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Negative Pressure Wave Leakage Location Algorithm Based on Difference Cross-Correlation Delay Estimation

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Negative Pressure Wave Leakage Location Algorithm Based on Difference Cross-Correlation Delay Estimation

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Abstract. Accurate estimate the time difference of the leakage negative pressure wave signals reached both sides of the sensor at the two sides of the leakage point is the key to accurate location of the leakage point. Based on the theoretical analysis of cross-correlation time delay estimation algorithm and characteristics of negative pressure wave signal, a cross-correlation delay estimation method for pipeline leakage negative pressure wave signal is proposed. Through wavelet transform, signal conversion and cross correlation function analysis of discrete negative pressure wave signal sequence obtained by high-speed sampling, the time difference of the negative pressure wave signal monitored by the sensors on both sides of the leakage point can be accurately obtained. In the laboratory's 102.8 meters pipeline, leakage was simulated through the valve, the time delay estimation and leak location experiment of the sensor at the two ends of the pipeline were analyzed, and compared with the wavelet analysis method. The experimental results show under the condition that the leakage is 10%, 5% and 2% of the total pipeline volume, the cross-correlation analysis algorithm has a positioning error interval of 0.97%-1.46%, which is better than the current positioning error 0.48%-2.43% of the wavelet analysis algorithm. At the same time, it avoids the influence of different wavelet types and analysis scales in the wavelet analysis algorithm on positioning accuracy, and is more suitable for pipeline leakage monitoring system to real-time online monitoring needs, has a wide application value.

1. Introduction

As the fifth largest mode of transportation, pipeline has the advantages of high efficiency, continuity and reliability, and is not disturbed by external environment. It is the most effective mode of transportation for rheological medium such as petroleum, natural gas, slurry, carbon dioxide and biofuels [1]. However, with the increase of pipe age, pipeline leakage accidents caused by aging corrosion, geological hazards and man-made damage are frequent. Therefore, real-time monitoring of pipeline leakage and accurate location of leakage points are of great significance to ensure public property and personal safety, protect the environment and reduce national economic losses [2, 3].

The existing pipeline leak detection technologies are mainly divided into four categories: leak medium detection method, pipe wall parameter detection method, acoustic detection method and optical fiber distributed sensing monitoring method [4-6]. Negative pressure wave monitoring method has become one of the research hotspots and main technical means in the field of pipeline leakage detection in recent years due to its simple implementation and easy maintenance [7]. In the actual application process, due to the influence of signal attenuation and environmental noise, the inflection point of the negative pressure wave signal is not clear, and the system positioning accuracy is not high [8]. Therefore, accurately capturing the inflection point of the negative pressure wave and accurately calculating the time difference of the negative pressure wave reaching the two ends of the pipeline is the key to improve the positioning accuracy of the system.

At present, the extraction of negative pressure wave inflection point signals mainly includes neighborhood interpolation method, transient negative pressure wave structure pattern recognition method, fast differential algorithm, etc [9-11]. The wavelet transform method detects the extreme points of the wavelet transform coefficients by multi-scale wavelet decomposition, and achieves accurate acquisition of signal abrupt points and singular points. This method can effectively reduce the interference of external noise and has a high positioning accuracy. It is a commonly used method in negative pressure wave pipeline leakage monitoring and positioning system at present [12, 13].

As a general method of signal delay estimation, cross-correlation theory can obtain higher delay accuracy and higher target location accuracy in the case of high background noise, low signal intensity and short duration. It is widely used in sound source location, seismic wave monitoring and other fields [14, 15]. In this paper, the cross-correlation delay estimation method and the characteristics of negative pressure wave signal are effectively combined, and a leakage location method of negative pressure wave pipeline based on difference cross-correlation is proposed, which realizes accurate acquisition of inflection point and time difference of negative pressure wave signal by means of wavelet denoising, signal conversion and correlation function analysis, improves positioning accuracy of the system and realizes real-time online monitoring of pipeline leakage.

2. Cross-correlation delay estimation algorithm

2.1. Theoretical analysis

With two different random signals $s_1(t)$, $s_2(t)$, and time difference τ, the general expression of the cross-correlation function is as follows.

$$R_{s_1s_2}(\tau) = E[s_1(t)s_2(t+\tau)] == \lim_{T\to+\infty}\frac{1}{T}\int_0^T s_1(t)s_2(t+\tau)dt \tag{1}$$

The discrete form of cross-correlation function of two signal sequences is as follows:

$$R_{s_1s_2}(m) = \sum_{i=0}^{n} s_1(i)s_2(i+m) \quad m = 0,\pm1,\pm2,\Lambda\ \Lambda \tag{2}$$

The product of the value m corresponding to the extremum of function R(m) and the sampling interval δ is the time difference Δt between two signals, as shown in formula 3.

$$\Delta t = m \bullet \delta \tag{3}$$

Under certain working conditions, the time difference $\Delta t = 2ms$ of negative pressure wave signal monitored at both ends of the pipeline, the pressure drop caused by the leakage negative pressure wave is Δp, and the pressure fluctuation caused by the noise in the steady state is d, when Δp >>d, establish negative pressure wave signal model at both ends of the pipeline as shown in Figure 1

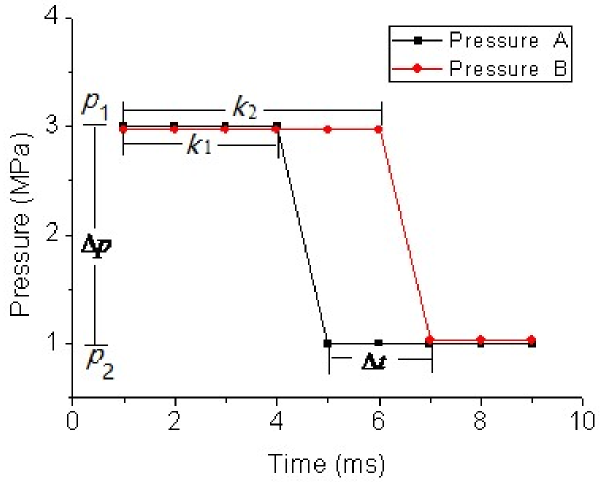

Figure 1. Negative pressure wave signal model.

The abstracted discrete negative pressure wave signal sequence functions s1, s2 are as follows.

$$s_1(i)=\begin{cases} p_1 & 0<i\le k_1 \\ p_2 & k_1<i\le n \end{cases} \quad s_2(i)=\begin{cases} p_1 & 0\le i\le k_2 \\ p_2 & k_2\le i\le n \end{cases}$$

In order to calculate the time difference Δt between the two negative pressure wave signals, substitute function s_1 and s_2 into formula 2, and calculate the maximum value Rmax(m) of R(m).

$$\begin{cases} R(m)=ap_1^2+bp_1p_2+cp_2^2 \\ 1\le a+b+c\le n \\ 0\le a\le k_1 \\ 0\le b\le k_2 \\ 0\le c\le n-k_2 \end{cases} \tag{4}$$

Under the above conditions, R(m) reaches its maximum only when two curves coincide, as shown in Figure 1.

$$R(m)=k_1p_1^2+(k_2-k_1)p_1p_2+(n-k_2)p_2^2 \tag{5}$$

At this time m=0, $\Delta t=m\bullet\delta=0$, contradicts the known. Therefore, it is impossible to estimate the delay of the monitoring negative pressure wave signal by cross-correlation analysis directly.

2.2. Negative Pressure Wave Delay Estimation Algorithms

In view of the limitation of cross-correlation function in time delay estimation of step-type negative pressure wave signals, a cross-correlation time delay estimation algorithm based on dynamic pressure variation sequence is proposed in this paper. The specific implementation is shown in Fig. 2.

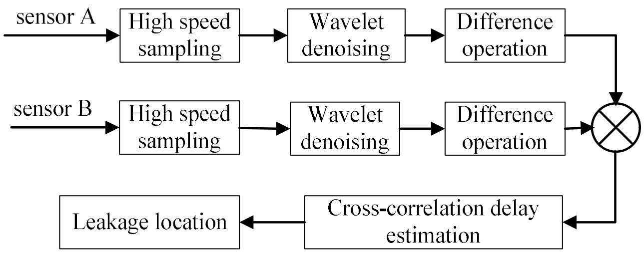

Figure 2. Flow chart of negative pressure wave delay estimation algorithm.

Firstly, high-speed sampling of leak negative pressure wave signals from sensors at both ends of the pipeline is carried out, and a finite length discrete sequence containing complete negative pressure wave inflection point signals is acquired. Then, the obtained discrete sequence is transformed by wavelet transform. After filtering and noise reduction, the negative pressure wave signal sequence at both ends of the pipeline are P_A(i) and P_B(i). P_A(i) and P_B(i) are transformed from step-type negative pressure wave signal to dynamic energy signal by differential operation of formula 6 (where n is the length of data sequence). At the same time, the dynamic pressure change sequence $X(i)$ and $Y(i)$ of adjacent pipeline sensors are obtained.

$$\begin{cases} X(i) = P_A(i+1) - P_A(i) & i = 1,2,3\Lambda\ \Lambda\ n \\ Y(i) = P_B(i+1) - P_B(i) & i = 1,2,3\Lambda\ \Lambda\ n \end{cases} \tag{6}$$

For the dynamic change sequence monitored by two adjacent sensors, the extremum of the cross-correlation function R_{xy} and the time difference Δt of negative pressure wave signal are calculated by using the cross-correlation algorithm (Formula 2 and Formula 3).

In the whole pipeline, the negative pressure wave leak location formula 7 is applied to locate the leak point for any two adjacent sensors where the leak point is located.

$$L_{AC} = \frac{S + v\Delta t}{2} \tag{7}$$

S is the distance between two sensors and v is the velocity of negative pressure wave propagating in the pipeline.

3. Pipeline Leakage Test Platform

Pipeline leakage test platform is established in laboratory as shown in Fig. 3 and 4.

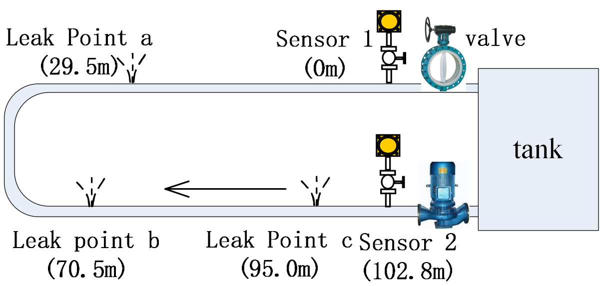

Figure 3. Pipeline experimental platform model.

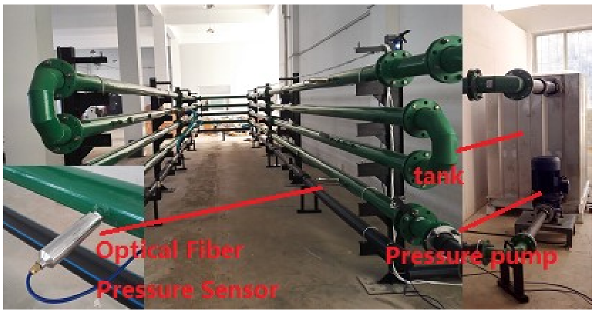

Figure 4. Pipeline Experimental Platform.

The total length of the pipeline is 112m. Carbon steel pipeline with inner diameter of 100mm is adopted. The wall thickness is 2mm, the diameter of the leakage hole is adjustable by 32mm, and the internal pressure regulation range of the pipeline is 0-0.4MPa.

The system sampling frequency is 1kHz, the sensor range is 0-1.0MPa, and the measurement accuracy is 0.1% FS.

4. Experiment and data analysis

4.1. Cross-correlation delay estimation and location

In order to further verify the effectiveness of the delay estimation algorithm, the traditional cross-correlation delay estimation algorithm and the delay estimation algorithm proposed in this paper are used to compare and analyze the monitored negative pressure wave signals. The specific steps are as follows:

Open the pressure pump, adjust the end valve, keep the internal pressure of the pipe stable 0.3MPa, and adjust the leakage valve c to keep the leakage amount about 10% of the total pipeline transportation. After filtering and wavelet transform of pressure wave signal monitored by sensor, the negative pressure wave signal curve is shown in Figure 5

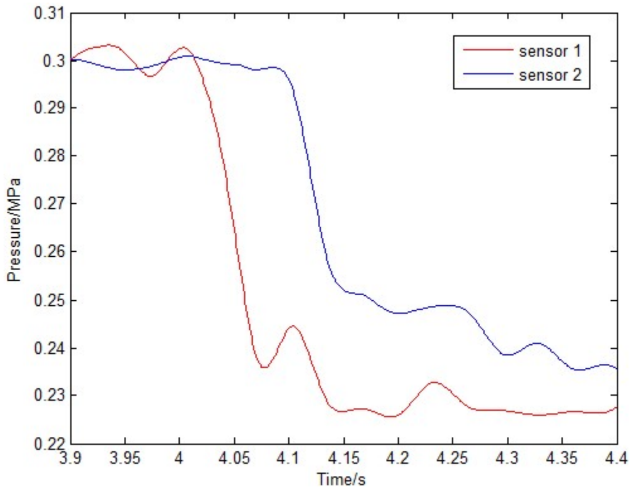

Figure 5. Filtered negative pressure wave signal.

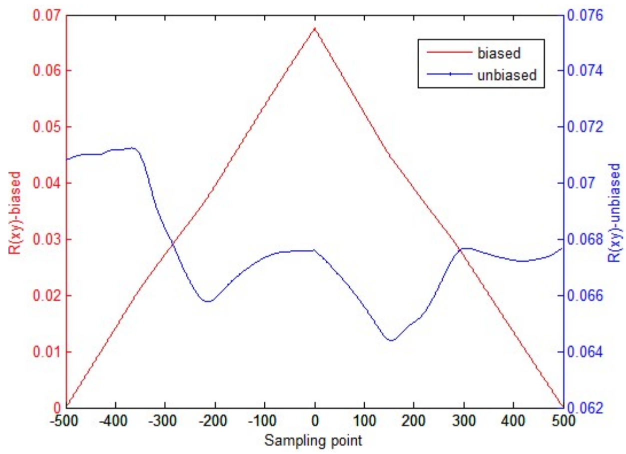

Figure 6. Delay estimation curve of sensor S1 and S2.

From the experimental data, it can be seen that the negative pressure wave signals monitored by the two sensors are clear and have obvious time difference, but the negative pressure wave signal falls along the inflection point boundary is not obvious. In order to accurately acquire the time difference of negative pressure wave signals monitored by sensors, the cross-correlation algorithm is used to estimate the time delay of negative pressure wave signals monitored by sensors S1 and S2.

For the monitoring of negative pressure wave signals by sensors S1 and S2 after wavelet denoising, Equation 2 is used to estimate the biased and unbiased delay of the two signals. The curve is shown in Figure 6.

According to the experimental data and formula 3, the time difference of negative pressure wave signals calculated by the two methods is Δt =0ms and Δt =350ms respectively. The results are in contradiction with the experimental results in Fig. 4. Therefore, direct cross-correlation delay estimation of negative pressure wave signals is not effective for time difference analysis of monitored negative pressure wave signals.

After wavelet denoising of negative pressure wave signals monitored by sensors S1 and S2, the dynamic difference sequence is calculated by formula 6, and the step signal is transformed into energy signal. The transformed negative pressure wave signal is shown in figure 7. Then the delay estimation analysis is performed on the two signals, and the corresponding biased and unbiased delay estimation curves are shown in figure. 8.

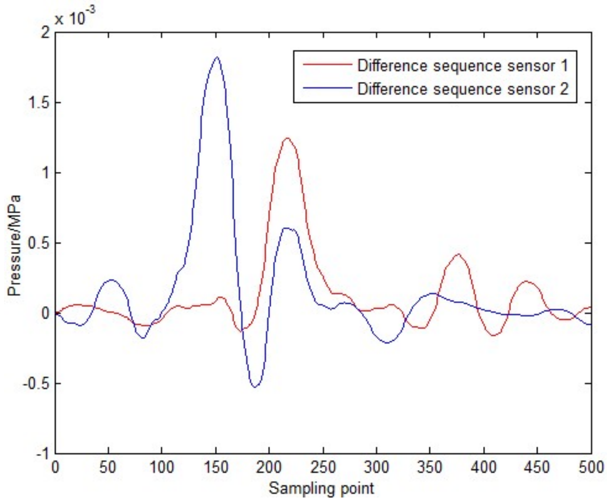

Figure 7. The difference curve between S1 and S2.

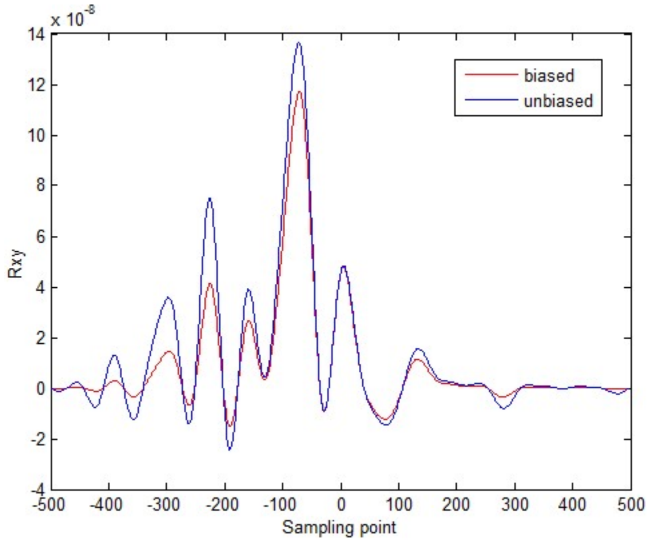

Figure 8. Delay estimation curve after the difference between the sensor S1 and the S2.

From the experimental results, it can be seen that there are obvious extremum points near zero in the delay estimation curve of negative pressure wave signal monitored by two sensors through dynamic difference calculation of signal sequence. The sampling frequency of the system is 1 kHz, the sampling interval $\delta = 1ms$, and the maximum value of the delay estimation curve corresponds to the abscissa m=-71. The time difference of the negative pressure wave signals monitored by the two sensors is calculated by formula 3 as $\Delta t = 71ms$. Calculating the average value of the negative pressure wave velocity v=1256m/s by the distance between the two adjacent sensors in the upstream and downstream of the leakage point and the time difference of the negative pressure wave signal [16]. Calculating the Distance L=96 m from Leakage Point to Sensor S1 by Formula 7, the positioning error is 0.97%.

4.2. Comparative experimental analysis

In order to further verify the effectiveness of the delay estimation algorithm, an experimental comparison between the proposed algorithm and the delay estimation algorithm based on wavelet analysis is carried out. By adjusting the opening of leak valve c, select different leakage amounts 10%, 5% and 2%, at the same time, multi-scale wavelet analysis of negative pressure wave signals detected by sensors S1 and S2 is carried out using db3-db7 respectively. The location of leakage point is determined by formula 7 as shown in Table 1.

Table 1. Leakage location error contrast.

		Wavelet type	Head scale	Tail scale	Leakage 10%		Leakage 5%		Leakage 2%	
					Position (m)	Error (m)	Position (m)	Error (%)	Position (m)	Error (%)
Leakage Point (95m)	Cross correlation algorithm	-	-	-	94.0	0.97	93.8	1.17	93.5	1.46
	Wavelet decomposition algorithm	db2	4	4	93.4	1.56	93.6	1.36	93.8	1.17
		db3	5	5	94.5	0.49	93.3	1.65	93.9	1.07
		db4	5	6	95.6	1.56	94.5	0.48	94.2	0.78
		db5	5	4	92.3	2.63	93.8	1.17	93.3	1.77
		db6	4	6	93.6	1.36	92.5	2.43	92.5	2.43
		db7	6	6	95.2	1.17	93.4	1.56	92.6	2.33

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The experimental results show that the selection of wavelet type and analysis scale is the key to determine the time point of signal mutation in the wavelet multi-scale analysis method. Under different conditions, different wavelet types and analysis scales will get different results. However, the cross-correlation delay estimation method can effectively avoid the influence of multi-variable selection in wavelet analysis on the time difference and positioning accuracy, and can more accurately and effectively obtain the time difference of negative pressure wave signals to both sides of the sensor. It can improve the positioning accuracy of the system, is more suitable for the real-time online monitoring requirements of pipeline leakage detection system.

5. Conclusion

According to the characteristics of negative pressure wave signal and the leak monitoring model of pipeline, a leak location algorithm of negative pressure wave based on differential cross-correlation delay estimation is proposed in this paper. In 102.8 meters of carbon steel pipeline in the laboratory, the time delay estimation and leak location experiments of negative pressure wave signals monitored by sensors are carried out by simulating the leak location and leak volume through valves. At the same time, it is compared with the current leak location algorithm based on wavelet analysis. The experimental results show that when the leakage is 10%, 5% and 2% of the total pipeline transportation, the cross-correlation analysis algorithm locates the error interval 0.97%~1.46%, compared with wavelet analysis error interval 0.48%~2.43%, which has high positioning accuracy. At the same time, it effectively avoids the influence of the selection of wavelet type and analysis scale on the positioning accuracy in the wavelet analysis algorithm, ensures the consistency of the system, improves the positioning accuracy of the system and is more suitable for the industrialization of pipeline leakage detection system, has a broader application prospect.

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