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Estimation of reflection location by the correlation coefficient function

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It is desirable to avoid excavation during the maintenance of gas pipes. As a no excavation method, the measurement of pipe length on the basis of reflected acoustic waves traveling in a pipe is considered. This method has the advantage in that an inspection device can be constructed in a relatively simple manner by combining a loudspeaker, a microphone, and an operating unit, but it also has the disadvantage that the types of pipe that can be examined are limited owing to the large decay of traveling acoustic waves.

In this study, the decay of acoustic waves traveling in a carbon-steel pipe that complies with the Japanese Industrial Standard (JIS) and methods of correcting measurement errors are described.

1 Introduction

It is necessary to carry out regular maintenance of gas pipes to ensure the safe supply of gas to consumers [1]. When gas pipes are buried underground, minimum excavation is a prerequisite to achieving quick and low-cost maintenance. In particular, owners are required to pay for the cost of gas pipe maintenance on their property. Therefore, an increase in maintenance cost may affect the continuous, stable and safe supply of gas.

Among the various tasks that should be carried out in the maintenance of gas pipes, we examine the prior measurement of the length of buried pipes, which is necessary for repairing the internal surface of gas pipes without excavation. Although the use of an in-pipe camera is one method of realizing such measurement, it is better to use acoustic waves to rapidly obtain measurement results. However, because of the large decay of acoustic waves traveling in a pipe, the amplitude of the acoustic waves observed as reflected waves is very low. In this study, the decay is quantitatively evaluated and the methods of correcting it are described.

Yunus et al. proposed a visually understandable method of measuring impulse response by removing incident signals from observed signals. However, in their method, it is necessary to connect single pipes for measurement, which inevitably causes a decrease in operation efficiency during the measurement [2]. We propose three methods of correcting the decay of acoustic waves without decreasing operation efficiency. In the first method, the decay is corrected on the basis of the correlation between the impulse response and the waveform extracted from the response. In the second method, standing waves are generated in a pipe and pipe length is measured from their frequency. In the third method, a correlation function for continuous signals generated in a pipe is used.

In this study, measurement experiments are carried out using a carbon-steel pipe that complies with the Japanese Industrial Standard (JIS) , and the validities of the above three methods are confirmed and compared. Prior to the description regarding those methods, the decay of acoustic waves traveling in a carbon-steel pipe is examined.

2 Decay Characteristics of Acoustic Wave in Carbon-Steel Pipe

2.1 Measurement of decay characteristics

The measurement system shown in Fig. 1 is used in the experiments. The pipes used in this study are carbon-steel pipes (length: 2,000mm; diameter: 27.6mm) that comply with JIS-G3452.

For the measurement of pipe length, the use of pulse waves whose incident waves and reflected waves are not superimposed is effective. The impulse response based on such properties was measured by the time-stretched pulse (TSP) method [3]. A signal pr(n) is a reverse sequence signal for the driving TSP signal p(n), n=0, 1, 2, …, N-1. The impulse response h(n) between the signal q(n) and the observed signal q(n) in the pipe is calculated by

$$h(n) = \sum_{k=0}^{N-1} q(k)\, pr(n-k) \tag{1}$$

Here, a driving signal p(n), which was obtained via D/A converter of a signal (N=32, 768) at a sampling frequency = 10 kHz, was used.

2.2 Measured amount of decay

The normalized impulse response calculated by the TSP method is shown in Fig. 2. The separated many waves are observed visually in the impulse response. The first wave is the response wave for the driving signal, and the second wave is the reflected wave generated at the pipe ends. The others are the reflected waves generated at the driving end and at the pipe end.

To represent the sound decay of the traveling waves quantitatively, we pay attention to the cumulative change in power calculated by squaring the impulse response shown in Fig. 2. The cumulative change for power as a function of the traveling distance significantly attenuates from the results shown in Fig. 3(a). From the amount of the acoustic decay of each power obtained at the traveling distance, the curve of sound decay for the traveling sound wave in the pipe is calculated. The symbol ∘ has shown in Fig. 3(a) represents the cumulative acoustic power as a function of the traveling distance of the observed reflected waves.

The normalized amplitude for distance from 0m to 12m is shown by the symbol ∘ in Fig. 3(b). In figure, a straight line is calculated from the obtained cumulative acoustic power by the least-squares method. The energy decay per propagation distance can be estimated. From the gradient of the line, the acoustic decay is up to -0.025dB/m.

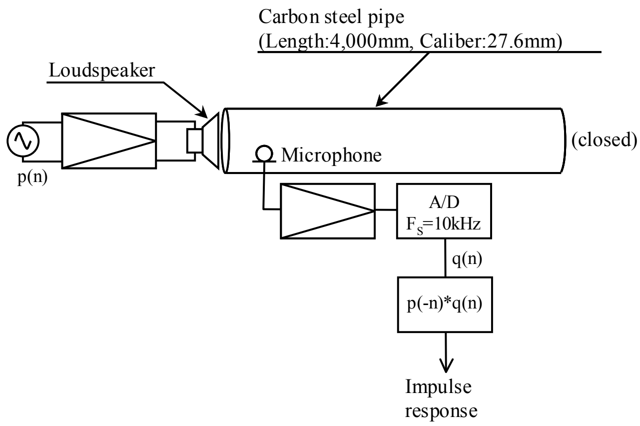

Fig. 1 The measuring block diagrams.

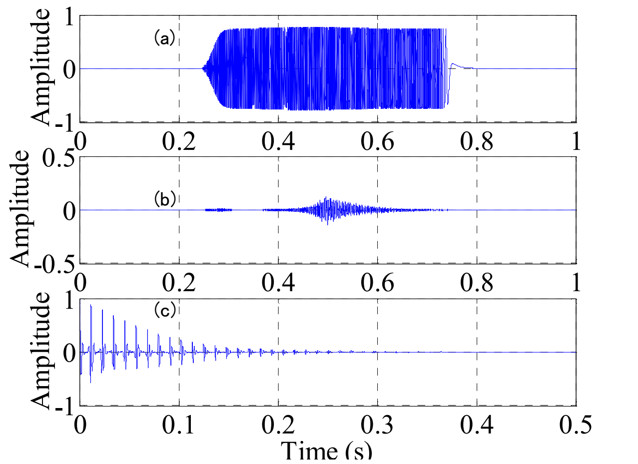

Fig.2 The TSP signal, the measured reflected waves and the impulse response. (a) TSP signal p(n). (b) The reflected wave q(n) of the measured TSP signal. (c) The impulse response obtained by the TSP method.

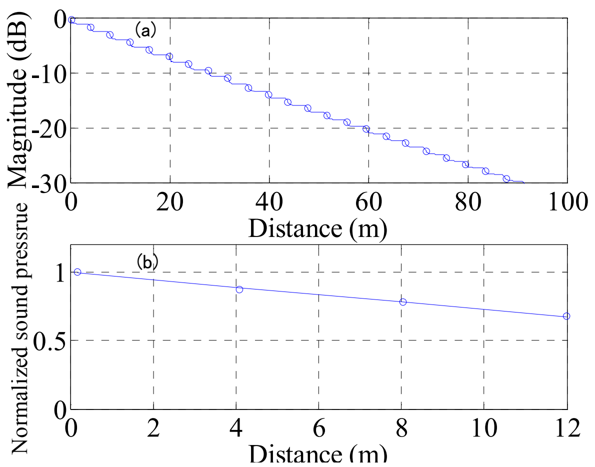

Fig. 3 Cumulative power curve and the decay curve. (a) The cumulative change in power for impulse response. The symbol ∘ represents the traveling distance of the observed reflected waves. (b) The cumulative power curve as a function of the traveling distance. The solid line is calculated by the least-squares method.

3 Correction Method for Decayed Acoustic Wave

3.1 [Method I] Measurement based on impulse response waveform

Because the amplitude of the measured acoustic waves decreases by the decay, a detecting method that is independent of amplitude for the reflected waves is necessary. In this study, the amplitude of reflected waves is estimated by the following procedure. First, a reference wave is selected from the observed acoustic waves. Next, reflected waves with the same elements that constructed the reference wave are selected at the every sampling rate. The correlation coefficient between the both selected signals is calculated. In procedure, the reference wave is fixed and selected reflected waves change in every sampling rate. Finally, the correlation coefficient sequence is obtained. We show the results calculated by the mentioned above method. Here, the reference wave that is included the 15th reflected wave is selected. And the other reference signal is selected in the reflected waves at every sampling rate starting from 0s. By changing the selected time, the correlation coefficient as a function of the time is calculated. The correlation coefficient depends on the inner product between the waves, and the amplitude of the wave is independent. Fig. 4(a) shows the calculated the correlation coefficient function. Each symbol ∘ in the figure indicates the propagated distance of the travelling waves. The local peaks correspond to the distance at which acoustic waves are reflected; the distances at which waves are actually reflected are compared with the theoretical distances in Fig. 4(b). The results indicate that the estimation of the distance with an accuracy of 20mm or better is possible for propagation distances of up to 150m and this estimation method can be comfortably applied to actually buried pipes. However, it is difficult to select the appropriate reference wave by this method because its required specifications have not been established.

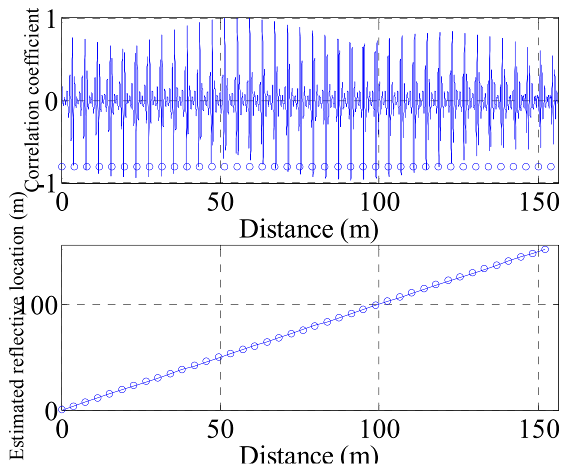

Fig. 4 Results estimated using correlation coefficient. Upper: calculated correlation coefficient function. The symbol ∘ expresses the estimated returns distance. Bottom: Comparison between the calculated and estimated distance. The solid line is calculated by the least-squares method.

3.2 [Method II] Detection of reflection distance using frequency data of standing waves

The distance measurement method by use of standing wave proposed by Uebo *et al*. has an advantage that enables in acoustic near-field measurement [4]. The minimum detection distance can theoretically be as short as 0m, if two detectors and a differential amplifier are introduced. Moreover, because the direct-current term included in the signal is not considered in the distance measurement system used for the estimation, signals with high SNR can be obtained using standing-wave radar, compared with that in the case of using conventional radar. Nakasako *et al*. measured the distance by the acoustic standing-wave method in which radio waves were replaced with acoustic waves. They placed a reflector at distances of 0.1 and 0.3m from the loudspeaker in an ordinary room without any acoustic material, such as acoustic absorption, and estimated the distance within errors of 2-3mm, demonstrating the feasibility of acoustic radar [5].

Considering that the reflection distance can be detected at a high accuracy when the standing-wave method is used, as shown by the measurement results obtained by Nakasako *et al*., we report the result of our experimental measurement of pipe length.

First, the distance measurement method based on the standing-wave radar proposed by Uebo is described.(4) Assuming that standing waves are generated by the interference of a travelling wave, V_T, with waves reflected from each reflection point V_{R1}, V_{R2}, …, V_{Rn} and that each reflection distance is d_k (k=1,2,…,n), d_k is obtained using standing waves.

The amplitude of the driving signal source, frequency, and acoustic velocity are denoted as A, f, and c, respectively. Let us examine the case in which a plane-wave acoustic source moves along the x-axis. The travelling wave at an arbitrary point x on the propagation path is expressed as

$$V_T(f,x) = Ae^{\frac{2\pi f}{c}x} \tag{2}$$

Denoting the distance from the kth reflection point as d_k, and the reflection coefficient and phase as γ_k and ϕ_k respectively, the wave reflected from the reflection point is expressed by

$$V_{Rk}(f,x) = Ar_k e^{j\phi k} e^{\frac{2\pi f}{c}(2dk\text{-}x)} \tag{3}$$

The output power of the microphone placed at a distance x=x_s is expressed by

$$P(f,xs) = \left| V_T(f,x) + \sum_{k=1}^{n} V_{Rk}(f,x) \right|^2 \tag{4}$$

When $\gamma_k \prec\prec 1$ is satisfied, the output power of the microphone is approximated as

$$P(f,xs) \approx A^2 \left\{ 1 + \sum_{k=1}^{n} r_k^2 + 2\sum_{k=1}^{n} r_k \cos\left(\frac{4\pi f(dk - xk)}{c} + \phi k \right) \right\} \tag{5}$$

The first, second and third terms represent the power of the driving acoustic wave, that of the reflected wave, and that generated by standing waves, respectively. Therefore, Equation 5 is separated into the direct-current term and power term of the reflected wave

$$P(f,xs) \approx P_{DC} + m(f)\cos\left(\theta(f) - \frac{4\pi f}{c} xs \right), \tag{6}$$

where the direct-current term is

$$PDC = A^2 \left(1 + \sum_{k=1}^{n} r_k^2 \right). \tag{7}$$

The power term of the reflected wave is

$$m(f) = 2A^2 \sqrt{a^2 + b^2}\ . \tag{8}$$

And, the phase term is

$$\theta(f) = \tan^{-1}\left(\frac{b}{a} \right), \tag{9}$$

where, a and b in Eq. (9) are expressed as follows:

$$a = \sum_{k=1}^{n} rk \cos\left(\frac{4\pi f}{c} dk + \phi k \right) \tag{10}$$

$$b = \sum_{k=1}^{n} rk \sin\left(\frac{4\pi f}{c} dk + \phi k \right) \tag{11}$$

The second term of the reflected wave includes the following parameters: the reflection coefficient γ_k, the driving frequency f, the generation point of the reflected wave d_k the observation point x_s, and the phase ϕ_k .Therefore, d_k should be determined to obtain the pipe length.

Figure 5 shows the measured response signal and the spectrum for a 2-m-long straight open pipe. It is found that the sensitivity of the reproducing frequency of the loudspeaker in the band from 0.38 kHz to 5 kHz is high. Because the standing-wave method has the advantage that the reflection distance can be estimated even within a limited frequency band, no particular care in measuring the frequency characteristics is necessary.

To estimate reflection distance, the results that are estimated in the frequency band from 0.2 kHz to 2.0 kHz are shown in Fig. 5. Figure 5(a) shows the power spectrum of the signal measured at the observing point. The power spectrum in Fig. 5(b) is Fourier transform of the spectrum in Fig. 5(a). In characteristics, regular frequency intervals are observed. To confirm this pitch frequency, Fourier transform of the spectrum shown in Fig. 5(a) carried out. And, it represents a kind of autocorrelation function in the frequency domain. The autocorrelation function of the power spectrum in a limited frequency band is shown in Fig. 5(b). It is found that the autocorrelation function has a pitch frequency f_p = 86 Hz. Because the room temperature is 20°C during the measurement, the acoustic velocity is 343.6m/s. Travelling distance of returns from the observing point to the end of the pipe is 2.0m calculated by the equation c / (2f_p).

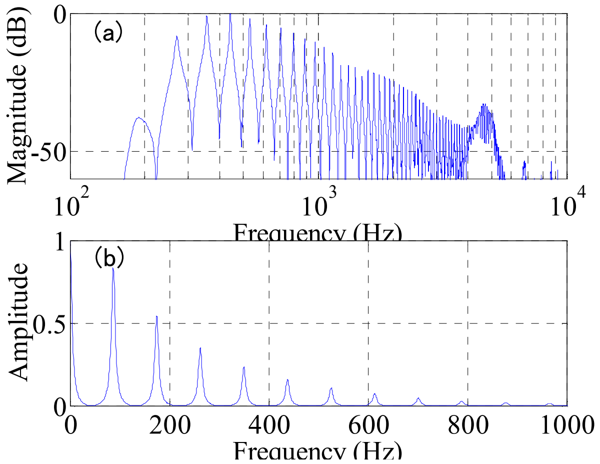

Fig. 5 Power spectrum and Autocorrelation function in frequency domain. (a) Power spectrum at measuring point. (b) Auto correlation function in the frequency domain in frequency band shown in Fig. 5(a).

The frequency resolution corresponding to the lag in the time domain is 0.33Hz. Hence, the estimated distance is in the range from 1.99 to 2.01m, indicating that the accuracy of the acoustic standing-wave method is sufficiently high.

3.3 [Method III] Method using correlation function

When the acoustic wave is travelling in the pipe, sound pressure decay of increases depending on frequency and pipe diameter. In high frequency range, decay is a marked large. Therefore, when the reflection distance is long, an impulse response wave mainly composed of components in a low-frequency narrow band is obtained. Therefore, an impulse response with filtered smooth waveforms is used for the estimation of reflection distance, which is a disadvantage in this method. The standing-wave method described in section 3.2 has the advantage of high accuracy in the near-field measurements [3, 4]. However, it has been experimentally confirmed that its accuracy decreases with increasing pipe length or pipe inner diameter.

As an evaluation parameter for determining the correlation between reference and response wave, the correlation coefficient is applied. The correlation coefficient, which is calculated from the inner product of the reference and response waves, has the advantage of being independent of amplitude.

The correlation coefficient between the basic and reference signals to which attention is paid shifts every sampling rate. The reflection position is estimated on the basis of sequence of the calculated correlation coefficient.

The signals measured are divided into N frames composed of time-series signals with n (consecutive integer) elements. A reference signal arbitrarily selected from such frames is denoted as x. Similarly, the reference signal in the ith frame is denoted as $y(i)$. Assuming $x=(x_1, x_2, x_3, \cdots, x_n)$ and $y(i)=(y(i)_1, y(i)_2, y(i)_3, \cdots, y(i)_n)$, the correlation coefficient between x and $y(i)$, $C_{xy(i)}$, is given as

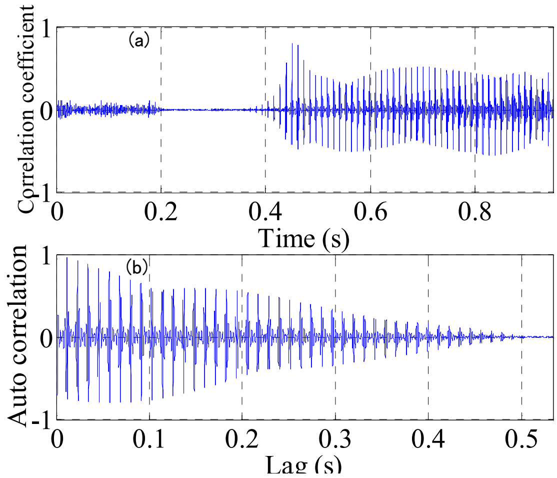

Fig.6 Correlation coefficient function and its autocorrelation function. (a) Correlation coefficient function between basic and reference signal. (b) Autocorrelation function of correlation coefficient function shown Fig. 6(b).

$$C_{xy}(i) = \frac{x \cdot y(i)}{|x||y(i)|}, \tag{12}$$

where the symbol • in the equation indicates the inner product operator.

Figure 2(b) shows the sound-pressure waveform generated by the TSP signals with duration = 1s. Duration of the observed waveform is up to 0.5s. In signals measured, a lot of reflected wave include. Figure 6(a) shows the correlation coefficient function between the basic and reference signals calculated from equation (12). The time on the abscissa represents the starting number of the selected frame. The window length of the frame is 25.6ms and shifts every sampling rate 50 μs . Figure 6(b) shows the autocorrelation function of the correlation coefficient function. The reflection distance calculated from the period of this autocorrelation function is 1,997mm, which is equivalent to the distance estimated from the impulse response. This method has the advantage in that the basic signal can be arbitrarily changed, therefore the observed signals can be effectively used. In addition, this method has an increased reliability of the estimated distance by including an averaging operation.

4 Validity of Proposed Methods and Their Comparison

In Section 3, we proposed three correction methods. To tabulate the features of these methods, their advantages and disadvantages are summarized in Table 1.

When the application of the methods to an actual device is considered, the device is operated outside; therefore, SNR is considered to significantly deteriorate in such a noisy environment. To solve this problem, we consider that the following two conditions are required for each method.

Table 1 Features of proposal methods.

	Merits	Demerits
[Method I] Using impulse response wave	Visually understand able.	1. The amount of de cay is large. 2. It is difficult to se lect the referenc e wave even wh en the correlatio n is used for cor rection.
[Method II] Using standing wave	Estimation with hig h accuracy is possib le.	The accuracy decre ase for long pipes.
[Method III] Using correlation coefficient	The frame used as t he reference of corr elation can be arbitr arily set.	Accuracy decrease s, unless the compo nent in an identical band appears many times, because the d riving signals are ob served in a wide fre quency band.

Condition 1: The measurement result must be presented on site as soon as possible.

Condition 2: Buried pipes 20-30 m or longer should be covered.

Among the methods examined in this study, the correlation coefficient method using the correlation function satisfies the mentioned above measuring conditions. We must examine the driving signal suitable for this method in the future.

5 Conclusion

For estimation the length of the carbon-steel pipe which city gas is mainly supplied through, we proposed three methods out of consideration of the decay of the acoustic waves under the condition of using acoustic waves. It is possible to correct such decay by any of the three methods proposed. However, considering the advantages, disadvantages, and future applications, the method using the correlation function (Method III) is the most advantageous among the three.

Gas pipes actually buried include not only straight pipes, such as those used in this experiment, but also pipes bent at right angles using joints. In the future, we would like to examine the decay in such pipes and correction methods for such decay.

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