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EVALUATION OF ATTENUATION OF ULTRASONIC WAVE IN AIR TO MEASURE CONCRETE ROUGHNESS USING AERIAL ULTRASONIC SENSOR

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ABSTRACT: In Japan, the total length of the main concrete agriculture irrigation canals is estimated to be about 50,000 km. These canals deteriorate over time and most of the canal surface has become rough. One method of measurement of the roughness of the concrete surface is by the aerial ultrasonic sensor. As far as the literature is concerned, no study of the use of 42-kHz sensors for the evaluation of ultrasonic attenuation during air propagation has been conducted. The aim of this study is to evaluate and correct the attenuated values of an ultrasonic wave. In this paper, the reflected wave of the ultrasonic wave was measured under different conditions of temperature, humidity, and atmospheric pressure with a smooth board and a rough board. These were corrected by using the ISO9613-1 equation. It is concluded that the relative error of the corrected value is small when compared with the measured value. The results of this study reveal that correction using the ISO9613-1 equation for attenuation of the 42-kHz ultrasonic wave is an effective method.

Keywords: Attenuation of aerial ultrasonic, ISO9613-1, Concrete surface roughness, Aerial ultrasonic sensor

1. INTRODUCTION

Japan has many concrete irrigation canals, which are mainly used for agriculture and have a total length of 49,239 km. When lateral canals are included, the total length amounts to about 400,000 km. These canals were constructed after the high economy era of 1954–1973 and have become too old for work. The cost of reconstructing the canals is too high. The government needs to repair old canals; in other words, it has promoted a policy of “stock management” in Japan. Stock management means improving the life of the facility by appropriate inspection.

The concrete surface of the canals is worn out by water and sand flows and becomes rough. The roughness of the concrete surface causes a decline in the water flow function. If the water flow function of the canal declines, there is a decrease of the flow velocity and a rise in the water level. As a result, irrigation water will not reach the end of some lateral canals. However, a method of measurement of the roughness of the concrete surface of irrigation canals has not yet been established. The roughness of the concrete surface is generally by the arithmetical mean roughness (ISO 25178).

Over the years, considerable attention has been paid to the study of measurement of the arithmetical mean roughness. Scientists have proposed the following methods of measuring the arithmetical mean roughness.

Sand patch test: This is one of the most commonly used methods of examining the macrotexture depth of concrete surfaces. This direct volumetric method consists in careful application of a given volume of granular materials (glass spheres or sand) of given granulometry onto the surface and subsequent measurement of the total area covered. The sand patch test is exposed to a greater probability of human error; it is a test that cannot be performed quickly without comprising accuracy [1], [2].

Concrete surface profiles (CSPs): This method is based on the visual inspection of the prepared surface, which is compared with nine standard CSPs of increasing roughness [3].

Outflow meter: This is a volumetric method used to assess the surface roughness of asphalt and concrete road pavements. The method gives an average value for the surface roughness but no other additional information [1], [4].

Moulage gauge method: This method allows the arithmetical mean roughness to be measured. It is a simple measurement method, since managers’ only pushes the moulage gauge to the concrete surface. However, managers need complication analysis that read the displacement from one by one the moulage gauge [5], [6].

Laser displacement sensor method: This method allows the arithmetical mean roughness to be measured. The measurement range of this method is line information of the concrete surface. This method has high precision, but measuring irrigation canals in this way is expensive [7], [8].

Aerial ultrasonic sensor: This method allows the arithmetical mean roughness to be measured and was developed by the authors. The frequency used was 42 kHz. The measurement range from 1000 mm height can measure a diameter of about 600 mm and from 550 mm height can measure a diameter of about 300 mm. One of these sensors can be bought for about 25 USD, and therefore this is an economical way of measuring canals [10].

The aerial ultrasonic sensor method is economical, wide range, and simple. However, a measured value of the aerial ultrasonic wave during propagation in air declines at wind velocities over 6 m/s. Similarly, the authors considered that propagation of an aerial ultrasonic wave in the air causes attenuation under different atmosphere conditions. The theory of this phenomenon is defined by ISO9613-1 [11]. However, the applicable range of frequencies is defined as 50 Hz to 10 kHz. Therefore the authors have used a 42-kHz sensor is over a range in ISO9613-1. Furthermore, there are no studies focusing on reflected waves. The attenuation of aerial ultrasonic waves is a problem when measuring the roughness of a concrete surface. This is the reason why the measured value changes under different conditions. The purpose of this study is to evaluate and correct the attenuated value of the ultrasonic wave.

2. MATERIALS AND METHOD

2.1 Aerial Ultrasonic Sensor

An LV-Maxsonar-EZ1 (MaxBotic, Inc.) was used as the aerial ultrasonic sensor. The sensor is designed the ultrasonic range finder. The frequency selected was 42 kHz. The sensitivities of the open type (minimum sensitivity = –80.5 dB) and the waterproof type (minimum sensitivity = –58.2 dB) were compared. The open type has 13 times higher sensitivity than the waterproof type at each output voltage. So, the open type was selected. But the measurement of the aerial ultrasonic wave must limit not to get wet. Table 1 shows other specifications. The aerial ultrasonic sensor was attached to a horn. The horn was attached in order to increase the wave of the aerial ultrasonic. It was made of resin and was made by the 3D printer. Figure 2 shows an example with the horn attached to the sensor. The measurement value was acquired by a TBS1152 digital oscilloscope (Tektronix, Inc.).

Table 1 Specification of aerial ultrasonic sensor

Frequency		42	kHz
Dimensions	A	16.4	mm
	B	15.5	mm
	C	19.9	mm
	D	22.1	mm
Weight		4.3	grams

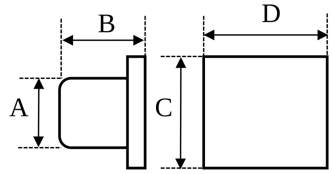

Fig. 1 Aerial ultrasonic sensor

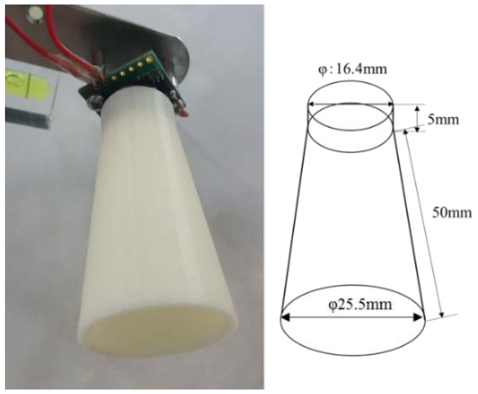

Fig. 2 Horn used to magnify sound

2.2 Thermometer and Hygrometer

A TR-73U thermometer and a TR-72wf-H hygrometer (both from T&D Corporation, Inc.) were used. The measuring range of the thermometer is –30 to 80°C, and that of the hygrometer is 0 to 99 humid. These sensors can record the data internally and send them to a PC with a USB connection.

Fig. 3 Thermometer and hygrometer (TR-72wf-H)

2.3 Concrete Board

A concrete board was made for this experiment through the cooperation of the Maruei Concrete Industry Co. The board’s dimensions were a length of 700 mm, a width of 700 mm, and a height of 50 mm. The weight of this board was 45 kg. We prepared two types of roughness. The first type of arithmetical mean roughness was 0.04 mm. The condition of the concrete surface was smooth. In this study, the first type was called a smooth board. The second type of arithmetical mean roughness was 1.04 mm. The condition of the concrete surface was rough. In this study, the second type was called a rough board.

2.4 Experimental Method

The measuring materials were set up as shown in Fig. 4. The aerial ultrasonic sensor was set at a height of 1000 mm height from the concrete board. The hygrothermograph was set at heights of 0 and 500 mm from the concrete board. The ultrasonic data were acquired under different conditions of temperature and humidity. We obtained measured values of the reflected wave, temperature, humidity, and air pressure. The measured value was the voltage (mV) from peak to peak of the reflected wave. The roughness of concrete was estimated from the measured value of the reflected wave. A preceding study (2016) showed the relationship between the measured value and the roughness of concrete [10].

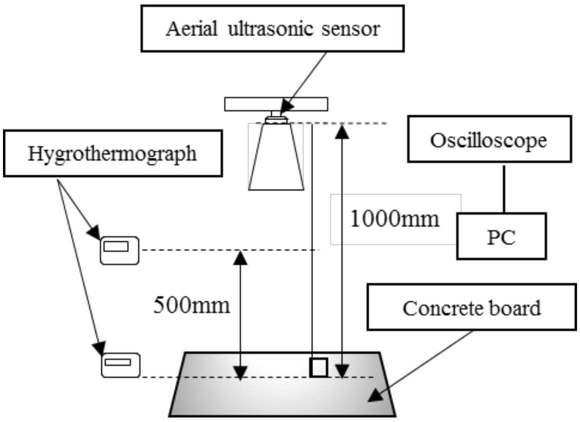

Fig. 4 Experimental system

3. THE ATTENUATION OF ULTRASONIC DURING PROPAGATION IN AIR

The attenuation of sound during propagation in the air was standardized by ISO 9613-1 in 1993. This standard considers noise problems of urban environmental noise and airplane noise. The absorption of sound during the air is due to shear viscosity, thermal conductivity or heat dissipation, and molecular relaxation due to oxygen, nitrogen, and water vapor vibrational, rotational, and translational energy. The attenuation of sound varies significantly with temperature, water vapor content, and frequency. The ranges specified by the standard are as follows:

- Frequency from 50 Hz to 10 kHz
- Temperature from –20 to +50 °C
- Relative humidity from 10 to 100%
- Pressure of 101,325 kPa (one atmosphere)

Equations are provided for wider ranges suitable for particular; however, the frequency of 42 kHz at which the aerial ultrasonic wave was used is over the range.

3.1 Calculation

Equation (1) is the basic equation of attenuation. The sound pressure $\boldsymbol{p_t}$ is exponentially attenuated from the sound pressure $\boldsymbol{p_i}$ by absorption in the air.

$$\boldsymbol{p_t = p_i \exp(-0.1151\alpha s)} \quad (1)$$

The attenuation of the pressure level $\boldsymbol{\delta L}$ is described using the coefficient $\boldsymbol{\alpha}$ and propagation distance in the air.

$$\boldsymbol{\delta L = 10\log\left(\frac{p_i^2}{p_t^2}\right) = \alpha s\ [dB]} \quad (2)$$

$$\boldsymbol{\alpha = 8.686 f^2 \left(\left[18.4 \times 10^{-11}\left(\frac{p_a}{p_r}\right)^{-1}\left(\frac{T}{T_0}\right)^{\frac{1}{2}}\right] + \left(\frac{T}{T_0}\right)^{-5/2} \times \left\{0.01275\left[exp\left(\frac{-2239.1}{T}\right)\right]\left[F_{rO} + \left(\frac{F^2}{F_{rO}}\right)^{-1}\right] + 0.1068\left[exp\left(\frac{-3352.0}{T}\right)\right]\left[F_{rN} + \left(\frac{F^2}{F_{rN}}\right)\right]^{-1}\right\}\right)} \quad (3)$$

$$\boldsymbol{m = \alpha/(20\log_{10} e)\quad [1/m]} \quad (4)$$

The attenuation is a function of the relaxation frequency of molecular oxygen $\boldsymbol{F_{rO}}$ and the relaxation frequency of molecular nitrogen $\boldsymbol{F_{rN}}$.

$$\boldsymbol{F_{rO} = \left(\frac{p_a}{p_r}\right)\left(24 + 4.04 \times 10^4 h \frac{0.02+h}{0.391+h}\right)} \quad (5)$$

$$\boldsymbol{F_{rN} = \left(\frac{p_a}{p_r}\right)\left(\frac{T}{T_0}\right) -\frac{1}{2}\left[9 + 280h\exp\left\{-4.170\left[\left(\frac{T}{T_0}\right)^{-\frac{1}{3}} - 1\right]\right\}\right]} \quad (6)$$

$\boldsymbol{h}$ is the molar concentration of water vapor as a percentage and $\boldsymbol{h}$ is calculated from the relative humidity as follows:

$$\boldsymbol{h = p_{s0}\left(\frac{h_r}{p_s}\right)\left(\frac{p_{sat}}{p_{s0}}\right)}\ [\%] \quad (7)$$

$$\boldsymbol{p_{sat}} = \boldsymbol{p_{s0}} \times \mathbf{10}^{-6.8346\left(\frac{T_{01}}{T}\right)^{1.261}+4.6151} \quad (8)$$

where

$\boldsymbol{F}$: Frequency of sound, in hertz
$\boldsymbol{h}$: Molar concentration of water vapor, as a percentage
$\boldsymbol{p_r}$: Reference ambient atmospheric pressure, in kilopascals
$\boldsymbol{p_i}$: Initial sound pressure amplitude, in pascals
$\boldsymbol{p_t}$: Sound pressure amplitude, in pascals
$\boldsymbol{p_a}$: Ambient atmospheric pressure, in kilopascals
$\boldsymbol{s}$: Distance, in meters, over which the sound propagates
$\boldsymbol{T}$: Ambient atmospheric temperature, in kelvins
$\boldsymbol{T_0}$: Reference air temperature, in kelvins
$\boldsymbol{\alpha}$: Pure tone sound attenuation coefficient, in decibels per meter, for atmospheric absorption

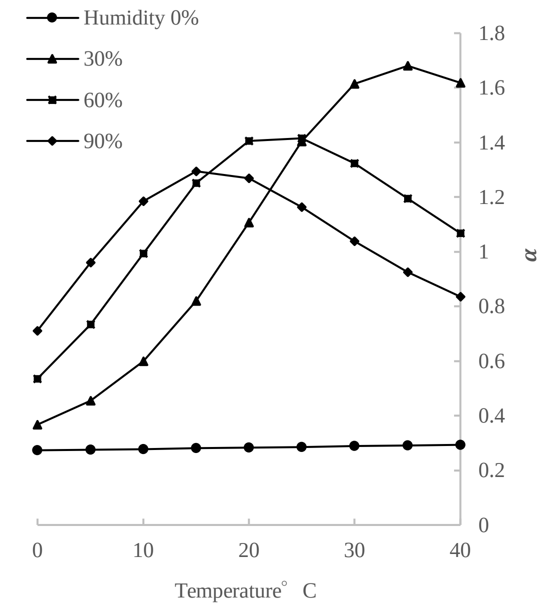

Fig. 5 Relation between $\boldsymbol{\alpha}$ and temperature

4. RESULTS AND DISCUSSION

4.1 Measurement Result of Attenuated Ultrasonic Wave

Figures 6 and 7 show 71 data obtained under different atmospheric conditions. Since the aerial ultrasonic sensor cannot acquire measurements in rainy weather conditions, the data were acquired mainly during fine weather.

The measured value was acquired using the aerial ultrasonic with the smooth board and the rough board. The measured value was the peak to peak of the reflected wave and was calculated 15 times on average. Since the measured value depended on the temperature, the temperature was taken on the horizontal axis.

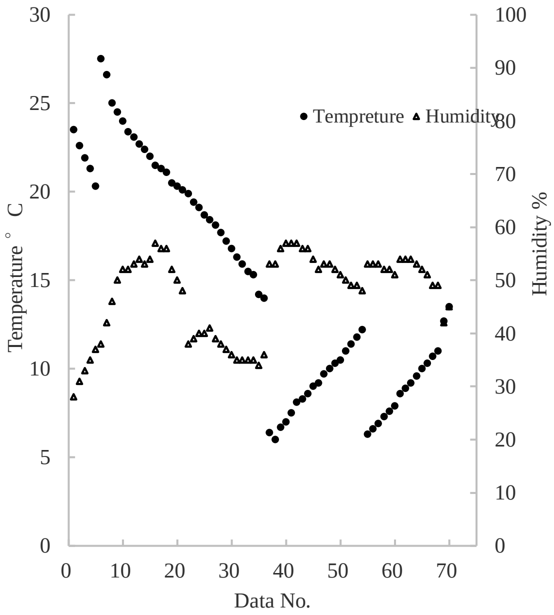

Fig. 6 Atmospheric condition with smooth board

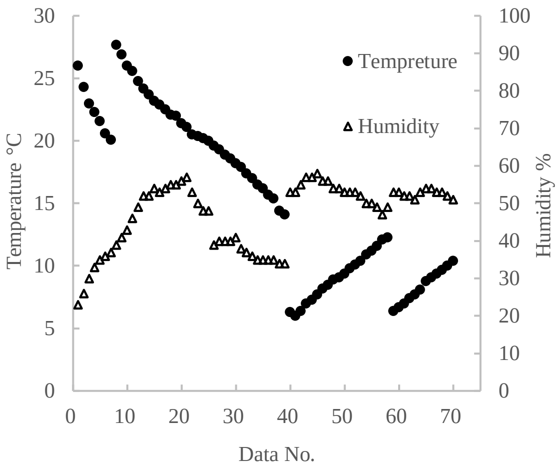

Fig. 7 Atmospheric condition with rough board

Figures 8 and 9 show that the measured value fluctuated due to attenuation. When the temperature of the atmosphere was under 20 °C, the attenuation tended to be small. When the temperature of the atmosphere was over 20 °C, the attenuation tended to be large. Figures 6 and 7 show that when the temperature was over 20 °C, the humidity was under 60%. Fig. 5 shows that when the humidity was low, the attenuation coefficient $\boldsymbol{\alpha}$ tended to increase as the temperature increased. There is no research showing that the phenomenon changes at the boundary of 20 °C. We considered to be the relationship between humidity, atmospheric pressure, and features of the sensor.

The slope of approximation of figure obtained for the smooth board is larger than that for the rough board. This was because the measured value of the smooth board was larger than the measured value of the rough board.

The rate of change of attenuation due to the difference in roughness of the concrete was investigated. The reference temperature was set to 20 °C and the rate of change was calculated by Equation (9). Figure 10 shows that the rates of change of the smooth and rough boards were similar. So the degree of the roughness is not related to the amount of attenuation of the aerial ultrasonic.

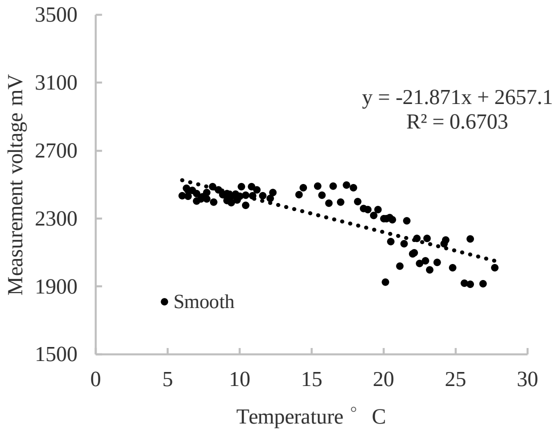

Fig. 8 Measured data using the aerial ultrasonic with the smooth board

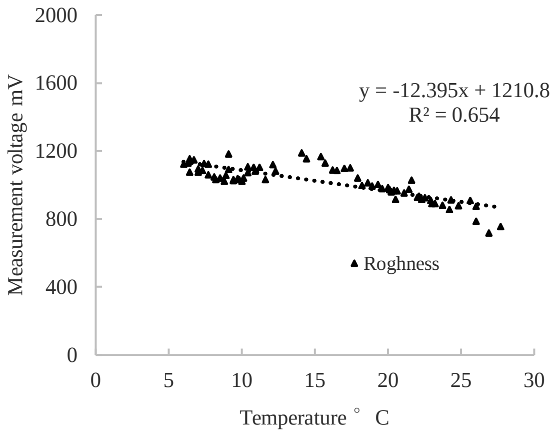

Fig. 9 Measured data using the aerial ultrasonic with the rough board

$$r = \frac{\textbf{\textit{Measurement Voltage}}(\mathbf{mV})}{\boldsymbol{Ave_{20}}(\mathbf{mV})} \tag{9}$$

$\boldsymbol{r}$: Rate of change; $\boldsymbol{Ave_{20}}$: Average voltage (mV) at a temperature of 20 ± 0.5 °C

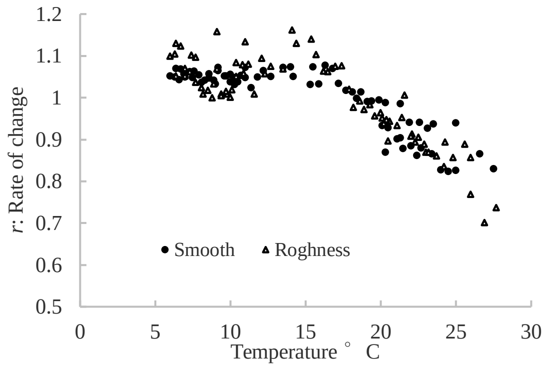

Fig. 10 Relation between rate of change and temperature

4.2 Corrected Result of Attenuated Ultrasonic Wave

The attenuated ultrasonic wave was corrected by Equation (10) from ISO9613-1. The corrected voltage $\boldsymbol{V_0}$ approached the initial voltage. Figures 11 and 12 shows that the slope of approximation of figure with the corrected value became small. A similar phenomenon was also observed for the rough board. The relative error was calculated. The theoretical value was taken as the average of all. Table 2 shows that the relative error of the corrected value was less than half of the measured value. This result shows that the corrected data did not depend on the atmospheric conditions. However, when the temperature was over 25 °C, the corrected value tended to become small.

$$\boldsymbol{V = V_0 exp(-ms)} \tag{10}$$

$\boldsymbol{V}$: Measured value (mV); $\boldsymbol{V_0}$: Corrected value (mV)

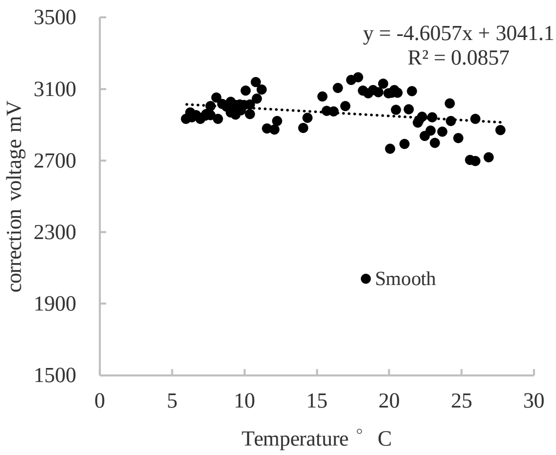

Fig. 11 Data corrected by the equation from ISO9613-1 for the smooth board

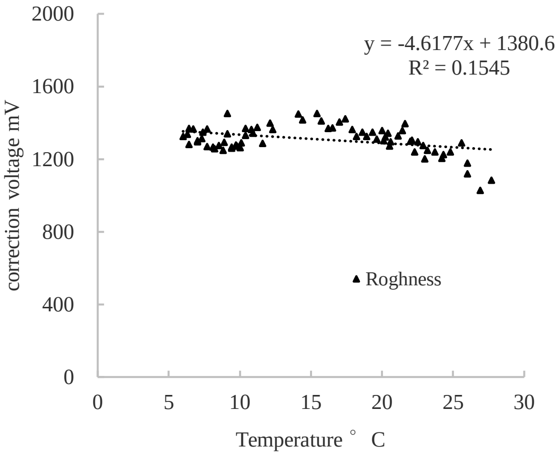

Fig. 12 Data corrected by the equation from ISO9613-1 for the rough board

Table 2 Comparison of corrected and measured values with relative error

	Corrected value	Measured value
Average of all (mV)	2970	2319
Relative error (%)	2.7	6.4

5. CONCLUSION

Seventy-one data were measured using the aerial ultrasonic sensor under different atmospheric conditions. The measured values fluctuated due to ultrasonic attenuation. It was noted that the data were highly dependent on the temperature. It was also noted that the attenuation increased at approximately 20 °C. Besides, the degree of roughness is not related to the amount of attenuation of the aerial ultrasonic.

The ISO9613-1 equation was used to correct the measured data. The slope of approximation with the corrected value was smaller than that obtained with the measured value. The relative error of the corrected value was less than half of that of the measured value. It is therefore concluded that the correction using the ISO9613-1 equation for attenuation of the 42-kHz ultrasonic wave is an effective method that can be used in all future roughness measurements of concrete agriculture irrigation canals.

6. ACKNOWLEDGEMENTS

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