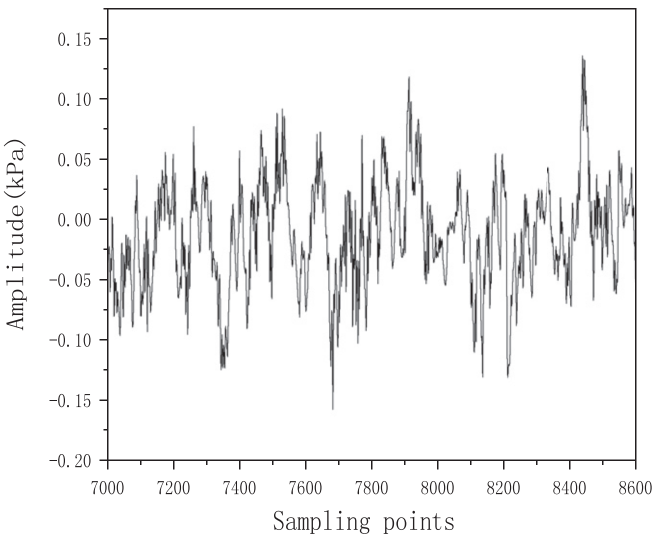

Fig. 6. Acoustic wave with leakage.

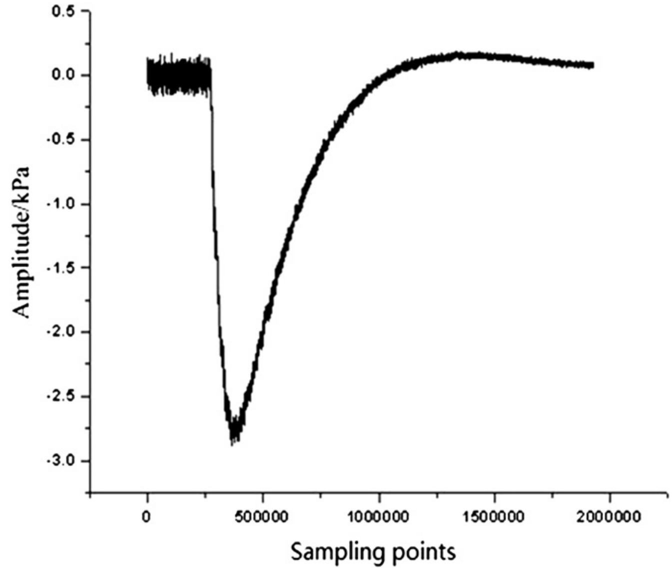

Fig. 8. Waveform of valve close signal.

Therefore, the exact arrival time of the acoustic signals at each monitor and the propagation velocity of acoustic signal are critical for locating the leak on the pipeline accurately.

Once a leak occurs, acoustic signals are generated at the leak point, which are detected by the acoustic sensors at both upstream and downstream. The cross-correlation analysis method can be used to determine the time difference corresponding to the two peaks of signals. When a leak occurs, the upstream acoustic signal is similar to the downstream signal but with a time difference. Therefore cross-correlation analysis is conducted by moving the acoustic signal from one end and comparing with the signal on the other side. There must be a maximum point, once the maximum point is found, the time difference of the acoustic waves between upstream and downstream can be calculated as shown in Fig. 2. The cross-correlation correlation is defined as follows:

$$r_{12}(\tau) = \frac{1}{T}\int_{-T/2}^{T/2} q_1(t)q_2(t+\tau)\mathrm{d}t \tag{2}$$

where T is the period that acoustic wave spreads between the two adjacent sensors, $T = L/c$, $\tau \in (-T/2, T/2)$.

When no leak occurs, the cross-correlation function will be maintained around a certain value. Once a leak occurs, that is theoretically when $\tau = \tau_0$, $r_{12}(\tau)$ will reach the maximum value expressed as below

$$r_{12}(\tau_0) = \max r_{12}(\tau) \tag{3}$$

By calculating the maximum value of cross-correlation function $r_{12}(\tau)$ and τ_0, the leak location can be determined.

The propagation velocity of acoustic waves along the pipeline in real conditions is influenced by operation pressure, temperature, etc. According to the mass conservation and momentum conservation law, the propagation velocity of acoustic waves in the rigid pipeline can be expressed as

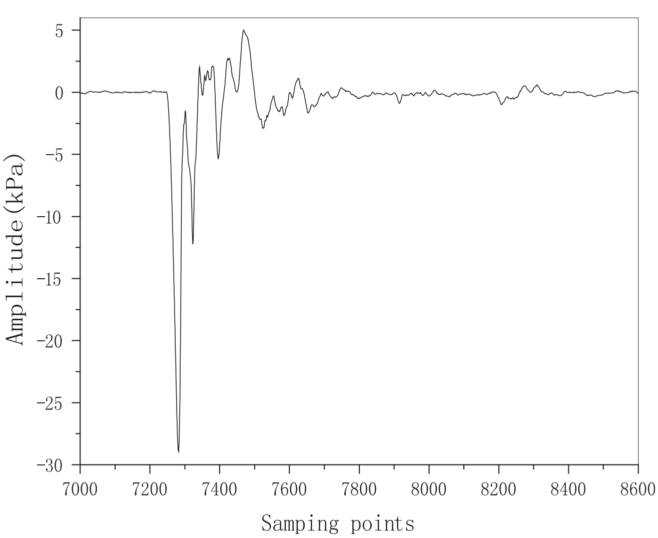

Fig. 7. Acoustic wave without leakage.

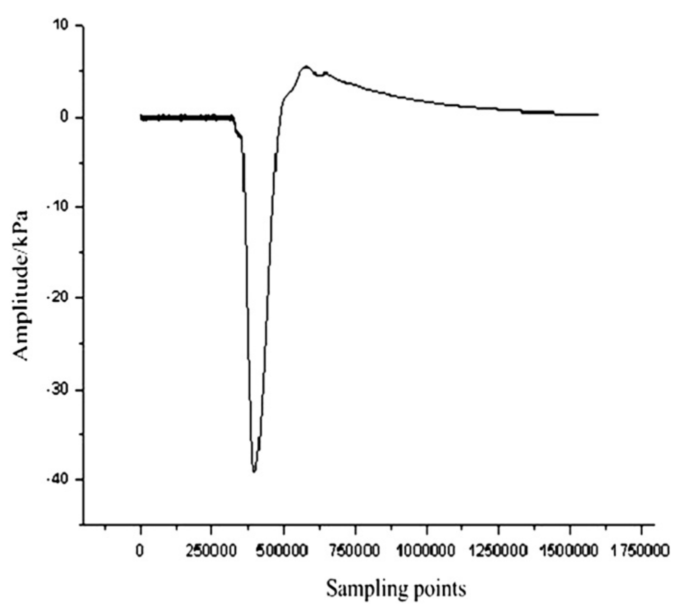

Fig. 9. Waveform of compressor shut-down signal.

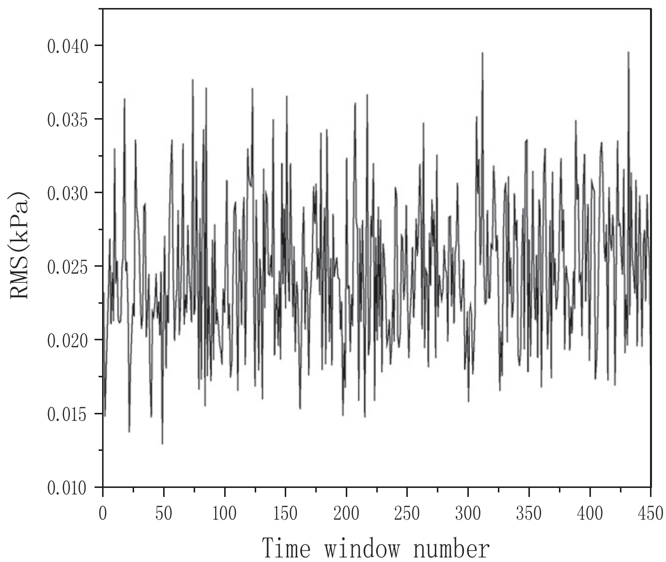

Fig. 10. RMS of acoustic signal without leakage.

$$c = \sqrt{k_v p/\rho} = \sqrt{k_v zRT_0} \tag{4}$$

The value of k_v and z can be calculated with the gas equation of state such as SRK (Liu, 2000).

However, the propagation velocity of acoustic waves will be affected by the fluid velocity and operating pressure. Therefore, the formula of location is modified as follows.

Assume the distance between the upstream and leak point is x in the section of pipeline ($0 \to x$), the average velocity of fluid is c_1, the propagation velocity of acoustic signal is a_1, the arrival time of the acoustic signal at upstream is t_1; the distance between downstream and leak point is $L-x$, in the section of pipeline ($x \to L$), the average velocity of fluid is c_2, the propagation velocity of acoustic signal is a_2, the arrival time of the acoustic signal at downstream is t_2.

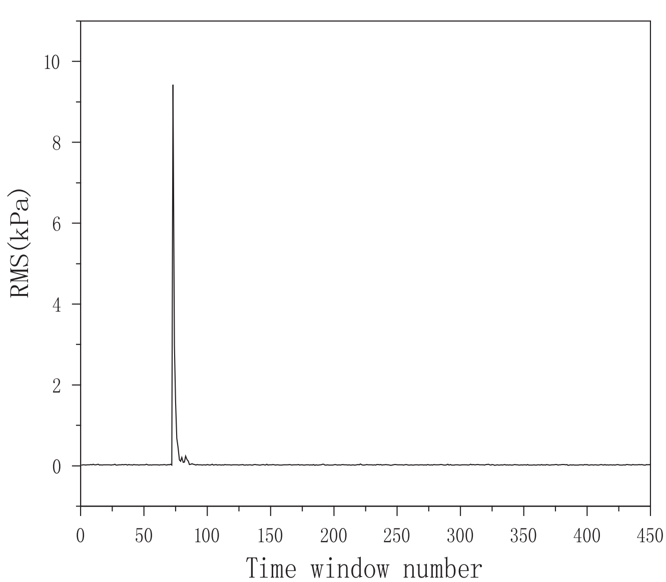

Fig. 11. RMS of acoustic signal with leakage.

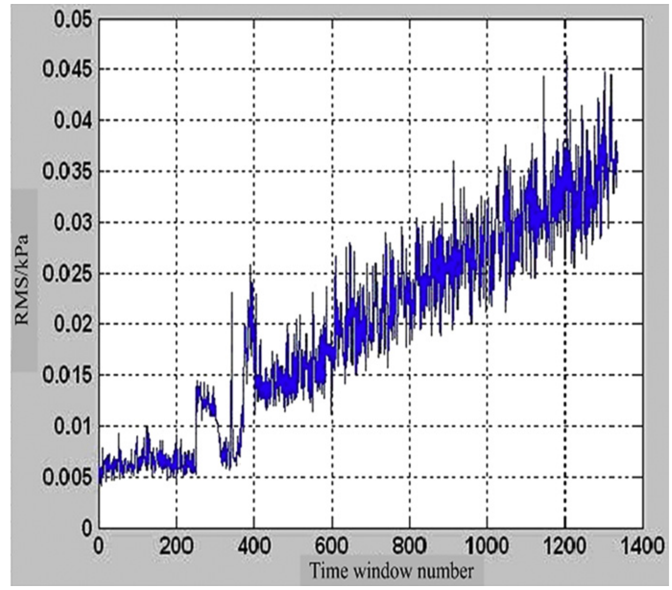

Fig. 12. RMS of compressor signal.

$$\begin{cases} t_1 = x/(a_1 - c_1) \\ t_2 = (L-x)/(a_2 + c_2) \end{cases} \tag{5}$$

Therefore, the modified formula for the leak location can be presented as follows:

$$x = \frac{L(a_1 - c_1) - (a_1 - c_1)(a_2 + c_2)\Delta t}{a_1 - c_1 + a_2 + c_2} \tag{6}$$

3. Experiments on acoustic leak detection and location of gas pipeline

3.1. Experimental facility

A high-pressure pipeline with leak detection and location system is designed and established by similarity analysis with field

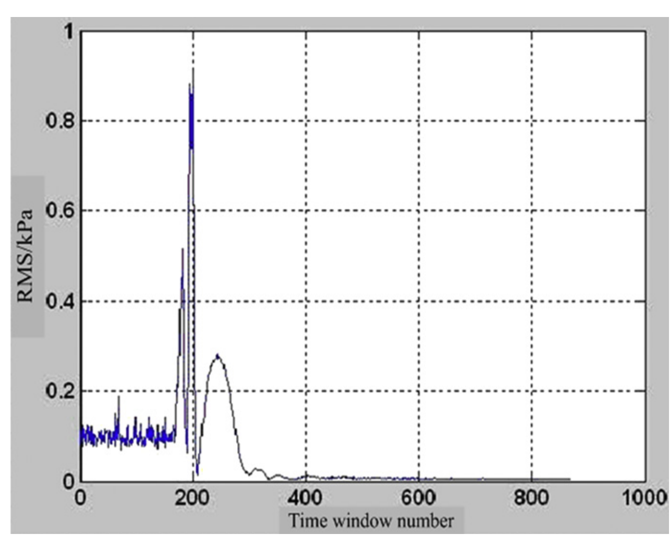

Fig. 13. RMS of valve signal.

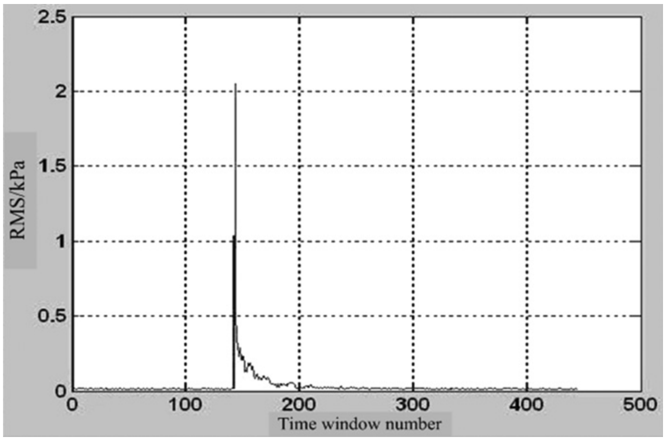

Fig. 14. RMS of pipeline knocking signal.

Table 2
Power spectral density of different frequency bands.

Frequency range/Hz	Power spectral density/W $Hz^{-1} \times 10^4$
0–1000	458019.56
1000–2000	3.14
2000–3000	0.62
3000–4000	0.01
4000–5000	0.01
5000–6000	0.01
6000–7000	0
7000–8000	0
8000–9000	0
9000–10,000	0
10,000–11,000	0
11,000–12,000	0
12,000–13,000	0
13,000–14,000	0
14,000–15,000	0

transmission pipelines as shown in Fig. 3. This acoustic leak detection system is the first high-pressure experimental facility in China with an operation pressure of 8 MPa. The length of full pipeline is 251.5 m with an internal diameter of 10 mm and the length of test pipeline is 200.8 m. The Reynolds number is greater than 10^7 which is similar to the field transmission pipelines. At both ends of the test pipeline, pressure transmitters, differential pressure transmitters, flow transmitters, temperature transmitters and other equipments are installed to measure parameters. Three leakage points are located at 39.8 m, 88.8 m and 149.6 m from the upstream of test section, respectively, where valve and orifice are installed to measure the leak flow rate from the orifice. The compressed air from the compressor is provided as the gas source in the experiments and water and oil droplets in the gas is removed by the cold and dry machine and filters. After flowing through a high-pressure surge tank, the gas enters into the test sections and finally goes into the medium-pressure surge tank and is discharged into the environment.

Acoustic sensors are installed at both ends of the test pipeline, and special data acquisition programs have been written to measure and process the acoustic signals. The data acquisition system mainly consists of acoustic sensors, pre-amplifier, signal conditioner, data acquisition card, computer, etc. The measurement range of acoustic sensors is 0–57.3 kPa and the sensitivity of sensors is 43.5 mV/kPa. The sampling frequency of acoustic signal is set by 30 kHz in the experiment.

3.2. De-noising and processing of the acoustic signals

The acoustic signals collected by sensors contain background noise, which need to be filtered. In the case without external interference, most of the noise is proved to be white noise. In this paper, Wavelet Transform and Fourier Transform are applied to signal de-noising, and signal to noise ratio (SNR) and value of root mean square (RMS) are considered as the criterion to judge the effectiveness of the de-noising. And the effect of de-noising becomes better with larger SNR and smaller RMS. The algorithms for SNR and RMS are showed as follows:

$$\mathrm{SNR} = 10\log_{10}\left[\frac{\sum_n x^2(n)}{\sum_n \left[x(n)-\hat{x}(n)\right]^2}\right] \quad \mathrm{RMS} = \sqrt{\frac{1}{n}\sum_n \left[x(n)-\hat{x}(n)\right]^2} \tag{7}$$

The calculated values are shown in Table 1. Through the calculation of SNR and RMS, the method of de-noising with Wavelet

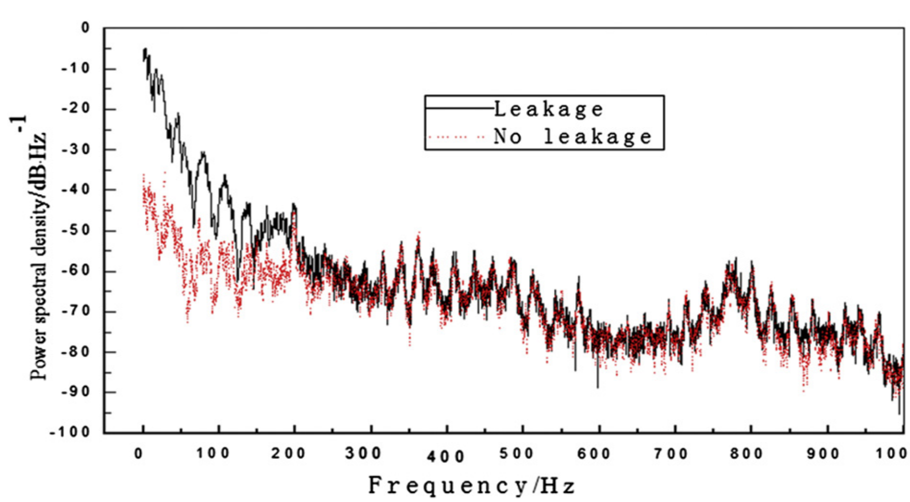

Fig. 15. Power spectral density of different conditions.

Table 3
Power spectral density relationship of different frequency bands.

Frequency range/Hz	Leak condition		No leak condition		Leakage/No leakage
	Power spectral density/W $Hz^{-1} \times 10^4$	Frequency range ratio	Power spectral density/W $Hz^{-1} \times 10^4$	Frequency range ratio	
0–100	457452.05	0.9988	291.73	0.7755	1568.067
100–200	507.31	0.0011	38.68	0.1028	13.11556
200–300	25.9	5.65E-05	14.61	0.038837	1.772758
300–400	14.46	3.16E-05	14.6	0.03881	0.990411
400–500	10.69	2.33E-05	9.09	0.024163	1.176018
500–600	2.09	4.56E-06	1.78	0.004732	1.174157
600–700	0.51	1.11E-06	0.43	0.001143	1.186047
700–800	4.58	1E-05	3.54	0.00941	1.293785
800–900	1.5	3.27E-06	1.35	0.003589	1.111111
900–1000	0.47	1.03E-06	0.38	0.00101	1.236842
Sum	458019.56	1	376.19	1	1217.522

Transform is superior to that of de-noising with Fourier Transform. Therefore, Wavelet Transform is chosen in signal de-noising in this article. Fig. 4 shows the acoustic signal with background noise and Fig. 5 shows the acoustic signal with de-noising of Wavelet Transform.

From Figs. 4 and 5, the variation trends of acoustic signals become more clearly after de-noising, and the peak and break part of signal can be easily recognized, which can be better for the leak detection.

3.3. Recognition and extraction of leak signals and disturbing signals

The leak of pipeline is detected by capturing the characteristics of acoustic signals and comparing with pre-set threshold of characteristics. The main methods of wave characteristics recognition and extraction are summarized and introduced as follows.

3.3.1. Characteristics of time domain

Characteristics of time domain refer to waveform, amplitude, mean value, root mean square value, kurtosis, skewness and correlation analysis, etc. Through the analysis of the characteristics of time domain for leak signals and disturbing signals, the appropriate characteristics of time domain are extracted to detect the leakage.

(1) Waveform and amplitude of acoustic signals

Waveform and amplitude of acoustic signals are the basic form of time domain. Fig. 6 shows that the amplitudes of acoustic signals are around zero and have some fluctuations without leak and external interferences. Fig. 7 shows that the amplitudes of acoustic signals would drop significantly when a leak occurs and then go back to zero quickly, which can be used as the characteristic for leak detection. But when an external interference occurs, the amplitudes of acoustic signals will also drop significantly, which will be considered as a leak and lead to a false alarm, from Figs. 8 and 9. Therefore, the amplitudes and waveform of acoustic signals cannot be used as the only way to detect leak and it needs to work with other characteristics of acoustic signals.

(2) Mean value, root mean square value, slope mean value, skewness and kurtosis

The mean value, root mean square value and slope value are parts of time domain characteristics. They can be calculated by a fixed time window for raw data, the formulas are shown as follows.

$\overline{X}$ is the mean value

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{8}$$

σ is the root mean square value (RMS)

$$\sigma = \left[\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{X})^2\right]^{\frac{1}{2}} \tag{9}$$

$\overline{K}$ is slope mean value

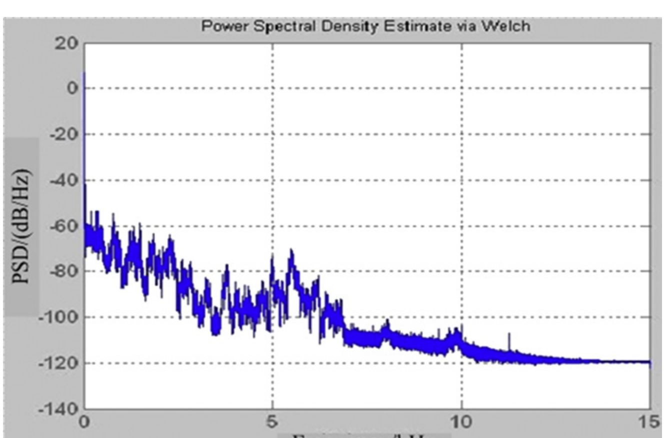

Fig. 16. Power spectral density estimation of compressor start-up signal.

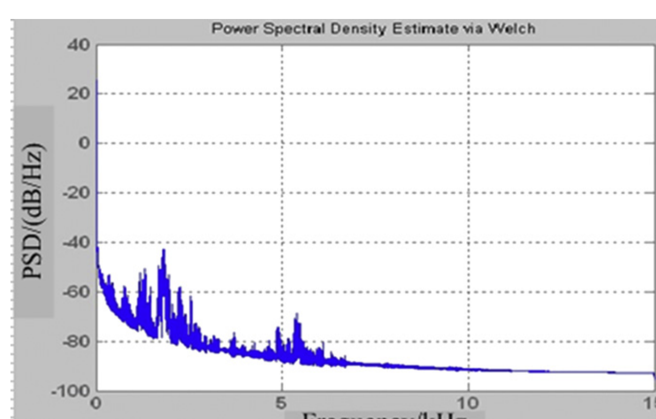

Fig. 17. Power spectral density estimation of valve signal.

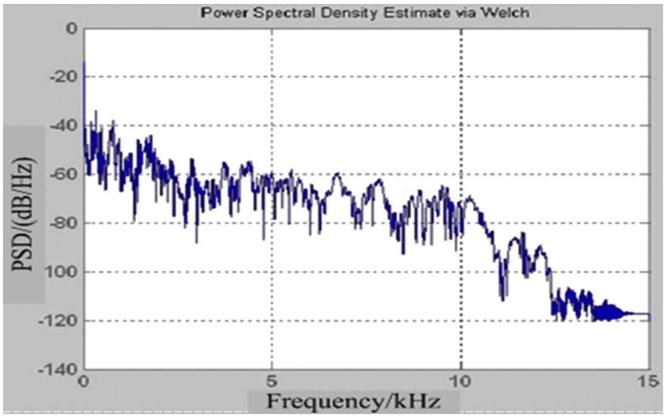

Fig. 18. Power spectral density estimation of knocking signal.

$$\overline{K} = \frac{1}{N-j}\sum_{i=1}^{n} K_i \tag{10}$$

Skewness can be used to describe the asymmetry between the density function and its mean value of random signal. Kurtosis refers to the change of peak in the average of probability density function of random data, which can reflect the change of waveform.

Skewness K_3 and kurtosis K_4 for finite length of discrete data can be calculated by

$$K_3 = \sqrt{\frac{1}{6N}\sum_{i=0}^{N}\left[\frac{x(t_i)-\overline{X}}{\sigma_X}\right]^3} \tag{11}$$

$$K_4 = \sqrt{\frac{1}{24N}\left[\sum_{i=0}^{N}\left(\frac{x(t_i)-\overline{X}}{\sigma_X}\right)^4 - 3\right]} \tag{12}$$

Here root mean square value (RMS) is chosen as an example to explain the differences between the leak signals and disturbing signals.

Figs. 10 and 11 respectively shows the change of RMS without a leak and with a leak. The changes of RMS with external interferences are shown in Figs. 12–14.

Though the analysis of those characteristics of time domain, the changes of mean values are in accordance with raw signals when the compressor start-up/shut-down or the valve switch. But the curve of mean value is different from the raw signals refer to a pipeline knocking signal, which can be used to distinguish the knocking signal with other signals. The RMS of compressor is different from other disturbing signals and leak signals in Fig. 12, which can be used as a trait of compressor. When an external interference occurs, skewness and kurtosis of acoustic signals change obviously, however, it is difficult to distinguish the disturbing signals from leak signals, which can only be used as auxiliary characteristics of time domain.

Autocorrelation function, cross-correlation function and covariance function of acoustic signals are also studied in this paper. All results used as the time domain characteristics for leak detection are shown in Table 1.

(3) Accumulative value difference, mean difference, peak value difference of signals in adjacent intervals

Besides the characteristic of time domain mentioned above, some new characteristics are concluded in this paper, such as accumulative value difference, mean difference, peak value difference of signals in adjacent intervals. The specific process is shown as follows.

The transient process is selected to extract the characteristics when the acoustic leak signals are from negative to positive and the signals are divided into positive and negative interval phases at a period of time according to the polarity of the amplitude; the accumulative value difference, mean difference, peak value difference of signal in adjacent intervals are chose as the characteristics of leak signals. Accumulated value in each interval is defined as

$$\mathrm{sumA}[k] = \sum_{i=1}^{N} a[i] \tag{13}$$

Therefore, accumulative value difference in adjacent interval is defined as follows:

$$\mathrm{sumAD}[k] = \mathrm{sumA}[k] - \mathrm{sumA}[k+1] \tag{14}$$

where $k = 1,2,3\ldots\ldots(M-1)$, M is the total number of the intervals in a period of test time. According to the definition of the interval accumulated value, mean difference in adjacent intervals is defined as follows:

$$\mathrm{meanAD}(k) = \frac{\mathrm{sumA}[k]}{N_1} - \frac{\mathrm{sumA}[k+1]}{N_2} \tag{15}$$

where N_1, N_2 is the total number of the signal points in adjacent intervals, respectively.

Peak value difference in adjacent intervals is defined as

$$\mathrm{PD}[k] = P[k] - P[k+1] \tag{16}$$

where $P[k]$ is the signal peak in the k-interval (Lin, Ping, & Jian, 2008).

Among those characteristics above, peak value, mean value and accumulated value represent the intensity of the signal, the average intensity, and the general characteristics of the signal, respectively, which can effectively reflect the characteristics of acoustic signals.

3.3.2. Characteristics of frequency domain

As further processing of acoustic signal is done, time-frequency analysis is used to analyze the characteristics of frequency domain.

Table 4
Mean rate of PSD.

	Leak signal	Compressor start-up signal	Compressor shut-down signal	Valve close signal	Valve open signal	Knocking signal
Maximum of PSD (dB/Hz)	−5.58	7.12	7.96	25.29	24.51	−13.58
Minimum of PSD (dB/Hz)	−119.2	−122.9	−120	−95.6	−98.6	−120
Variation of PSD (dB/Hz)	113.62	130.02	127.96	120.89	123.11	106.42
Frequency range (Hz)	15000	15000	15000	15000	15000	15000
K ($\times 10^3$)	7.57	8.67	8.53	8.06	8.21	7.09

Remarks: $K = |\mathrm{PSD_{max}} - \mathrm{PSD_{min}}|/(f_{\max} - f_{\min})$.

Since the random signals cannot be expressed by the function of time, the power spectrum is chosen to describe the characteristics of frequency domain. After wavelet preprocessing, the acoustic signals are processed by time-frequency conversion and the power spectrum of signals are shown as follows.

From Fig. 15, the power spectrum at leak conditions is roughly the same as that of normal conditions in a large frequency band, only with some difference near the start point. As the frequency increases, the power spectral density decreases gradually and becomes stable. The high frequency is basically white noise. In order to analyze the energy characteristics of the power spectrum, the signals are divided into 15 sections with 1000 Hz each section by frequency and the power spectrums of each section are calculated, as shown in Table 2.

From Table 2, the power spectral density range is from 0 to 6000 Hz, and almost 99% is in the range of 0–1000 Hz, which is similar to that of normal condition. The power spectral density with leakage is larger than that without leakage, which means the energy with leakage is larger than that without leakage in a certain period.

Then the signals within the frequency range of 0–1000 Hz are divided into 10 sections with 100 Hz for each section by frequency, as shown in Table 3.

From Table 3, it can be shown that the energy of low-frequency sections occupy the majority at the normal and leak condition. The energy of 0–100 Hz is largest which can reach 99.0% of total energy with leakage and 77.6% without leakage. For the ratio of power spectral density with leakage to that without leakage, it has the largest value between 0 and 100 Hz. The ratio decreases with frequency until it reaches 1, which means that the high frequency cannot be used to detect the leakage.

In this paper, frequency domain of disturbing signal is analyzed and shown in Figs. 16–18. Mean rates of PSD are shown in Table 4 to make the comparison of leak signals with disturbing signals. From Table 4, the mean rate of PSD of compressor is maximum, which can rate to 8.67. The frequency spectrum and PSD curve of valve signal change smoothly and have active rush where PSD can rate to the maximum, 25.29. This phenomenon can be used as the characteristic of valve switch Mean rate of PSD of knocking signal is minimum, the frequency spectrum and PSD are different with those of other signals. Therefore, the power spectrum of signals can be used as another characteristic of leak detection.

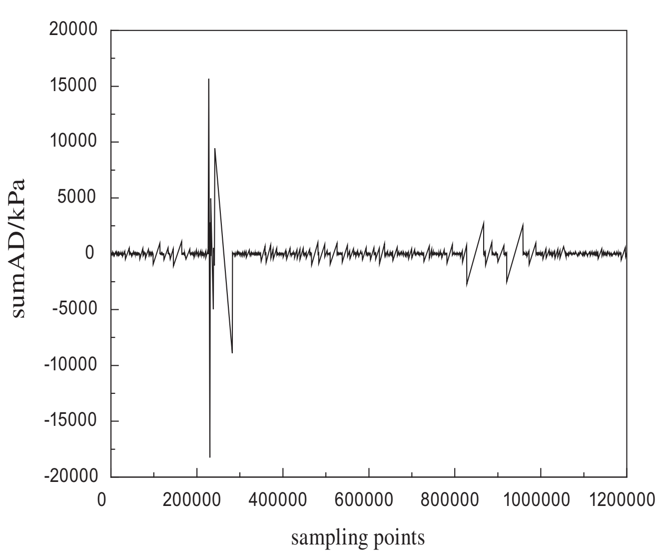

Fig. 19. SumAD of signal from downstream.

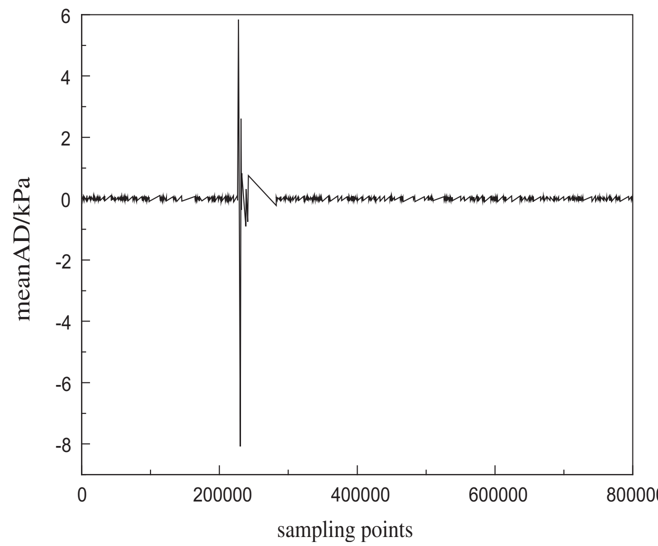

Fig. 20. MeanAD of signal from downstream.

3.4. Leak detection and location with test data

3.4.1. Leak detection by new characteristics of acoustic signals in adjacent interval

From the time-frequency analysis of acoustic signal, the amplitude and power spectral density of signals can be used as the characteristics for leak detection. The accumulative value difference (sumAD), mean difference (meanAD), peak value difference (PD) of signals in adjacent intervals mentioned in Section 3.3.1 can also be used as the characteristics of leak detection. When the pipeline pressure is around 4.6 MPa and the leakage aperture is around 0.45 mm, a leak occurs at the leak point 1. This method is used to process the acoustic signal, and the results are shown as follows.

From Figs. 19–21, the characteristics of this method are much easier to identify than that of the amplitude of the leak. Therefore, the accumulative value difference (sumAD), mean difference (meanAD), peak value difference (PD) of signals in adjacent intervals can all be used as the characteristics of leak detection. If all the characteristics can be used together to detect the leak, it can greatly reduce the false alarm rate.

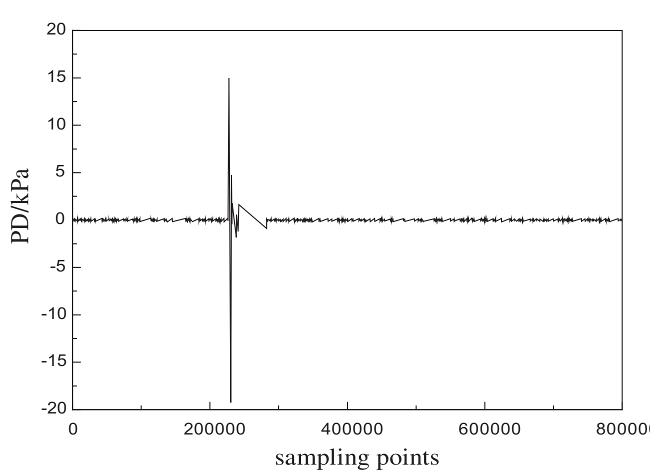

Fig. 21. PD of signal from downstream.

Table 5
Leak detection table under different factors.

Pressure rating (MPa)	Leak point	Leak apertures (mm)	Accumulative value difference		Mean difference		Leakage or no leakage
			Threshold	Actual value	Threshold	Actual value	
1.6	–	0.5	5866.3	1294.4	0.23	0.07	No
	1	0.5	4451.8	71199.6	0.30	0.53	Yes
	2	0.5	5479.2	104322	0.25	0.73	Yes
	3	0.5	8476.1	130610	0.24	0.99	Yes
	–	0.45	9551.4	1254.37	0.32	0.084	No
	1	0.45	12032.9	9070.23	0.19	0.13	No
	2	0.45	5396.2	31684.6	0.23	1.31	Yes
	3	0.45	4635.5	66093.3	0.22	3.27	Yes
2.6	–	0.5	3737.1	1117.8	0.45	0.11	No
	1	0.5	4723.2	66740	0.39	0.46	Yes
	2	0.5	4696.2	140490	0.37	3.86	Yes
	3	0.5	5111.5	157317	0.36	5.58	Yes
	–	0.45	3011	937.3	0.24	0.13	No
	1	0.45	5643.6	12711.6	0.43	2.00	Yes
	2	0.45	11556.7	49079.9	0.40	3.68	Yes
	3	0.45	4610.2	89766.3	0.44	5.02	Yes
3.6	–	0.5	9913.8	2561.3	0.53	0.16	No
	1	0.5	8200.1	115493	0.45	3.47	Yes
	2	0.5	10809.7	169041	0.50	6.17	Yes
	3	0.5	4780.9	198075	0.52	9.67	Yes
	–	0.45	3652	546.1	0.57	0.19	No
	1	0.45	3735.7	10118.4	0.65	3.68	Yes
	2	0.45	3997.5	70072.1	0.88	6.90	Yes
	3	0.45	3076.6	115242	0.94	13.12	Yes
4.6	–	0.5	12034.9	1742	0.38	0.13	No
	1	0.5	10087.9	133303	0.55	5.37	Yes
	2	0.5	4853.4	188968	0.46	9.93	Yes
	3	0.5	6645.3	215755	0.54	15.38	Yes
	–	0.45	12056.4	1776.1	0.35	0.11	No
	1	0.45	4900.7	18249.3	0.34	8.08	Yes
	2	0.45	7745.9	64631.8	0.37	12.04	Yes
	3	0.45	3105.2	112392	0.41	17.39	Yes

3.4.2. *Leak detection analysis under different operation conditions*

The accumulative value difference and mean difference mentioned above are chosen as the criterion to test the robustness of leak detection in different conditions. The maximum value of characteristics in normal conditions without a leak is used as the threshold, and the signals received by the acoustic sensors in the downstream are chosen for leak detection. If the received value is larger than the threshold, a leakage will be detected; otherwise the pipeline is in normal condition. The results are shown in Table 5.

From Table 5, the characteristics of leak signal do not perform well under the condition of 0.45 mm leakage aperture and 1.6 MPa pressure level. As pressure increases, the characteristics with leak are much more different from those in normal conditions and it becomes much easier to judge. Errors occur in the small aperture of leakage and low pressure conditions. It can be solved by dynamic threshold which will be studied in the future.

The figures of the difference of the accumulative value difference (sumADD: actual value-threshold) changing with pressure (Fig. 22), the sumADD changing with leakage aperture (Fig. 23), and

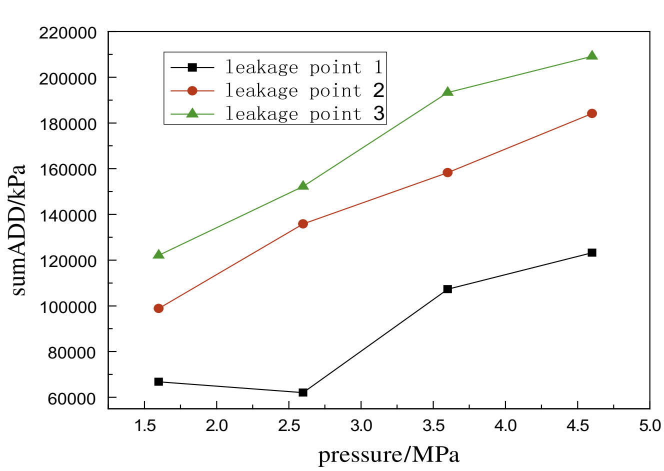

Fig. 22. SumADD of signal changing with pressure.

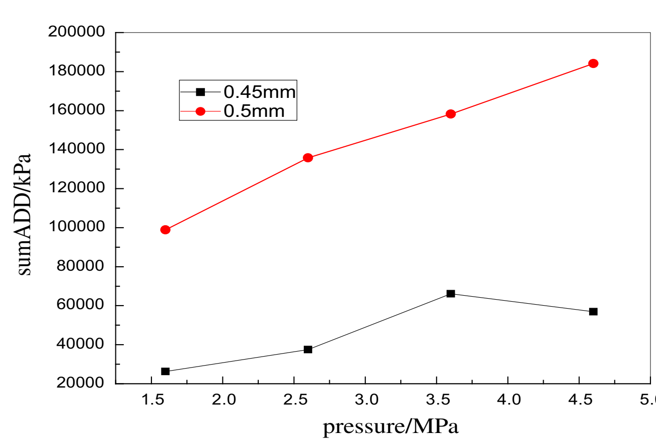

Fig. 23. SumADD of signal changing with leakage aperture.

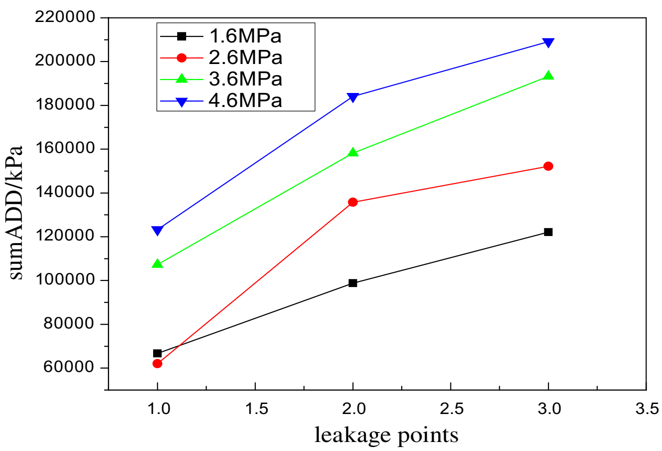

Fig. 24. SumADD of signal with different leakage points.

the sumADD changing with different leak locations (Fig. 24) are plotted.

Fig. 22 shows that the sumADD increases gradually with the pressure of pipeline and with the distance between the leak point and upstream, which makes the leak detection more easily.

From Figs. 23 and 24, it can be shown that the sumADD gradually increases with the increase of leakage aperture and pressure. Therefore, the leakage can be detected easily with high-pressure and large leakage aperture. Besides, the experiment results using the difference of mean difference (actual value-threshold) are similar to the sumADD, which will not be listed here.

3.4.3. Location analysis under different conditions

The acoustic signals gathered at both ends of pipeline under different conditions are processed by de-noising method and input into the leak location system, adaptability and location errors analysis at different conditions, as shown in Table 6.

Table 6 shows the errors of all leak location are very small under different conditions and the maximum error rates to 1.37%. With the formula of leak location modified, the sensitivity and leak location accuracy is significantly improved.

Table 6
Leak location under different conditions.

Pressure rating/ MPa	Leak point	Leak hole diameters/ mm	Distance between l eak point and upstream/m	Time difference Δt/s	Location errors/ %
1.6	1	0.5	39.54	0.35	0.65
	2	0.5	87.58	0.068	1.37
	3	0.5	149.7	−0.29	0.07
	1	0.45	39.5	0.35	0.75
	2	0.45	89.07	0.059	0.31
	3	0.45	149.75	−0.29	0.10
2.6	1	0.5	39.93	0.34	0.33
	2	0.5	88.28	0.064	0.58
	3	0.5	150.03	−0.29	0.29
	1	0.45	39.92	0.34	0.29
	2	0.45	88.21	0.064	0.67
	3	0.45	149.92	−0.29	0.22
3.6	1	0.5	40.00	0.34	0.53
	2	0.5	88.31	0.064	0.55
	3	0.5	149.61	−0.29	0.01
	1	0.45	39.80	0.34	0.01
	2	0.45	88.37	0.064	0.48
	3	0.45	149.73	−0.29	0.087
4.6	1	0.5	39.97	0.34	0.44
	2	0.5	88.42	0.064	0.42
	3	0.5	149.77	−0.29	0.11
	1	0.45	39.94	0.34	0.35
	2	0.45	88.32	0.065	0.54
	3	0.45	149.85	−0.29	0.167

4. Conclusions

In this paper, the leak signal is compared with disturbing signal, and lots of work have been done to summarize and validate the methods of acoustic signals recognition and extraction of time and frequency domain by test data. Then comparisons are done to obtain the best model. And a high-pressure and long distance pipeline leak detection and location system is designed and established by similarity analysis with field transmission pipelines. The leak location formula is modified, and the correlation analysis is applied to the leak location. The main obtained conclusions include:

(1) The acoustic leak signals are compared with the disturbing signals by time domain analysis, which mainly contains waveform, amplitude, mean value, root mean square value, kurtosis, skewness and correlation analysis, etc. Through the analysis of those time domain characteristics, kurtosis can be adopted to distinguish the leak signal from others, the compressor signal can be distinguished by waveform, amplitude and kurtosis, while correlation analysis and covariance function can be used to extract the valve switch and knocking signals. If those characteristics can be used together for leak signal recognition, the false alarm will be reduced greatly.
(2) The acoustic signals gathered by sensors are de-noised by Wavelet Transform, frequency domain of disturbing signals and leak signals are analyzed, and time-frequency analysis is used to analyze the characteristics of frequency domain. Most of the acoustic leak signals are in the range of 0–100 Hz and the power spectrum density and the frequency spectrum of signals can be used as other characteristic for leak detection.
(3) Accumulative value difference (sumAD), mean difference (meanAD), peak value difference (PD) of signals in adjacent intervals are recommended as new characteristics for leak detection, which can significantly reduce the false alarm rate if used together.
(4) The leakage location formula is modified by temperature and pressure and the correlation analysis is applied to the leak location. The relative errors of leak location are controlled in the range between 0.01% and 1.37%. Therefore, the sensitivity and leak location accuracy is significantly improved.
(5) The leak detection and location are significantly affected by the operation pressure of pipeline and the leakage aperture.

According to the experiment results, the acoustic leakage detection method has good sensitivity and high locating accuracy in natural gas pipeline. With the new recognition and extraction method of leak signals and disturbing signals and the modified location formula, the leak can be detected with lower false alarm rate and leak location can be determined with higher location accuracy, which can assure the safety of natural gas pipelines.

Acknowledgments

The paper was funded by the New Century Educational Foundation (NCET-07-0847) and National Science Foundation of China (51074175). Thank for the permission to publish this paper.

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