A New Measuring Method for Underwater Displacement Utilizing Sound Signal* (Experimental Relationship between Sound Frequency and Displacement)

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This paper deals with a newly developed underwater displacement sensor utilizing the acoustic resonant frequency of water in a submerged pipe. Both ends of the pipe are closed. A speaker to generate sound is fixed on the end of the pipe with the reflector at the other end. A piezoelectric ceramic is used as a speaker. Sweeping signal is radiated from the speaker to the water column in the pipe. The sound pressure takes the largest value at the resonant frequency. The displacement of the reflector which is inserted from the other end of the pipe by the plunger, corresponds to the length of the water column. The displacement of the reflector has good correspondence to the resonant frequency of the water column. It is found from the experiment that it is possible to measure accurately underwater displacement using this sensor.

Key Words: Sensor, Measurement, Accuracy, Sound, Underwater Displacement, Resonance, Frequency, Speaker, Microphone

1. Introduction

Sensor technology using ultrasound has been applied in the fields of measurement, and communication, supported by the development of a piezoelectric ceramic used as an ultrasound source. The velocity of ultrasound is less than that of other carrier waves such as electromagnetic waves in liquid, thus the resolution of the measuring distance is improved at the same frequency. This means that the measurement accuracy with ultrasound is higher because of its shorter wavelength. Also, the measuring equipment used here is less expensive than those used in other methods. This study introduces a new measurement method of the distance utilizing the acoustic resonant frequency of water in a submerged pipe.

Ultrasound measurement in liquid is widely used to determine the distance, velocity, and physical properties of liquid, among others. This paper introduces a newly developed sensor, which allows measurement of the precise displacement of a substance in liquid utilizing the resonant frequency of ultrasound. The principle of the sensor for measuring the displacement in air reported previously⁽¹⁾ was applied to measure the displacement in water. In our experiments, pure water was used as the liquid medium.

The physical properties of the pure water are different from those of air. Several problems should be considered when water is used, for example, the vibration of the pipe wall caused by the sound pressure propagated from a sound source. In this study, the relationship between the resonant frequency and the underwater displacement is determined. Consequently, this method of measuring the underwater displacement is useful.

2. Principle of Measurement Method

A detailed drawing of the sensor measuring the displacement in water is shown in Fig.1. The sensor consists of a cylinder, a piston in contact with the measuring object, a microphone and a speaker. The

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length of the water column between the speaker and the reflector varies with the displacement of the measuring object. When the sound signal from the speaker travels through the pipe, a standing wave is generated by the interference between an incident wave and a reflection wave. The sound pressure at a certain frequency determined from the length of the water column resonates and increases to the maximum value. Thus the resonant frequency corresponds to the movement of the reflector which is in contact with the measuring object via a piston. The inner diameter of the pipe is considerably smaller than the wavelength of the sound. Under the assumption that the plane wave exists in the water column, the equation of the resonant frequency of the water column is

$$f = \frac{nc}{2L} \quad (1)$$

where f : resonant frequency

c : sound velocity in the submerged pipe

L : length of the water column

n : number of harmonics ($n=1, 2, 3, \dots$).

It is not possible to assume that the pipe wall is perfectly rigid because of the oscillation of the water column. This makes the sound velocity in the pipe smaller than that in the free field⁽²⁾. This result must be taken into consideration in the design of the sensor.

3. Design of the Acoustic Pipe

Since the compressibility of water is about 0.6×10^{-3} times smaller than that of air, the propagation of the sound wave in the water column contained in the pipe leads to vibration of the pipe wall, which in turn, decreases the sound velocity. This decrease of the sound velocity results in a decrease of the resonant frequency obtained from Eq. (1).

The sound velocity in water contained in the pipe is expressed in Eq. (2)^{(3),(4)}.

$$\frac{c}{c_0} = \left[1 + \frac{2\kappa}{E} \frac{(1+h/a)^2 + 1}{(1+h/a)^2 - 1} \right]^{-1/2} \quad (2)$$

c_0 : sound velocity in free field

a : inner radius of pipe

h : wall thickness of pipe

E : Young's modulus of pipe

Fig. 1 Detailed drawing of underwater displacement sensor

κ : bulk modulus of water

Therefore, the sound velocity in the pipe, which is given by Eq. (2), must be substituted into Eq. (1).

The sound velocity in water is given by the empirical formula of Greenspan-Tschiegg⁽⁵⁾.

$$c_0 = 1402.736 + 5.03358T - 0.0579506T^2 \\ + 3.31636 \times 10^{-4}T^3 - 1.45262 \times 10^{-6}T^4 \\ + 3.0449 \times 10^{-9}T^5$$

T : water temperature

Since this sensor utilizes the resonance of the water column in the pipe, the measurement accuracy is dependent on the Q factor which determines the resonant power. Namely, the Q factor is mainly determined by the vibration of the pipe wall. In the design of the sensor, attention must be paid to the Young's modulus and the wall thickness of the pipe in order to increase the Q -value.

Table 1 shows the dimensions of the acoustic pipe used in the experiment. The material of the pipe is SUS 304 which is a rust resistant material. The rigidity of the pipe is assumed to be sufficient because the decreasing ratio of the sound velocity in the tube is kept within 2%.

Figure 2 shows an enlargement of a portion of the sensor. Sensors were manufactured with various dimensions of the inner radius of the pipe (D) and the inner diameter microphone's hole (D_{mh}), but the length of the microphone's hole (L_{mh}) was kept constant at 0.5 mm for all experiments. Attention was paid to remove air bubbles in the pipe and to keep the water temperatures inside and outside of the pipe constant.

Table 1 Dimensions of acoustic pipe

	Inner Diameter of Pipe (mm)	Wall Thickness (mm)	$\frac{c_0 - c}{c_0} \times 100(\%)$
Pipe-1	$\phi 8$	4	2
Pipe-2	$\phi 6$	5	1.5

Fig. 2 Enlargement of a portion of the sensor

4. Experimental Equipment and Method

The structure of the speaker is shown in Fig. 3. A piezoelectric ceramic transducer is pasted to a plastic disk where the outer face acts as a radiation surface. A urethane foam is set on the other face of the piezoelectric ceramic in order to absorb the radiation of extra sounds. A silicone sealant is used to seal the open end of the plastic case. Table 2 shows the resonant frequency for each mode of the piezoelectric ceramic transducers A and B. Table 3 shows the combination of the transducer and the material of the plastic disk.

Figure 4 shows the schematic drawing of the experimental set up. In order to measure the frequency response of the sensor in water, sweeping sine wave signals from 0 to 100 kHz generated from the function generator are transmitted to the speaker and the input channel A of the FFT analyzer through an amplifier. The output voltage of the power amplifier is confirmed by the signals from the CH-A of the FFT analyzer in order to confirm the input voltage to the speaker.

The sound wave radiated into the pipe from the speaker assumes a stationary wave distribution corresponding to the length of the water column. The sound pressure in the pipe is detected by the microphone (B&K 8103) and this signal is input to the channel B of the FFT analyzer. Data obtained from the FFT analyzer are input to a personal computer.

The displacement of the measuring object can be determined from the digital counter interlocked to the precision micrometer which measures the displacement of the object. Thus, the correlation between the length of the water column in the pipe and the resonant frequency is obtained.

Table 2 Resonant frequency for each mode of piezoelectric ceramic transducers

	Radial Mode	Thickness Mode
A	—	140kHz
B	200kHz	1MHz

Table 3 Combination of transducer and material of plastic disk

	Piezoelectric Ceramic	Disk Material
Speaker-1	A	Epoxy resin
Speaker-2	B	Polyethylene
Speaker-3	B	Epoxy resin

5. Experimental Results

Figure 5 shows the results of the spectrum analyses for various lengths of the water column and

Fig. 3 Structure of piezoelectric ceramic transducer

Fig. 4 Schematic drawing of experimental setup

Fig. 5 Spectrum analyses of sound pressure using Sensor-1

Sensor-1 shown in Table 4. In Fig. 5, the length of the water column was varied every 1 mm in order to express clearly the moving resonant points. Resonant points 1 and 2 express the fundamental and second harmonics, respectively.

The + symbol in Fig. 6(a) shows the experimental results of the relationship between the length of the water column and the resonant frequency. The solid

Table 4 Specifications of sensors

	Speaker	D	Dmh
Sensor-1	Speaker-2	$\phi 8$	$\phi 1$
Sensor-2	Speaker-2	$\phi 6$	$\phi 1$

(a) Relationship between length of water column and resonant frequency

(b) Relationship between sound pressure and sound frequency at resonant point

Fig. 6 Experimental results of Sensor-1

lines show calculated values obtained from Eq. (1). It is apparent from Figs. 5 and 6(a) that the resonant frequency decreases regardless of the length of the water column for all harmonics. The variation of the length of the water column is equal to the displacement of the measuring object. Thus, the wide displacement in water can be derived from the variation of all resonant frequencies. Figure 6(b) shows the relationship between the sound frequency and the sound pressure for four harmonic tones $n=1\sim 4$.

When the resonant frequency increases to more than 55 kHz for Sensor-1, the sharpness of the peak at the resonant frequency gradually disappears and it becomes difficult to find the peak of the sound pressure. However, from the results using Sensor-2 which are shown in Fig. 7, sharpness of the peak is observed even up to the frequency of 69 kHz. It was also observed that there were certain frequency bands which resulted in unstable relationships between the resonant frequency and the length of the water column. The assumption that the plane wave travels in the pipe when the inner radius of the pipe is smaller than the wavelength is not applicable when the frequency becomes extremely high. Therefore, this problem may be solved by designing a pipe with a smaller inner radius with consideration of the transducer surface. Such a suitably designed pipe is expected to measure the displacement accurately.

Figure 8 shows experimental results of the relationship between the resonant frequency and the micro displacement using Sensor-1 and the running

Fig. 7 Relationship between length of water column and resonant frequency

zoom of the FFT analyzer. In the case of Fig. 8(a), the unit displacement and the frequency resolution are $50\text{ }\mu\text{m}$ and 15.625 Hz , respectively. In the case of Fig. 8(b), they are $10\text{ }\mu\text{m}$ and 7.8125 Hz , respectively. It became evident that this sensor could measure the underwater displacement with the accuracy of $10\text{ }\mu\text{m}$.

6. Interpretation

From the relationship between the length of the water column and the sound frequency shown in Figs. 6(a) and 7, the resonant frequencies tend to be discontinuous in some frequency bands. In Fig. 6(a), these discontinuities arise at the frequency to range of about 33 to 55 kHz. Similarly, in Fig. 7, they arise at about 35 to 50 kHz. The results of the spectrum analyses for Sensor-2 are shown in Fig. 9.

(a) Unit displacement quantity is $50\text{ }\mu\text{m}$

(b) Unit displacement quantity is $10\text{ }\mu\text{m}$

Fig. 8 relationship between micro displacement and resonant frequency using Sensor-1

Fig. 9 Spectrum analyses of sound pressure using Sensor-2

	Speaker	D	Dmh
+	Speaker-1	$\phi 8$	$\phi 1$
o	Speaker-2	$\phi 8$	$\phi 1$
◇	Speaker-3	$\phi 8$	$\phi 1$

(a) For three speakers

	Speaker	D	Dmh
o	Speaker-2	$\phi 8$	$\phi 1$
+	Speaker-2	$\phi 6$	$\phi 1$

(b) Effect of inner radius of pipe

Fig. 10 Comparison between experimental value and calculated value obtained from Eq. (1)

The peak of the resonant point 1 shown in Fig. 9 increases with the decrease of the length of the water column. This peak, however, moved towards another peak at about 35 kHz with the decrease of the sound pressure. On the other hand, the sound pressure of the peak appearing at about 35 kHz gradually increased. Therefore, it seemed that the peak frequency at about 35 kHz separated into two parts. Resonant point 2 shows a similar tendency.

Figures 10(a) and 10(b) show the deviation of the frequency ($\Delta f^* \equiv \text{experimental/calculated} - 1$) between the experimental value and the calculated value obtained from Eq. (1). Figure 10(a) shows the movement of the resonant frequency for the three speakers by using Pipe-1. It is found that the discontinuous frequency bands appear at about 35 to 55 kHz regardless of the harmonic tone.

Figure 10(b) shows the effect of the inner radius of the pipe (Pipe-1, 2) on the frequency by using Speaker-2. The discontinuous frequency band in Pipe-1 appeared at about 33 to 55 kHz regardless of the harmonic tone; however, in Pipe-2, it is found at about 35 to 50 kHz. From the above results, it became evident that the inner radius of the pipe influenced the discontinuous frequency band. Resonances in the radial and circular directions in the pipe may exist during these frequency bands. This consideration may be supported by the phenomenon that the separation of the resonant peak is due to the combination of the vibrations in vertical and lateral directions of the piezoelectric transducer.

For this new underwater displacement sensor, the temperatures of water inside in the pipe and the ambient are assumed to be the same. If a temperature difference exists, a correction will be required. There is another problem caused by the presence of air bubbles in water, which prevents propagation of the sound wave and thus the resonant peak will not appear. Therefore, it is necessary to remove the bubbles to obtain accurate results.

7. Conclusions

When a sound wave propagates in the pipe in water, the resonance corresponding to the length of the water column can be observed. The resonant frequency depends upon the length of the water column which varies with the displacement of the

measuring object.

A new measurement method of the underwater displacement applying this phenomenon was designed and experimental results were obtained. The conclusions are as follows.

(1) A new measurement method of underwater displacement using sound frequency was developed. It was clarified that this method can measure the underwater displacement with high accuracy for a wide measurement range.

(2) The accuracy of the measurement sensor of this method can be kept within $10\mu\text{m}$.

(3) Measurement of the displacement in liquid is difficult compared with that in air; however, this method features the use of simple and inexpensive equipment.

(4) This measurement method can be applied to other liquids such as heavy oil where the measuring object could not be observed from the outside.

Acknowledgments

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