Research of Water supply pipeline correlator

Xiaowei Yan*, Fan Yang, Yulong Li, Tao Chen, Wengqiang Ge
Beijing Institute of Radio Metrology and Measurement, Beijing, China

*Corresponding Author e-mail: 646180306@qq.com

Abstract. Compared with traditional leak detector, correlator has obvious advantages. Based on the study of acoustic leak detection, IT technology and mathematical analysis model are added to locate the leak point more quickly, accurately and reliably. On the basis of studying the characteristics of sound wave propagation in the pipeline and filtering and noise elimination, a correlator is developed and tested in the actual water supply pipeline. Many experimental results can accurately locate the leakage point of water supply pipeline, which fully verifies the feasibility of this study.

1. Introduction
Water supply pipeline correlator is a leak detection instrument based on acoustic principle. Compared with the traditional leak detector, the correlator can not only detect the leak through rivers, railways and buildings, but also detect the leak of some water pipelines which are buried too deep to hear the leak. In addition, with the development of IT technology and mathematics, high-end calculation models such as automatic frequency analysis, automatic filtering and multiple correlation techniques are added to the software and hardware of correlator, which can locate the leakage point more quickly, accurately and reliably. In contrast, the traditional leak detector mainly amplifies the sound signal received on the ground, and leak listeners judge the location of the leak point by the way of the ground listening. Due to the influence of transmission medium and peripheral noise, the results of leak location often have great deviation. It takes a lot of manpower and experience to accumulate in the process of leak location, and it is difficult to train and teach [1].

In this paper, through the study of the generation and propagation of acoustic signals in the pipeline network system, wavelet threshold de-noising and correlation time delay estimation algorithm are used to detect and correlate the acoustic signals of leak points, so as to determine the location of leak points in the pipeline network. On the basis of algorithm research, a correlator product is developed and tested in water supply network. The result of positioning is consistent with the design requirement, which fully proves the feasibility of acoustic positioning algorithm in this study.

2. Acoustic signal characteristics of pipeline leakage
When pipeline leakage occurs due to rupture, the fluid loss at the leakage position will cause the pressure drop, thus destroying the original stable state. The underwater sound generated by pressure change will also spread from the leakage point to both sides of the pipeline, and the intensity of noise propagation decreases exponentially with distance [2].

The acoustic impedance characteristic of the leakage point is very complicated when the pipeline is leaking. There is no reasonable mathematical model at present. In this study, acoustic propagation in pipes is studied from an acoustic point of view.
2.1. Theoretical analysis

When the fluid in pipe is ideal fluid, the wave equation of axial uniform flow field in cylindrical coordinate system as [3]:

$$\nabla^2 \left( \frac{1}{c} \frac{\partial}{\partial t} + M \frac{\partial}{\partial x} \right)^2 p = 0$$

In the formula \(\nabla^2 = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}\), \(c\) is the free wave velocity in the fluid, \(M = \frac{\bar{V}}{c}\), \(\bar{V}\) is uniform velocity of fluid. In the water supply pipe, the velocity of water is very small, \(\bar{V} \ll 10\text{ m/s}\), Therefore, without considering the influence of Mach, only the propagation of plane waves in the axis direction must be considered, that is:

$$\frac{\partial^2 p}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0$$

The solution of the sound pressure field satisfying the upper form has the following form of solution: \(p = p_0 e^{i(\omega t - kx)}\). In the formula, \(k = \frac{\omega}{c}\) is free wave number in fluid, \(p_0\) is amplitude of sound pressure.

Suppose the pipe radius is \(R\), the hole diameter of the simulation leakage point is \(d\), the thickness of the pipe wall is \(h\), fluid density is \(\rho\). Impedance original, the origin of the coordinates is at the leakage point, and the specific form of each sound wave:

- Incident wave: \(p_i, U_i\)
- Reflected wave: \(p_r, U_r\)
- Transmitted wave: \(p_t, U_t\)
- Leaky wave: \(p_b, U_b\)

In the formula \(\rho c\) is the characteristic impedance of flow field in pipeline, \(p_i, p_r, p_t, p_b\) are incident waves, reflected waves, transmitted waves, and leaky waves, \(p_i, p_r, p_t, p_b\) are the amplitude of the incident wave, reflected wave, transmission wave and leakage wave. \(U_i, U_r, U_t, U_b\) are the particle velocity of incident wave, reflection wave, transmission wave and leaky wave. \(s\) is section area for opening, \(Z_b\) acoustic impedance for leakage points.

According to the condition of sound pressure continuity and volume continuity at the gap:

- Incident wave: \(p_i, U_i\)
- Reflected wave: \(p_r, U_r\)
- Transmitted wave: \(p_t, U_t\)
- Volume velocity of leaky wave: \(p_b, U_b\)

In the formula, \(U_i, U_r, U_t, U_b\) are incident wave, reflected wave, transmission wave and volume velocity of the leaky wave respectively. \(S\) is cross section for pipes. The relationship between the amplitude of reflected sound pressure and projected sound pressure and the amplitude of admission sound pressure is obtained by introducing the public announcement into the equation:

- Reflected wave: \(p_r = -\frac{\rho c/2S}{\rho c/2S + Z_b} p_i\)
- Transmitted wave: \(p_t = 1 - \frac{\rho c/2S}{\rho c/2S + Z_b} p_i = \frac{Z_b}{\rho c/2S + Z_b} p_i\)
2.2. Impedance analysis

It can be seen from the above study that the acoustic propagation characteristics can be analyzed as long as the acoustic impedance of the leakage point is known. In this study, we use the Green function to derive the theoretical formula for acoustic impedance of holes on the wall [3]:

\[ Z_a = jR_0 (a/b)^2 (jk + \phi) \]
\[ kt = \frac{1}{2} \left( \frac{a}{b} \right)^2 \cot(kl) \]

In the formula \( R_0 = \frac{\rho c}{\pi a^2} \) is characteristic impedance of fluid in pipes, \( a \) is pipe radius is hole diameter is wave number is the distance from the center of a hole to one end. It can be seen that the acoustic impedance of the small hole is related to the frequency and the diameter of the hole and the radius of the pipe.

When water passes through the leak point, the soil medium around the pipe wall is eroded and a cavity is formed around the leak point. The leak point reflects back and forth in the cavity to form a miscible sound field, and the acoustic impedance characteristics of the leak point are largely related to the velocity and pressure of the fluid in the pipe. Therefore, the method can be used to calculate the acoustic impedance of leaky points.

3. Wavelet threshold denoising algorithm

3.1. Theoretical analysis

Wavelet transform is very suitable for the processing of non-stationary signals. Wavelet denoising is to decompose the signal at different scales. The wavelet coefficients decomposed at different scales represent the information of the original signal at different frequencies. Effective signal and random noise have different transmission characteristics and representation characteristics on wavelet of different scales. By analyzing the different characteristics of signal and noise on wavelet coefficients of scale space, proper processing can realize effective denoising of signal [4].

In this study, threshold de-noising method is used to study the de noising effect of pipeline leaky sound signal. The signal model of noise can be expressed as follows:

\[ a(i) = s(i) + \varepsilon n(i), i = 0,1, \ldots l - 1 \]

In the form, \( a(i) \) is noise signal; \( s(i) \) is low frequency signal; \( n(i) \) is high frequency signal.

The threshold denoising method is mainly divided into three steps [5]:

1. Orthogonal wavelet transform, select appropriate wavelet and wavelet decomposition levels \( j \), obtained corresponding wavelet decomposition coefficients \( w_{j,k} \).
2. Threshold quantization processing, select appropriate threshold \( \gamma \), set the wavelet coefficient below the threshold to 0, for those above threshold \( \hat{w}_{j,k} \), the wavelet coefficients are estimated by preserving them, the ultimate goal of threshold quantization is to get the estimated wavelet coefficients \( \hat{w}_{j,k} \).
3. Donoho divided the threshold function into hard threshold and soft threshold [6], the soft threshold method is adopted in this study:

\[ \hat{w}_{j,k} = \begin{cases} \sin(w_{j,k})(|w_{j,k}| - \gamma), & |w_{j,k}| \geq \gamma \\ 0, & \text{otherwise} \end{cases} \]

Inverse wavelet transform, reconstruct the wavelet coefficients according to the reconstruction formula, and restore the original signal estimation value.

In this study, the vibration signal of pipeline leakage is collected by experiment, and the appropriate threshold is selected through many experiments. The noise signal after de-noising is taken as input by soft threshold function wavelet de-noising method to locate the leakage point of water supply pipeline.
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4. Experimental research
Based on the research of algorithm model, a leak location product for water supply pipeline is designed and developed. The product design interface is as shown in figure 1.

![Example diagram](image)

**Figure 1.** Example diagram

During the experiment, the cast iron pipe with diameter of 200 mm and length of 97.5 mm was selected as the research object. Correlator A and B were installed in the overhaul wells at both ends of the pipe, and the leakage point of the pipe was simulated near the center point of the pipe.

When there is a leak point, the acoustic wave will propagate along the pipeline to both sides. Equipment A and B receive the acoustic signal and process it separately. Then the filtered acoustic signal is transmitted to the upper host computer. After receiving the acoustic signal transmitted by the two monitoring devices, the host computer of the correlator calculates the model to locate the leak point of the pipeline. The way to display graphics is shown in figure 2.
From the above diagram, it can be seen that the location of leakage point is completely consistent with the actual location, and the positioning accuracy can meet the daily requirements of pipeline leakage location, which fully confirms the feasibility of this study and achieves the desired results.

5. Summary
Based on the propagation characteristics of sound wave in the pipeline, and the research of wavelet de-noising technology, this paper designs a location calculation model, and develops a leak detection equipment for correlator combining with software and hardware technology. It is tested and verified in the actual water supply pipeline. In the experiment, the leak point is located accurately and the expected result is satisfied, which fully proves the technical feasibility of the correlator designed.

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