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Research on Leak Location of Liquid-filled Pipe Based on Frequency Dispersion Characteristics

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Abstract:
Due to the material problems and force majeure factors, the leakage will be occurred on the liquid-filled pipe resulting in waste of resources, environmental pollution and even endangering safety. Acoustic wave detection technology is widely used in buried pipeline leak detection, this technology mainly uses the wave (n=0, s=1) in the pipeline acoustic wave to locate the leak. When the leakage acoustic signal propagates along the liquid-filled pipe, the frequency dispersion characteristics can be obtained by wavelet decomposition. And there is a time delay (time difference) value between the leaky acoustic signals collected by the sensors at both ends of the leak. The outputs show that the results obtained by wavelet decomposition are in good agreement with the theoretical calculation results. Based on the obtained dispersion relation, the time delay values at different characteristic frequencies are analyzed by the cross-correlation method, and the leak location accuracy is discussed. This research content provides theoretical support and engineering application guidance for pipe leakage location technology.

Keywords: *Liquid-filled pipe; Frequency dispersion characteristics; Leak location; Time delay estimation value*

1 Introduction

With the progress of urbanization in China, the number of underground liquid-filled pipes in cities and towns is increasing. According to statistics, the total length of liquid-filled pipe is 8668.2 million kilometers, the annual water supply volume is 61.5 billion cubic meters in China[1].In the context of urbanization, buried water supply pipelines are inevitably damaged due to self-aging or force majeure factors. When the liquid-filled pipe is leaking and cannot deal with it in time, it may cause waste of resources and major safety accidents. Moreover, according to relevant statistics, the average leakage rate of the urban water supply system is 21.5% in China[2], but the standard leakage rate needs to be controlled at 10%[3]. The leakage rate of the water supply pipelines is not up to the standard. To cut down the waste of water resources and prevent safety accidents, it is important to locate the leakage point of liquid-filled pipe in time and accurately.

At present, there are many kinds of research results on acoustic leak detection and positioning. J M Muggleton[4] *et al* proposed that the acoustic generated by the leakage of buried pipe propagates at a relatively low frequency, it includes axisymmetric waves with n=0 and n=1. Here, the n=0, s=1 wave occupies the main part of the leakage acoustic signal. R J Pinnington[5] *et al* had studied the coupling equation of the axisymmetric wave in the buried liquid-filled pipes, introduced the mathematical correlation between the speed of the axisymmetric wave and the wavenumber of free fluid. The determination of the wavenumber depends on the pipeline parameters, and these parameters do not have enough time to determine in actual engineering. By studying the coupling equation of buried liquid-filled pipe under vacuum, Fuller and F J Fahy[5] obtained the dispersion characteristic curve of acoustic signal of leakage point at low frequency. The dispersion characteristics are limited to vacuum pipelines, it may vary in the actual pipeline. By studying plastic pipes, Osama Hunaidi[7] *et al* found that the frequency characteristic of leakage acoustic signals is different in different environments and the leakage signal of plastic pipes has dispersion characteristics. The frequency range of the research is small, the frequency can increase appropriately. Based on the cross-correlation location algorithm, Shuaiyong Li[8] *et al* proposed the wave speed of the signal can be determined by the frequency of the signal in gas pipes, then determined the location of the leakage point. Using the above article for reference, it can

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be clarified that the wave speed of the leakage acoustic signal of the liquid-filled pipe can be determined by its dispersion characteristics. Gao Y[9] *et al* proposed to use spectral analysis algorithm to determine the location of the leakage point, Yan Hongmei[10] studied the propagation characteristics of leakage acoustic signals in the buried liquid-filled pipeline, located the leakage point according to its propagation characteristics. According to references 9 and 10, it can be used to analyze the characteristics of the leakage signal and select the characteristic frequency band. The above researches show, the leakage acoustic signal has dispersion characteristics, and the dispersion characteristics can be solved by numerical calculation with the help of some parameters.

After obtaining the dispersion characteristics and characteristic frequency bands of the leakage sound signal, try to locate the leakage point. Before locating the location of the leakage point on the underground liquid-filled pipe, it is necessary to predetermine the dispersion characteristics of the leakage acoustic signal under actual conditions. An intrinsic property of the pipeline and the environment related to the wave speed, which needs to study and get the actual pipe dispersion characteristics.

Regarding the determination of the location of the leakage point of the liquid-filled pipe, the main difficulty lies in the calculation of the wave speed and the time delay. If the wave speed or the time delay produces errors, it will affect the determination of the leak location of the liquid-filled pipe. The study found that the frequency distribution of leakage acoustic signal in the low-frequency portion, and leaked acoustic signals may be covered by noise at low frequencies. To ensure the accuracy of locating the leakage point of the liquid-filled pipe, a band-pass filter is used to de-noising the measured signal based on the power spectral density characteristics of the measured signal. Then, try to obtain the dispersion characteristics and time delay. After obtaining the wave speed and time delay according to the actual situation, the accuracy of locating the leakage point of the liquid-filled pipe can be improved.

2 Theoretical research

In urban liquid-filled pipes, due to the presence of fluid, the water pressure is inevitable. When the pipe is damaged due to some reasons, a leakage acoustic signal will be generated at the damaged place due to the pressure difference between the inside and outside, and the leakage acoustic signal will propagate along the liquid-filled pipe to both ends of the leakage point. For the location of the leakage point of the liquid-filled pipe, the key is to determine the wave speed and time delay of the leakage vibration signal. If the calculated wave speed and time delay values are close to the actual situation, the accuracy of the leakage point location will be improved.

2.1 Positioning theory

When the pipe leaks, sensors are arranged at both ends of the leak point, then the sensors will collect the leakage acoustic signals that propagate along the pipeline to the measuring point. The leak location theory bases on propagation characteristics of the leakage acoustic signal, and liquid-filled pipe leak location model as shown in Fig.1.

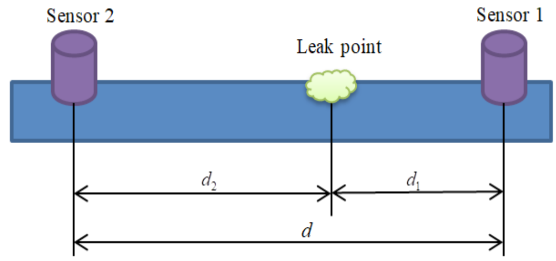

Fig.1 Liquid-filled pipe leak location model

In Fig. 1, two sensors are arranged at measuring point 1 and point 2, and the signals collected by the two sensors are $x_1(t)$ and $x_2(t)$, the distance between the two measuring points and the leak point is d_1 and d_2; the distance between the two measuring points is d. The model of the vibration signal collected by the sensors at the two measuring points is:

$$\begin{cases} x_1(t) = \alpha_1 s(t) + n_1(t) \\ x_2(t) = \alpha_2 s(t-\tau) + n_2(t) \end{cases} \quad (1)$$

Among them, $s(t)$ is the acoustic signal that generates at the leak point, n_1(t) and n_2(t) are uncorrelated noise signals, α_1 and α_2 are the attenuation of the leakage vibration signal propagate to the measuring points 1 and 2. Assuming that the time taken for the leakage acoustic wave signals to propagate to sensor 1 is t_1, the time taken to propagate to sensor 2 is t_2, the time delay value is $\tau = t_1 - t_2$, which represents the time difference between the acoustic signal at the leak point reaching the sensor 1 and sensor 2.

Assuming that the acoustic signal at the leak point propagates along the pipe to both sides of the pipe at a constant wave speed, set this speed as v, and the time delay obtained by an algorithm is τ.

$$d_1 = \frac{d + v\tau}{2} \quad (2)$$

$$d_2 = d - d_1 \quad (3)$$

In the project, the time delay is calculated by using the cross-correlation algorithm[11], adaptive algorithm[12] and generalized cross-correlation algorithm, etc. The cross-correlation algorithm is easy to use and takes a short time, the cross-correlation algorithm is taken to determine the time delay estimation value here.

It can be seen from Fig.1 and formula 1, the acoustic signals measured by the sensor are $x_1(t)$ and $x_2(t)$ respectively. Before using the cross-correlation algorithm to determine the time delay estimation value, it is necessary to perform de-noising processing on the measured signal, and the signals that are obtained after de-noising processing are $X_1(t)$, $X_2(t)$.In fact, $X_1(t)$ and $X_2(t)$are discrete signals, but when the sampling frequency is high, it can be regarded as a continuous signal during calculation. The cross-correlation function of the two signals after de-noising processing is $R_{X_1X_2}(\tau)$, and the cross-correlation coefficient is $\rho_{X_1X_2}(\tau)$.

$$R_{X_1X_2}(\tau)=\int_0^{+\infty}X_1(t)X_2(t+\tau)dt \tag{4}$$

$$\rho_{X_1X_2}(\tau)=\frac{R_{X_1X_2}(\tau)-\overline{X_1X_2}}{\sqrt{D(X_1)}\sqrt{D(X_2)}} \tag{5}$$

In formula 5, $\overline{X_1}$ and $\overline{X_{1(t)}}$ respectively the mean of $X_1(t)$ and $X_2(t)$; $\sqrt{D(X_1)}$ and $\sqrt{D(X_2)}$ respectively the standard deviation of $X_1(t)$ and $X_2(t)$; τ is the time delay estimation value.

From the definition of the correlation coefficient, if the leakage vibration signal $X_1(t)$ and $X_2(t)$ is correlated, a series of correlation coefficients can be obtained, and there is $|\rho_{X_1X_2}(\tau)|\le 1$. When the correlation coefficient of the two leakage vibration signals reaches the maximum, the most accurate time delay estimation value can be obtained, and $\tau_{\max}=\arg\max(\rho_{X_1X_2}(\tau))$.

In the actual application of the location of the leakage point of the liquid-filled pipe, the wave speed v is related to the pipe and the surrounding environment of the pipe and is not a constant value. Three sensors are arranged on the liquid-filled pipe, two of which can be used to determine the wave speed of the leakage vibration signal [13], but the wave speed is measured by this method inaccurately. According to the material properties of the pipe and the coupling equation, the propagation speed can be derived [14], and the speed on some parameters is difficult to get in a short time. Given the shortcomings of the above two methods, a method that can determine the wave speed at the corresponding frequency according to the dispersion characteristics can be adopted.

2.2 Axisymmetric wave propagation characteristics

In the leakage point positioning model of the liquid-filled pipe, when calculating the distance between the measuring point 1 and the leakage point, the propagation speed of the vibration signal of the leakage point is a certain value theoretically, but in actual engineering applications, the wave speed is changing. By the coupling equation of buried liquid-filled pipes, the propagation characteristics of the leaky acoustic signal in a liquid-filled pipe can be derived, and the propagation speed of the leakage acoustic signal in the pipe can be determined.

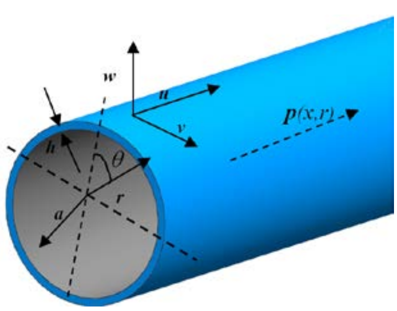

Fig.2 The coordinate system of buried liquid-filled pipe

In the coordinate system, the buried liquid-filled pipe shown in Fig.2, u represents the axial displacement of the shell, w represents the radial displacement of the shell, v represents the tangential displacement of the shell, $p(x,r)$ represents the fluid pressure, a represents the shell radius, h represents the shell wall thickness.

In the buried liquid-filled pipe, the axial force and radial force inside the pipe are in a balanced state, which can be obtained:

$$\rho\ddot{u}=-\partial\sigma_x/\partial x \tag{6}$$

$$p(a/h)=\sigma_\theta+\rho a\ddot{w} \tag{7}$$

$$\sigma_\theta=\frac{E}{1-v^2}\left(\frac{w}{a}+v\frac{\partial u}{\partial x}\right) \tag{8}$$

$$\sigma_x=\frac{E}{1-v^2}\left(\frac{\partial u}{\partial x}+v\frac{w}{a}\right) \tag{9}$$

In the above formulas, E is Young's modulus of the pipe, w/a is the circumferential strain, v is the Poisson's ratio, $\partial u/\partial x$ is the axial strain, and ρ is the pipe density; σ_θ is the axial stress, σ_x is the circumferential stress.

Combining formula 6 and formula 9, get:

$$\rho\ddot{u}+\frac{E}{1-v^2}\left(\frac{\partial^2 u}{\partial x^2}+\frac{v}{a}\frac{\partial w}{\partial x}\right)=0 \tag{10}$$

Combining formula 7 and formula 8, get:

$$\frac{E}{1-v^2}\left(\frac{w}{a}+v\frac{\partial u}{\partial x}\right)+\rho a\ddot{w}=\frac{pa}{h} \tag{11}$$

In formula 10 and formula 11, the axial displacement u, the radial displacement w, and the amplitude of the axial motion of the soil medium U_s, the amplitude of the radial motion W_s have the following relationship: $u=U_s e^{i(\omega t-k_s^r x)}$, $w=W_s e^{i(\omega t-k_s^r x)}$. And $(k_s^r)^2=k_f^2-k_s^2$, in here: k_s^r is the radial wave number, k_f is the free fluid wave number, k_s represents the wavenumber of axisymmetric wave s=1 or s=2.

Combining formula 7 and formula 8, get:

$$(\Omega^2-\alpha_s^2)U_s=\mathrm{i}v\alpha_s W_s \tag{12}$$

$$W_s(1-\Omega^2)-\mathrm{i}v\alpha_s U_s=\left(\frac{P_s a^2}{hE}\right)(1-v^2)\mathrm{J}_0(\alpha_s^r) \tag{13}$$

In formula 12 $\alpha_s=k_s a$, and $\Omega=k_L a$, the compression wave number $k_L^2=w^2\rho(1-v^2)/E$. In formula 13, the relationship is $p=\sum_{s=1}^{2}P_s J_0(k_s^r r)e^{i(\omega t-k_s^r x)}$ between p and P_s.

Combining formula 12 and formula 13, get:

$$W_s=(1/\rho_f\omega^2)P_s(\alpha_s^r/a)J_0'(\alpha_s^r) \tag{14}$$

$$P_s=\frac{-2B}{1-(\alpha_s/\alpha_f)^2}\frac{W_s}{a} \tag{15}$$

In the buried liquid-filled pipe, the first type of s=1 wave in the axisymmetric wave (n=0) accounts for most of the leakage acoustic signal, $k_1^2 \gg k_L^2$. When studying the dispersion characteristics, only the s=1 wave is discussed. By combining formula 11 and formula 15, get the wavenumber of s=1, $k_1=k_f^2(1+2Ba/(Eh+i\alpha Eh))$ [15], and B is the bulk elastic modulus of the fluid in the pipe, and α is the attenuation factor. From the expression, k_1 is a complex number, and the real and imaginary parts have a mathematical relationship with the wave speed and attenuation coefficient respectively. By calculating, the specific corresponding relationship can be seen In Fig. 3 and Fig. 4.

In Fig. 3 and Fig. 4, the real and imaginary parts of the *s*=1 wave are both curves which indicate that the wave speed and attenuation change with the frequency at all times, that is the leakage acoustic signal exists dispersion characteristics when it propagates in the pipe. The situation in Fig.3 shows that in the process of locating the leakage point of the liquid-filled pipe, the wave speed of the acoustic signal leaking in the pipe cannot be regarded as a constant value. Otherwise, it will have a great impact on the accuracy of the positioning. In Fig.4, the imaginary part of the *s*=1 wave does not all gradually increase. In the vicinity $k_f a = 0.06$, the imaginary part of the *s*=1 wave reaches a peak, which may be due to resonance between the liquid-filled pipe and the earth, and it can be used to measure the frequency of the earth. According to the propagation characteristics of the leakage acoustic signal, its dispersion characteristics can be deduced, which can improve the positioning accuracy.

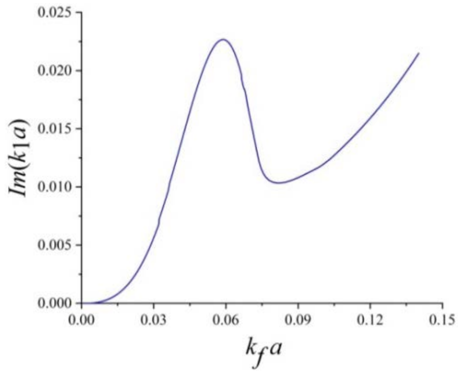

Fig.3 The relationship between the real part of *s*=1 wave and $k_f a$

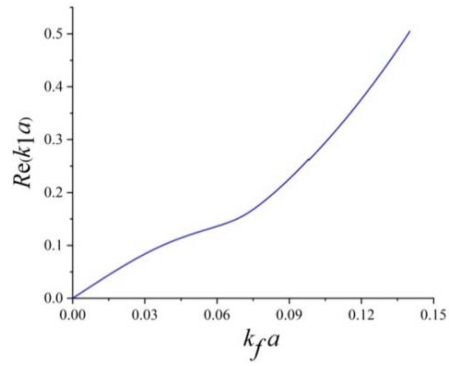

Fig.4 The relationship between the imaginary part of *s*=1 wave and $k_f a$

To obtain the frequency dispersion characteristics of the leakage vibration signal, the relationship among $k_f a$, $Re(k_1 a)$ and $Im(k_1 a)$ can be converted into the relationship between angular frequency, wave speed, and attenuation, and the results are shown in formula 16 and formula 17.

$$c_1 = a\, w / \mathrm{Re}(k_1\, a) \tag{16}$$

$$Loss(dB/m) = -20\frac{\mathrm{Im}(k_1 a)}{\ln(10)} \tag{17}$$

In formula 14, $w = k_f c_f$ is the angular frequency, c_f is the speed of the free fluid, k_f is the free fluid wave number. In here, $c_f = \sqrt{B_f/\rho_f}$, and B_f is the elastic modulus of the fluid, ρ_f is the density of the fluid.

The calculation results of formula 14 and formula 15 showed that the leakage acoustic signal has the frequency dispersion characteristic. The dispersion characteristics are related to the characteristics of the pipe material. Some material characteristics of the pipe can see Table 1.

Table 1 Material characteristics

Material	Density(kg/m^3)	Young's modulus (N/m^2)	Bulk's modulus (N/m^2)	Poisson's ratio	Loss
Fluid	1000	--	2.25×10^9	--	--
Pipe	2000	5.0×10^9	--	0.4	0.065
Medium	2000	--	4.5×10^9	--	--

3 Experimental Research

From a theoretical point of view, the determination of the location of the leakage point lies in the determination of the wave speed and the time delay. Combining the dispersion characteristics and characteristic frequency bands, the wave speed of the leaking acoustic signal can be obtained. The frequency spectrum analysis of the signal is used to find the characteristic frequency band that contains the most information of the leakage vibration signal, and filter out the signals of the remaining frequencies by the band-pass filter. The final signal should contain less noise information and more leakage acoustic signal information. Use a cross-correlation algorithm to do correlation analysis of two final signals, and obtain the cross-correlation function. When the degree of cross-correlation function between the two signals is the largest, the corresponding time is the time delay. The wave speed in the characteristic frequency band can be obtained by the dispersion characteristic curve, then under the condition of obtaining the wave speed and time delay in the characteristic frequency band, the leakage point of the liquid-filled pipe can be located.

To verify the feasibility of the theory, a field experiment was done in the school. Taking the school's water supply pipelines as the experimental object, the situation when the fire hydrant is opened is regarded as a pipe leakage condition, a sensor is arranged on the pipe under the manhole cover at the left and right ends of the fire hydrant to measure the pipe leakage acoustic signal. Try to keep the surroundings quiet during the experiment to prevent sudden noise interference. The distribution of sensors and the opening of the fire hydrant during the experiment are shown in Fig.5 and Fig.6.

During the experiment, keep the two sensors located at the left and right ends of the fire hydrant respectively, and name the sensors on the left and right sides of the fire hydrant as measuring point 1 and measuring point 2. Four sets of data were measured during the experiment: the first set: d_1=21.6, d_1=28.7; the second set d_1=21.6, d_2=42.3; the third set: d_1=32.9, d_2=28.7; the last set: d_2=32.9, d_2=42.3.

Fig.5 Open fire hydrant to simulate pipe leakage

Fig.6 Place sensors downhole

3.1 Signal acquisition and analysis

During the experiment, a sensor was arranged at the fire hydrant to measure the leakage acoustic signal. The time-domain signal collected by the sensor is shown in Fig.7. The power spectrum density of the signal at the fire hydrant can be calculated by the period diagram method, as shown in Fig.8. In Fig.8, there are three frequency bands with prominent peaks in the power spectral density (PSD). These three frequency bands may contain the information of leakage signal, and it can be seen from Fig.8 that the frequency ranges of band 1, band 2, and band 3 are 450 Hz. to 530Hz, 560Hz to 790Hz, and 1000Hz to 1200Hz, respectively.

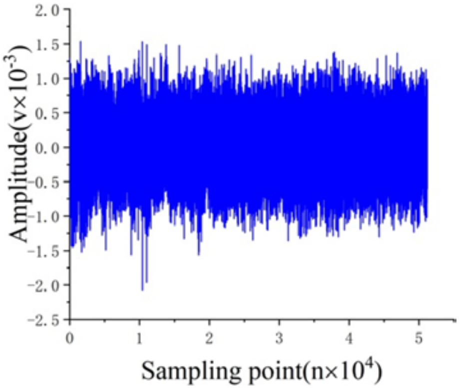

Fig.7 The time-domain signal measured at a fire hydrant

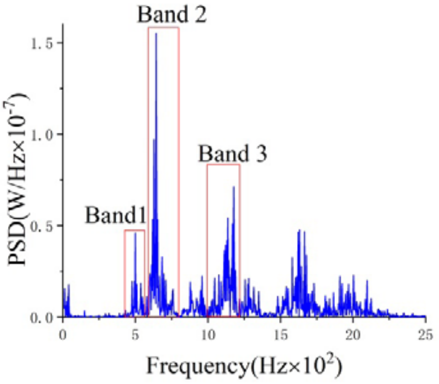

Fig.8 PSD of a signal at a fire hydrant

In the experiment, the leakage of a fire hydrant can simulate the leakage of pipe in water supply pipelines, and the signal measured by the sensor arranged at the fire hydrant can best represent the leakage acoustic signal. As shown in Fig.8, the PSD of the measured signal at the fire hydrant contains the three most representative frequency bands, and the characteristic frequency band of the leakage vibration signal may be in one or more frequency bands. In the process of leakage signal propagation, due to environmental noise and attenuation in the process of propagation, the leakage acoustic signal information contained in the signal measured at the measuring point may be lost or covered by the noise information. In the course of the experiment, in addition to the spectrum analysis of the signal at the fire hydrant, the power spectral density of the four groups of measured points is also analyzed, and the three frequency bands with prominent power spectral density are selected, and the frequency range is from small to large. The specific results are shown in Table 2.

Table 2 The frequency range where the PSD at the measurement point is prominent

Test group	Measuring point	Band 1(Hz)	Band 2(Hz)	Band 3(Hz)
Group 1	Point 1	470-570	580-800	1000-1400
	Point 2	480-560	570-800	1000-1400
Group 2	Point 1	470-550	570-800	980-1400
	Point 2	470-520	580-800	1010-1370
Group 3	Point 1	420-570	575-800	1020-1370
	Point 2	460-580	580-700	--
Group 4	Point 1	475-560	570-810	1020-1375
	Point 2	470-570	580-730	--

From Table 2, the three bands where the power spectral density of the measured signal is more prominent, band 1 and band 2 are different except for some measurement points, and the other measurement points are not different. The power spectral density of the measuring point 2 of the third and fourth groups does not have a third prominent frequency band, which may be that the high-frequency part of the leakage acoustic signal attenuates too much during propagation, so the noise covers the acoustic signal.

Based on band 1, band 2, and band 3 obtained from the spectrum analysis of the signal at the fire hydrant, the prominent frequency range of the power spectrum density at the measuring point and the fire hydrant is compared. For band 1, most of the frequency range obtained by measuring point signal includes the frequency range of the signal power spectrum density at the fire hydrant, which indicates that the leakage acoustic signal in this frequency range will not have a great change in the frequency range. For band 2, compared with the two frequency ranges, it is found that except for a few measuring points, the other points are not different, which indicates that although the leakage signal will be affected by the external environment during the propagation of the pipe, it is still within a reasonable frequency range. For band 3, the frequency range of the measured signal is larger than the standard frequency range or there is no prominent power spectrum density in the third segment, which indicates that the attenuation is too large here. That meant that band 3 is affected by noise and the pipe, the corresponding portion of the original signal and there is a big difference.

From the comparison results, the frequency range between the measuring points 1 and 2 and the fire hydrant is partially out of the way. In engineering, the use of a frequency characteristic of the measured signal would be difficult to select the frequency band. The frequency distribution range will be affected by human or environmental factors, and it's difficult to choose the right one. To make the result close to reality, the frequency distribution range at the fire hydrant can be assumed to be the frequency distribution of the measuring point.

3.2 Propagation characteristics verification

In the course of the experiment, the signal collected at point 1, point 2, and fire hydrant are decomposed by wavelet with the same number of layers, and the detail coefficient and approximate coefficient of the signal can be obtained respectively. Each set of coefficients corresponds to a specific frequency range; To calculate easily, regard the average frequency within that frequency range as the frequency range.

In theory, the relationship between angular frequency and wave speed and attenuation can be calculated by formulas 16 and 17 respectively, as shown in Fig.9 and the blue line in Fig.10. By the wavelet decomposition, the measurement signal is decomposed into signals at different frequencies. Then try to calculate the time delay by cross-correlation algorithm, get the wave speed of corresponding frequency finally.

In Fig.9, the average wave speed calculated by the four groups of corresponding measuring points is taken as the wave speed of the measuring point. In the experiment, the amplitude of the signal after wavelet decomposition can be used to calculate the attenuation at the corresponding frequency. In Fig.10, the attenuation calculated by the four groups of corresponding measuring points is taken as the average attenuation coefficient of the measuring point.

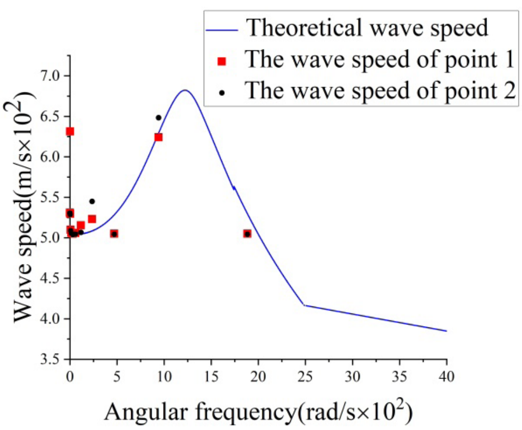

Fig.9 The relationship between angular frequency and wave speed

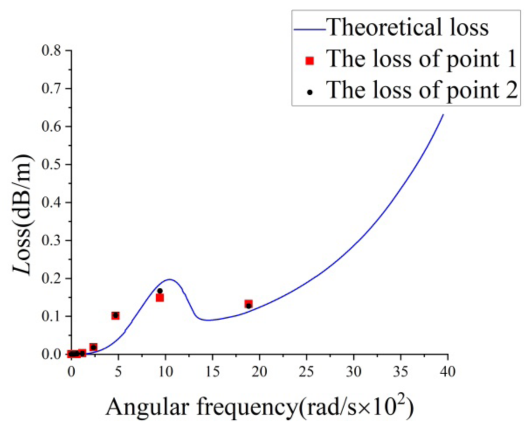

Fig.10 The relationship between angular frequency and loss

From Fig.9 and Fig.10, it can be seen that the results obtained by theoretical calculation and experimental calculation show that there is a dispersion characteristic when the leakage acoustic signal propagates in the liquid-filled pipe. The above-mentioned phenomenon indicates that when locating the leakage point of the pipe, the wave speed needs to be determined according to the characteristic frequency of the signal. Compared with the theoretical results, it is found that the experimental results and theoretical results of wave speed and attenuation are mostly consistent with the overall trend. In the aspect of wave speed, the place where there is a large deviation at low frequencies, and the reason may be the noise attached to the acoustic signal affects the calculation of the time delay, which will cause errors in calculating the wave speed.

3.3 Signal analysis

Before calculating the time delay by cross-correlation algorithm, the signal collected at the measuring point should be de-noised. From Fig.8, it can be seen that there are three bands with high power spectrum density in the measured signal, and the three bands have the possibility of containing the information of leakage acoustic signal. To determine the characteristic frequency band of leakage acoustic signal, take a frequency band as the research object individually. De-noising the measured signal based on the frequency domain characteristics of the leakage signal, which can retain the information of the leakage vibration signal to the greatest extent and reduce the influence of noise. After de-noise, the time delay can be obtained by cross-correlation algorithm, and take the average wave speed calculated from the measuring point as the propagation speed in the corresponding frequency range. Then the location of the leakage point can be determined by formula 2.

After the signal at the measuring point in the four groups of experiments is processed, the correlation between the degree of correlation $R_{X_1X_2}(\tau)$ and time τ is obtained by cross-correlation algorithm, the experimental calculation results as shown in Fig.11, Fig.12, Fig.13, and Fig.14. To make the calculation results clear, the time delay and the corresponding leakage point location error rates are listed in Table 3.

Table 3 Analysis of time delay calculation results of four sets of experiments

Test group	Band	TDE (s)	Wave speed (m/s)	Distance(m)	Error rate (%)
Group 1	Band1	0.02453	404.242	9.92	39.72
d1=21.6m	Band2	0.00672	942.243	6.33	10.84
d2=28.7m	Band3	0.01586	1220.000	19.35	172.54
Group 2	Band1	0.05828	404.242	23.56	13.82
d1=21.6m	Band2	0.02117	942.243	19.95	3.62
d2=42.3m	Band3	0.06695	1220.000	81.68	294.59
Group 3	Band1	0.00336	404.242	1.36	67.62
d1=32.9m	Band2	0.00523	942.243	4.93	17.38
d2=28.7m	Band3	0.01336	1220.000	16.30	288.10
Group 4	Band1	0.03031	404.242	12.25	30.32
d1=32.9m	Band2	0.00922	942.243	8.69	7.55
d2=42.3m	Band3	0.03766	1220.000	45.95	388.83

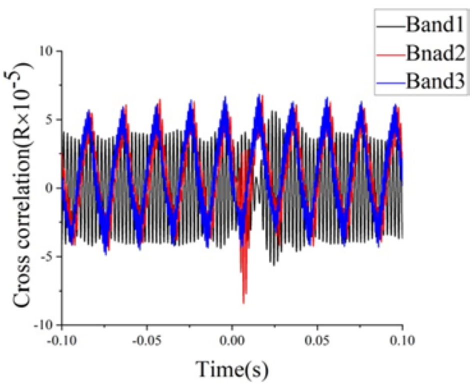

Fig.11 Estimated time delay of the first set

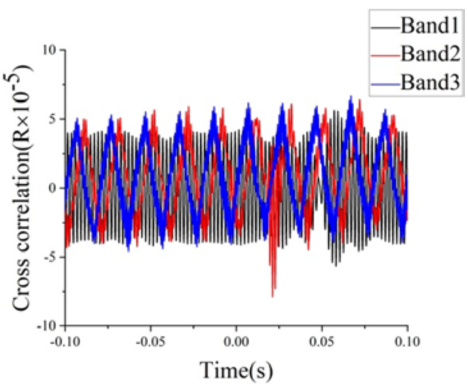

Fig.12 Estimated time delay of the second set

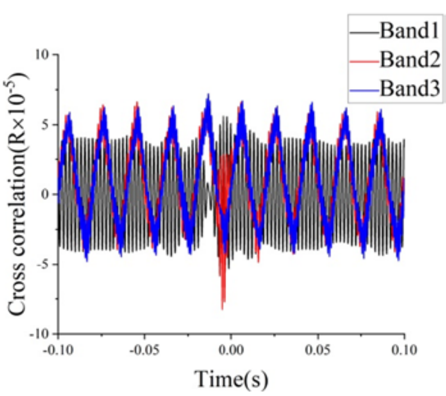

Fig.13 Estimated time delay of the third set

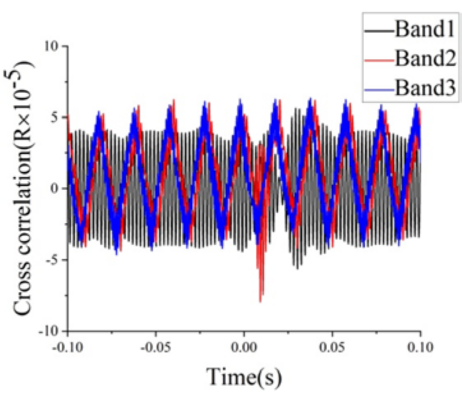

Fig.14 Estimated time delay of the last set

In Table 3, the predicted wave speed is calculated by the theoretical angular frequency and wave speed curve in Fig.9, and the average wave speed in the corresponding frequency range represents the wave speed of the frequency band. Since the frequency range given in Fig.9 is limited, so the wave speed that is not in the frequency range can take the experience wave speed is based on the nature of the pipe. After a series of processes, the wave speed can be obtained and the wave speeds of band 1, band 2, and band 3: 404.242 m/s,942.243m/s, and 1220 m/s respectively. In Table 3, TDE is the time delay estimation value.

In the field experiment, the layout of the sensor is determined according to the position of the manhole cover on the campus. Two manhole covers are taken on each side of the fire hydrant, and the two-by-two combination can be four groups of experiments.

From the results in Table 3, among the four sets of experiments, the positioning results obtained from band 2 are the most accurate, followed by band 1, and band 3 is the worst. The results obtained from the positioning to see band 1, after analysis, the distribution in the band 1, the signal and interference signal modulated signal ground vibration, plus the effect of noise, resulting in positioning accuracy is not high. Judging from the positioning results of band 3, the positioning accuracy is very low and the error is large; After analysis, it is believed that due to the large signal attenuation in band 3, when the signal propagates to the sensor, the leakage acoustic signal attenuates greatly, and the noise covers the leakage acoustic signal, resulting in inaccurate final calculation results. From Fig.8, the PSD in band 2 is the largest, indicating that the energy of the leakage signal is the largest in band 2, that is, most of the leakage acoustic signal is in band 2. The calculation result obtained by frequency band 2 is the most accurate, indicating that the information in band 2 contains the most leaked signals. Among the four groups of experiments, the positioning result of the second group is the most accurate, and the positioning result of the third group is the least accurate. In the third set of experiments, the distance difference between the two measuring points and the leaking point is the smallest, the wave speed is very fast, and the resolution of the equipment is not high, the time delay obtained has errors, which leads to the accuracy of the final result. In the second set of experiments, the distance between the two measurement points and the leakage point is very large, which reduces the influence of the error of the time delay on the positioning result.

In engineering application, apply research results to acoustic leak detection engineering. Also, it provides a theoretical basis for future research and technical guidance for engineering practice.

4 Conclusion

In theory, the pipe's dispersion characteristics of axisymmetric waves are derived from the coupling equations of buried liquid-filled pipe. In the field test, the characteristic frequency was obtained with the help of sensors and computers. Wave speed and attenuation under characteristic frequency are solved by wavelet decomposition. Theoretical analysis and test results are in agreement with each other, both showed that the dispersion characteristic of axisymmetric wave exists in the characteristic frequency band of leakage signal. By using the obtained dispersion relation, the acoustic signals with different characteristic frequencies are studied by cross-correlation method, the time delay of the leakage signal is carried out, and the accuracy of leakage location is discussed. The output shows that the accuracy is low when the high-frequency signal is used to leakage location, which attributes to the fast attenuation of the high-frequency signal. The characteristic signal with low amplitude in the low-frequency band is easily affected by the propagation path and is not suitable for leakage location. The vibration signal with high energy in the low-frequency band has higher accuracy for leakage location, and the average error is 9.86%, which meets the engineering requirements.

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