Development of Vibration Sensor with Wide Frequency Range Based on Condenser Microphone -Estimation System for Flow Rate in Water Pipes-

Hironori Kakuta, Kajiro Watanabe, and Yosuke Kurihara

Abstract—Water leakage is a serious problem in the maintenance of a waterworks facility. Monitoring the water flow rate is one way to locate leakage. However, conventional flowmeters such as the wet-type flowmeter and the clamp-on type ultrasonic flowmeter require additional construction for their installation and are therefore quite expensive. This paper proposes a novel estimation system for the flow rate in a water pipeline, which employs a vibration sensor. This assembly can be attached to any water pipeline without the need for additional high-cost construction. The vibration sensor is designed based on a condenser microphone. This sensor detects vibration caused by water flowing through a pipeline. It is possible to estimate the water flow rate by measuring the amplitude of the output signal from the vibration sensor. We confirmed the validity of the proposed sensing system experimentally.

Keywords—Condenser microphone, Flow rate estimation, Piping vibration, Water pipe.

I. INTRODUCTION

WATER is an indispensable element in human life and its demand increases in proportion to economic growth. In Asia, water demand was 2,231km^3/year in 1995, and it is said that this demand will exceed 3,254km^3/year in 2025 [1]. In Tokyo, Japan, the water supply pervasion rate is 100% and its total distribution is 156,557×10^{4}m^3 per year [2]. Since an efficient and uninterrupted water supply provides the basis for citizens' well-being and a productive economic growth, the Waterworks Bureau strives for a well-maintained waterworks facility and an efficient water distribution system. One of the factors responsible for in efficient water distribution is leakage caused by defective pipelines; further, 14,578 cases of water leakage were reported to occur every year in Tokyo [2]. Furthermore, in 97.2% of the total water leakage cases, leakage occurs from service pipes that supply water to the end consumers [3]. In most cases, however, this water leakage from pipelines goes unnoticed until the general consumers receive hefty water bills or notice leakage on their walls. Since late detection of water leakage leads to increased damages, it is essential that leakage be detected as early as possible to prevent these damages. The Waterworks Bureau uses several methods to detect leakage in pipelines, for example, the acoustic leakage sound detection method, which measures piping vibration as sound at midnight; the cross-correlation flowmeter method, which detects leakage sounds at two points and determines the time difference between them [4]; the acoustic emission method, which detects a leak from a metal with a high-frequency sensor [5]; and the magnetic flowmeter method [6]. However, since these methods can be applied to detect the precise leakage location only after a leakage is detected by the consumer, they are inappropriate as methods for early detection of water leakage.

Given these circumstances, methods that monitor the water flow rate using a flowmeter have been proposed for early detection of water leakage [7]. By these methods, it is possible to detect water leakage by comparing the flow rates under normal conditions with those under a water leak. However, a wet-type flowmeter requires additional construction to be installed into pipelines. Furthermore, although clamp-on type ultrasonic flowmeters can easily measure the flow rate, they are too expensive to install in ordinary households.

This paper proposes a novel estimation system for flow rate, which measures piping vibrations caused by changes in the water pressure. The vibration sensor employed in the proposed system has been developed based on a condenser microphone. Although the condenser microphone is actually an acoustic sensor, it can also measure the pressure or acceleration [8], and the proposed system can be easily installed into a water pipe. Furthermore, since the construction is simple, it does not cost as much as the wet-type flowmeter and the clamp-on type ultrasonic flowmeter.

II. METHOD

A. Description of Model Variables

Here, we describe the mathematical model of water flowing in a pipeline and determine the relation between the water flow rate and the pressure in the pipeline. The variables used in our model are defined as follows.

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General variables:
g : gravitational acceleration[m^2/s]
T : sampling time[s]
Pipeline variables:
ρ : density of water[kg/m^3]
μ : viscosity of water[(N/m^2)·s]
d_p : diameter of pipeline[m^2]
Condenser microphone variables:
[Mechanical factors]
M : mass of pickup and pressured film[kg]

m : mass of electret film [kg]
C : damping factor of pickup and pressured film [N/(m/s)]
c : damping factor of electret film[N/(m/s)]
K : spring constant of pickup and pressured film [N/m]
k : spring constant of electret film[N/m]
k_f : air spring constant in front of electret film[N/m]
k_b : air spring constant at the back of electret film[N/m]
x_p : displacement of pickup and pressured film[m]
x_e : displacement of electret film [m]
γ : ratio of air specific heat
p_{in} : input pressure[N/m^2]
P_0 : atmospheric pressure head [N/m^2]
P_f : atmospheric pressure in enclosure in front of electret film [N/m^2]
P_b : atmospheric pressure in enclosure at the back of electret film [N/m^2]
S_p : cross-sectional area of pickup[m^2]
S_c : cross-sectional area of enclosure [m^2]
S_e : cross-sectional area of electret film[m^2]
d_e : distance between electrode and electret film [m]
h_f : length between pressured film and electret film[m]
h_b : length between electrets film and enclosure termination[m]
C_l : loss coefficient
[Electrical factors]
Q_e : permanent electric charge of electrets film [C]
ε : dielectric constant [N/V]
e_c : input voltage to FET[V]
Cc : capacitance of FET[C/V]
R_c : input impedance of FET[Ω]
G : gain of FET

B. Model of Water Flow and Distribution of Piping Vibration
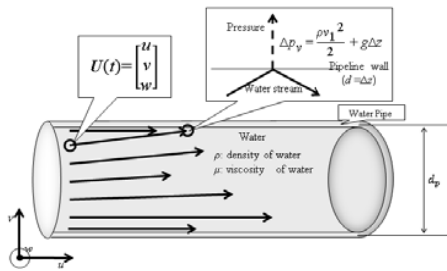
Fig. 1 shows the model of water flow in a pipeline.

Fig. 1 Model of water flow in a pipeline

In this model, we assume the following:

1) Water is an incompressible fluid and its density is constant.

2) The pipeline is completely filled with water.

Since water is a low-viscosity fluid, the flow is turbulent when the water flow rate is low. The Reynolds number, given by (1), is used to determine whether the flow is turbulent or laminar.

$$R_e = \frac{\rho d_p}{\mu} u \tag{1}$$

When $Re > 2320$, the water flow is turbulent. Water swirl caused by the turbulent flow generates fluctuation of internal water pressure. Owing to this pressure fluctuation, an external vibration force acts on the pipe wall [9]. Further, the velocity of the water is in not only the main stream direction but also the direction vertical to the wall. Let $U(t)$ be the velocity vector whose elements are three-dimensional velocities given as follows.

$$U(t) = \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{2}$$

u is the velocity component in the direction of the main stream flow. U is sum of $\bar{u}$ and u'.

$$u = \bar{u} + u' \tag{3}$$

$\bar{u}$ and u' are calculated as in (4) and (5) with adequately long T.

$$\bar{u} = \frac{1}{T} \int_0^T u \cdot dt \tag{4}$$

$$\bar{u}' = \frac{1}{T} \int_0^T u' \cdot dt = 0 \tag{5}$$

Moreover, the direction of the velocity component v is the same as the direction of gravity, and the direction of the velocity component w is defined as the horizontal direction. v and w are calculated using the following equations.

$$v = v' \tag{6}$$

$$\bar{v}' = \frac{1}{T} \int_0^T v' \cdot dt = 0 \tag{7}$$

$$w = w' \tag{8}$$

$$\bar{w}' = \frac{1}{T} \int_0^T w' \cdot dt = 0 \tag{9}$$

Velocity components v and w become 0 near the pipeline wall because these directions are interrupted by the pipe wall. In this model, the water flow velocity obeys Bernoulli's principle as expressed in (10).

$$\frac{v^2}{2} + \frac{p}{\rho} + gz = \text{const.} \tag{10}$$

Velocities in the area adjacent to the pipe wall are v_1 and w_1. Internal water pressures are p_{v1} and p_{w1}. External pressures on the pipe wall are p_{v2} and p_{w2}. Z coordinates are z_1 and z_2. These are expressed in equation form as (11) and (12). v_2 And w_2 in (11) and (12) are omitted because v_2 and w_2 are 0.

$$\frac{v_1^2}{2} + \frac{p_{v1}}{\rho} + gz_1 = \frac{p_{v2}}{\rho} + gz_2 \tag{11}$$

$$\frac{w_1^2}{2} + \frac{p_{w1}}{\rho} = \frac{p_{w2}}{\rho} \tag{12}$$

When $\Delta p_v = p_{v2} - p_{v1}$, $p_w = p_{w2} - p_{w1}$, $\Delta z = z_2 - z_1$ are substituted in (11) and (12), equations related to pressure are obtained as (13) and (14). These show that the pressure fluctuation depends on the velocity in the area adjacent to the pipe wall.

$$\Delta p_v = \frac{\rho v_1^2}{2} + g\Delta z \qquad (13)$$

$$\Delta p_w = \frac{\rho w_1^2}{2} \qquad (14)$$

Here, we solve (13) and(14) for v and w; this is done as shown in (15) and(16), respectively.

$$v_1 = \sqrt{2 \cdot \frac{\Delta p_v - g\Delta z}{\rho}} \qquad (15)$$

$$w_1 = \sqrt{2 \cdot \frac{\Delta p_v}{\rho}} \qquad (16)$$

The flow velocity in the main stream direction is given as in(17).

$$u_1 = \sqrt{2 \cdot \frac{\Delta p_u}{\rho}} \qquad (17)$$

Values of v and w velocities fluctuate in the original fluid energy range as long as there is no external force. Therefore, the relationship between fluid energy and velocities is given as in(18).

$$|U(t)| = \sqrt{u^2 + v^2 + w^2} \qquad (18)$$

Eq.(18) is translated from (15)–(17) and expressed as in (19).

$$|U(t)| = \sqrt{\frac{2}{\rho}(\Delta p_u + \Delta p_v + \Delta p_w - g\Delta z)} \qquad (19)$$

Therefore, we consider that Δp_v and Δp_w are related to the piping vibration, which is proportional to the water flow energy. Moreover, v and w fluctuate irregularly with time; velocity fluctuation frequency appears as the vibration frequency. The frequency characteristic of piping vibration is scattered over a wide range. In particular, the output frequency response is accentuated at the resonant frequency of a piping system, which comprises components of various materials and shapes [10].

Hence, the vibration sensor in the proposed system must be sensitive to a wide frequency range to be able to accurately measure the piping vibrations caused by water flow.

The flow rate Q in the pipeline is given by(20).

$$Q = C_l \cdot (d_p^2 \pi) \cdot u \qquad (20)$$

The relationship between pressure fluctuation and flow rate is given by(21).

$$Q = C_l \cdot \left(\frac{d_p}{2}\right)^2 \cdot \pi \sqrt{2 \cdot \frac{\Delta p_u}{\rho}} \qquad (21)$$

The flow rate determined from the weight of water, q, and the measurement time T is given by(22).

$$Q = \frac{1}{\rho} \cdot \frac{q}{T} \qquad (22)$$

C. Structure of Condenser Microphone

Here, we describe the design of a vibration sensor device that is sensitive to a wide frequency range. Fig.2 shows the structure of a condenser microphone. In order to construct a mathematical model of a condenser microphone, we assume the following.

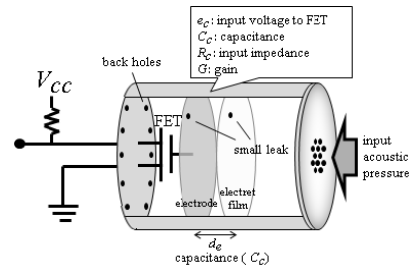3) Pressure fluctuation in the condenser microphone is an adiabatic change.

Fig. 2 Structure of a condenser microphone

D. Structure of Condenser Microphone as Vibration Sensor

Fig. 3 shows an enclosed condenser microphone used as a vibration sensor. A general directional microphone has a hole on both its front and back sides for directivity.

We cover the chamber with the pressured film in order to enclose the atmospheric pressure in the chamber and attach the pickup to the center of the pressured film to use it as a vibration sensor. The pressured film is vibrated by input vibration pressure p_{in} and the vibration is transferred to an air spring by internal atmospheric pressure fluctuation, which vibrates the electret film.
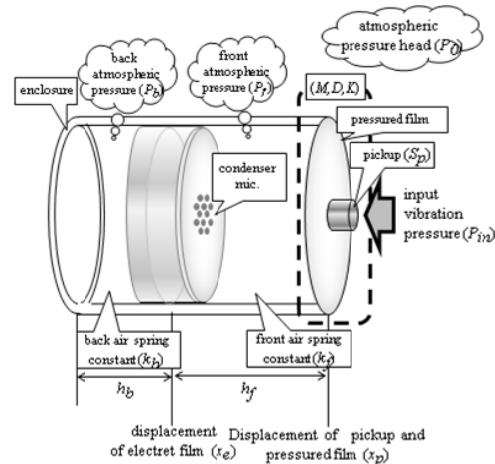

Fig. 3 Structure of an enclosed condenser microphone as vibration sensor

The equation for the motion of the pickup and pressured film is given as in(23).

$$M\frac{d^2x_p(t)}{dt^2}+C\frac{dx_p(t)}{dt}+Kx_p(t)=S_p p_{in}-k_f(x_p(t)-x_e(t)) \qquad (23)$$

The equation for electret film motion is given as in (24).

$$m\frac{d^2x_e(t)}{dt^2}+c\frac{dx_e(t)}{dt}+kx_e(t)=k_f\left(x_p(t)-x_e(t)\right)-k_b x_e(t) \qquad (24)$$

Since the pressure fluctuation in the condenser microphone is an adiabatic change as mentioned above(in assumption 3), the air spring coefficients k_f and k_b can bewritten as (25) and(26).

$$k_f=\gamma P_f\frac{S_c}{h_f\text{-}(x_p(t)-x_e(t))} \qquad (25)$$

$$k_b=\gamma P_b\frac{S_c}{h_b-x_e(t)} \qquad (26)$$

Ideal gas law, given by (27), is valid under assumption 3).

$$PV=\text{const.} \qquad (27)$$

Then, the internal pressures in the chamber,P_f and P_b, are given by(28) and(29)

$$P_0 S_c h_f=P_f S_c(h_f-(x_p(t)-x_e(t))) \qquad (28)$$

$$P_0 S_c h_b=P_b S_c(h_b-x_e(t)) \qquad (29)$$

Equations for the microphone capacitor and FET input resistor are given by(30)–(32).

$$e_c(t)=\frac{Q_e}{\varepsilon S_e}\left(d-x_e(t)\right) \qquad (30)$$

$$\frac{1}{Cc}\int i(t)dt+R_c i(t)=e_c(t) \qquad (31)$$

$$e(t)=R_c i(t) \qquad (32)$$

The output voltage from the FET is given by(33).

$$e_{out}(t)=Ge(t) \qquad (33)$$

E. Processing of Waveform Signal

We integrate the waveform over time t_1 to t_2 and define this as an index P given by(34).

$$P = A\cdot\int_{t_1}^{t_2}|e_{out}(t)-e_0|dt \qquad (34)$$

Moreover, P is passed through high-pass filter to remove the direct current, and the output from the high-pass filter,P_{out},is given by(35).

$$P_{out}=P-\frac{\sum_{i=1}^{n}P}{n} \qquad (35)$$

n isthe number of data points in the interval of integration;e_0 is the median in the interval of integration to cancel the offset voltage and outlier influence in (34) and (35), respectively.

P_{out} Corresponds to $\Delta p_u.A$ is a trophic coefficient between the theoretical value Q and the index P_{out} and is determined experimentally.

III. VALIDATION EXPERIMENT

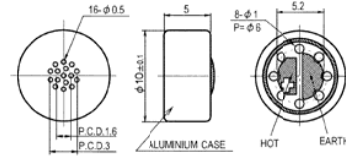*A. Experimental Setup and Procedure*

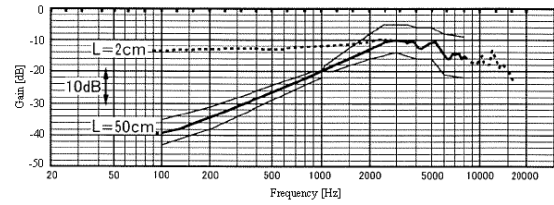

Fig. 4 General condenser microphone EM114

Fig. 5 Frequency response of EM114

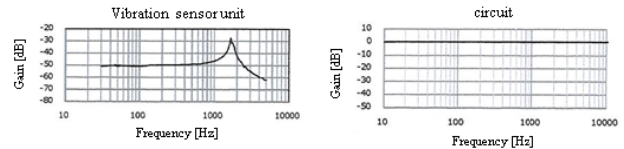Fig. 6 Vibration sensor unit and amplifier

Fig. 7 Frequency characteristics of proposed system

Fig. 4 shows a general condenser microphone (EM114, PRIMO CO.), and Fig. 5 shows its frequency characteristic. It is difficult to measure a low-frequency-range signal with a general condenser microphone.

We developed the vibration sensor based on the mathematical model shown in Fig.3. Fig. 6 shows the proposed vibration sensor unit and its amplifier. Fig. 7 shows the frequency characteristics of the developed vibration sensor unit and amplifier. As shown Fig. 7, this sensor unit is able to measure signals over a wide frequency range and its internal structure is very simple. Therefore, it is costless than a conventional flow meter.
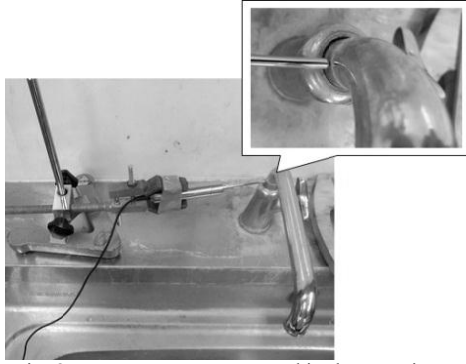
Fig. 8Measurement system used in the experiment

Fig. 8 shows the measurement system used in the experiment. The vibration sensor is fixed to the faucet in front of the elbow.

We performed an experiment to investigate the relationship between the flow rate and the amplitude of piping vibration. The output voltage of the proposed vibration sensor was sampled by a data logger (NR-2000, KEYENCE Co.) after being amplified. The sampling frequency was 5 kHz.

B. Parameter Settings

We used the values of parameters in this experimental environment to calculate the Reynolds number as per (1). The water viscosity μ was $1.004 \cdot 10^{-3} \, \text{m}^2/\text{s}$ at 20 °C and the density ρ was $0.998 \cdot 10^3 \, \text{kg}/\text{m}^3$; hence, the Reynolds number R_e was calculated as $R_e \cong 13 \cdot 10^3 \cdot u$. Therefore, when $Q > 23.61 \cdot 10^{-6}$ and also $u > 0.178$ m/sand Reynolds number $Re > 2320$, thewater flow is turbulent. We substituted $d_p = 13 \cdot 10^{-3}$ m, $\rho = 1000 \text{kg}/\text{m}^3$, and $C_l = 1$ in(21) to calculate the flow rate as (36).

$$Q = \frac{4225}{\sqrt{500}} \cdot 10^{-5} \cdot \sqrt{\Delta p_u} \qquad (36)$$

We assumed that the flow rate has no loss factor in this experiment and the loss coefficient is $C_l = 1$. Therefore, the pressure fluctuation Δp_u is calculated as (37).

$$\Delta p_u = \frac{1}{169} \cdot 10^9 \cdot Q^2 \qquad (37)$$

Although (37) is related to Δp_u, it is possible to apply it to Δp_v and Δp_w because the fluctuation components of turbulent flow velocity vectors increase or decrease irregularly.

C. Experimental Procedures and Signal Processing

We measured the faucet vibration using the vibration sensor for a flow rate ranging from 0 L/sto0.20 L/s per 0.05L/s (approximately), and we simultaneously measured the flow time.

Then, with the approximate values of $\rho = 1000 \text{kg}/\text{m}^3$ and $q = 1.0 \times 10^{-3} \text{kg}$, the flow rate was calculated from each flow time T in which the water fills up to 1.5×10^{-3} kg.

The output voltage of the vibration sensor was translated to pressure in the water pipeline using (34) and (35). In this experiment, t_1 was set to 5s, which was decided by the time the water flow began, and t_2 lagged t_1 by 1 s in each case. Thus, we substituted the pressure in(36) and were able to estimate the flow rate Q.

IV. RESULTS

Figs. 9 and 10 show the output waveforms and spectra of the vibration sensor at Q of 0.029 L/s and 0.058 L/s, respectively. The water flow was turbulent in each case.

The water flowed between approximately 5 s and 57s in Fig.9 (a) and between approximately 5 s and 32 s in Fig.10 (a). Very large impulse-like responses can be seen at 5s and 57s in Fig.9 (a) and at 5s and32s in Fig.10 (a). We assume that this response is caused by the vibration that occurred owing to the turning of the faucet's bulb. Moreover, larger amplitude than that in the steady state is found between these impulses. We confirm that this sensor can certainly detect piping vibration due to the water flow because it hardly responded to any environmental noise such as voice or atmospheric pressure fluctuation. Moreover, the amplitude at 0.058 L/s is larger than that at 0.029 L/s and we believe that this result demonstrates the proportional relationship between the amplitude and flow rate.

The spectra shown in Fig. 9(b) and Fig. 10(b) demonstrate that the proposed sensor is able to measure a wide range of frequencies, including very low frequencies, without direct current.
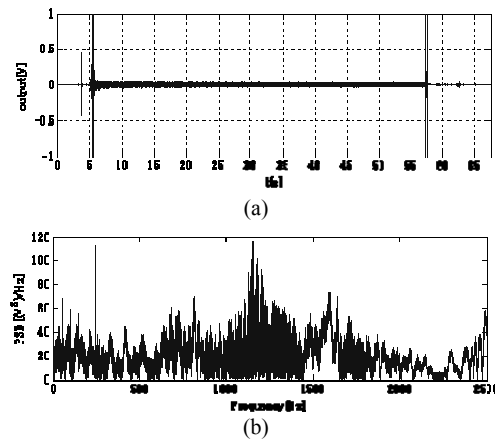

(a)

(b)

Fig.9 (a)Output voltage waveform and (b) spectrum at a flow rate of 0.029 L/s
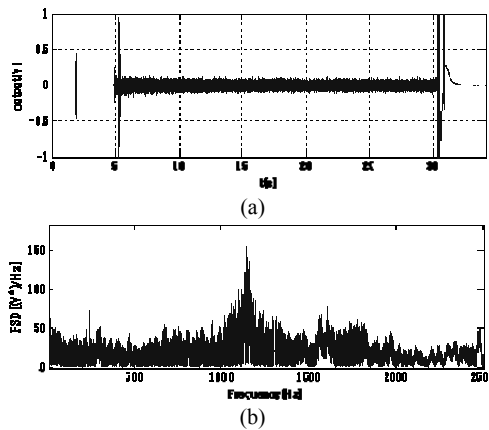
(a)

(b)

Fig. 10(a) Output voltage waveform and (b) spectrum at a flow rate of 0.058 L/s

Fig. 11 shows the scatter diagram between the flow rate Q and the output index P_{out}. Eq. (37) is plotted in Fig.11 as a solid line. The trophic coefficient is taken as $A = 5.0 \times 10^5$.

Experimental data are fitted to the theoretical curve between 0–0.12L/s and 0.18–0.20L/s.

Between 0.12L/s and 0.18 L/s, the error becomes larger than that between 0–0.12L/s and 0.18–0.20L/s.

We consider that our mathematical model based on Bernoulli's principle is useful for measuring the piping vibration. Furthermore, it is possible to estimate the water flow rate from the output voltage of the vibration sensor.
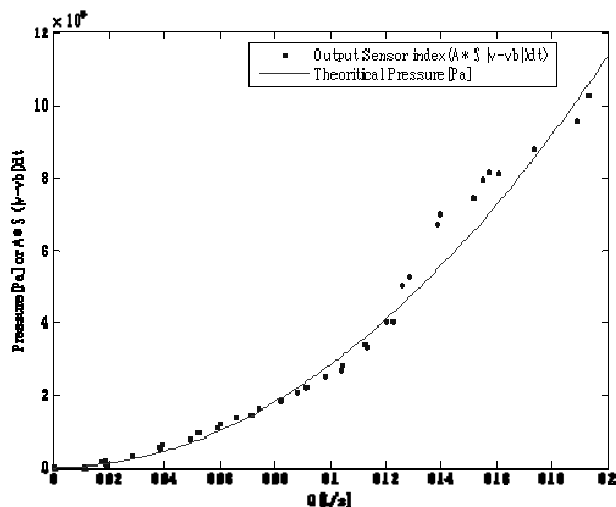

Fig. 11 Scatter diagram between flow rate Q and output index P_{out}

V. DISCUSSION

We observed a large output voltage at approximately 0.20L/s, accompanied by the occurrence of very high-frequency sound.

In this case, since the error becomes large, the trophic coefficient needs to be modified to a more suitable value.

According to Fig. 9(b) and Fig. 10(b), the proposed sensor is able to detect the vibration over a wide frequency range. Hence, it is capable of identifying whether a pipeline is clogged in terms of the frequency response changes.

VI. CONCLUSION

This paper proposes an estimation system for the water flow rate in pipelines that uses a vibration sensor sensitive to a wide frequency range; this sensor is based on a condenser microphone. From experimental results, we confirmed that the proposed sensor is able to detect piping vibration in a water flow and it is possible to estimate the flow rate between 0L/s and 0.20L/s. However, output voltage fluctuates considerably over 0.20 L/s.

Early and easy detection of water leakages facilitated with the proposed system. However, actual leakage or clogging detection and the accuracy of the proposed sensor remain to be verified.

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