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A measurement technique of sound absorption coefficient and impedance using an impedance tube and two cardioid microphones

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Abstract
Two omnidirectional microphones and an acoustic tube are usually used to measure the surface normal impedance and absorption coefficient of materials. This measurement technique is specified in ISO10354-2, JIS1405-2, and so on. In this paper, we tried to obtain the surface normal impedance of material using two cardioid microphones in the tube. As a result, it was clarified that the ratio of sound pressure and velocity effect on the value of impedance measurement. Therefore when the ratio is equalized, the values of impedance and absorption coefficient can be obtained as with the values using two omnidirectional microphones.
Keywords: Cardioid microphone, Absorption coefficient, Surface normal impedance

1 INTRODUCTION

The measurement method of normal incident impedance in a tube is specified ISO10354-2[1], and this method has some limitations caused by examined in a laboratory. Recently, our needs are increasing yearly for obtaining absorption coefficients of mounted materials in in-situ. Accordingly, several methods for measuring in a free field[2, 3] or a random incident noise field[4, 5] have been proposed, and these methods were reviewed[6].

On the other hand, we are focusing on the sensor for acoustic impedance measurement. The most major technique is known as using two omnidirectional microphones (called P-P sensor) and the transfer function of obtained from the receiving signals. However, the distance of these microphones affects measurement precision. A specific acoustic impedance at the measurement position can be directly obtained by a P-U sensor which has an omnidirectional microphone and a sound velocity sensor[7]. Humidity significantly affects, however, on the value of sound velocity measured by the P-U sensor[**?**]. Therefore the P-U sensor is too delicate and hard to treat in in situ conditions because the calibration procedure must be done before the measurement daily.

Hence, we have been trying to use two cardioid microphones for in-situ impedance measurement[9, 10, 11], this technique, what is called C-C method[12, 13], is based to pick out sound pressure and velocity. In this study, we propose how to measure an acoustic impedance and absorption coefficient using the cardioid microphones and acoustic impedance tube, and report the measurement results with the proposed method.

2 ESTIMATION METHOD OF THE SURFACE IMPEDANCE OF THE MATERIAL BY SOUND PRESSURE AND VELOCITY IN A TUBE

Jacobsen et al. have proposed the estimation technique of the surface impedance, which is calculated from the values of sound pressure and velocity using the P-U sensor[14].

Let us consider a acoutic tube like shown in Figure 1. When the sound source which has complex amplitude A is exposed from a loudspeaker located $x = 0$, sound pressure $p(x)$ and x direction velocity $u_x(x)$ are described as follows:

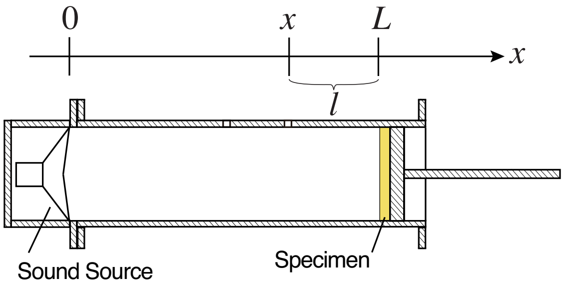


Figure 1. An acoustic impedance tube for pressure and sound velocity measurement at x.

$$p(x) = A\left(e^{-jkx} + r\,e^{jk(x-2L)}\right), \tag{1}$$

$$u_x(x) = \frac{A}{\rho c}\left(e^{-jkx} - r\,e^{jk(x-2L)}\right), \tag{2}$$

where r is the reflection coefficient, ρc is a specific impedance of the air at the position x. Thus, the specific impedance $Z(x)$ at x is given by

$$Z(x) = \frac{p(x)}{u_x(x)} = \rho c\,\frac{1 + r\,e^{2jk(x-L)}}{1 - r\,e^{2jk(x-L)}}. \tag{3}$$

Therefore, when l is defined as $l = L - x$, the reflection coefficient r is expressed as

$$r = \frac{Z(x) - \rho c}{Z(x) + \rho c}\,e^{2jkl}. \tag{4}$$

Finally, The surface impedance $Z(L)$ and absorption coefficint α can be obtained as follows:

$$Z(L) = \rho c\frac{1+r}{1-r}, \tag{5}$$

$$\alpha = 1 - |r|^2. \tag{6}$$

These equations indicate that the surface impedance can be obtained from both values of specific impedance $Z(x)$ and the distance from the sensor to the material. This method was verified by Jacobsen et al. using P-U regular sensor (Microflown Co. Ltd.) which was calibrated in an anechoic room[14].

3 ESTIMATION METHOD OF THE SURFACE IMPEDANCE OF THE MATERIAL USING CARDIOIDMICROPHONE(S)

In this section, we propose how to measure acoustic impedance and absorption coefficient of material using one or two cardioid microphone(s) and acoustic impedance tube.

3.1 Measuring twice with a cardioid microphone

The measurement condition is shown in Figure 2. The signal $M^{+}(t)$ is received at x with a cardioid microphone which heads the directivity heads for the specimen, and the signal $M^{-}(t)$ is done with it which heads the directivity for the loudspeaker. The receiving signals consist of both sound pressure and sound velocity, so that receiving signals M^{+} and M^{-} are described with complex constant α, β:

$$M^{+}(x) = \alpha\,p(x) - \beta\,\rho c\,u_x(x), \tag{7}$$

$$M^{-}(x) = \alpha\,p(x) + \beta\,\rho c\,u_x(x). \tag{8}$$

Thus, the specific impedance at x equals

$$Z(x) = \frac{p(x)}{u_x(x)} = \frac{M^+ + M^-}{M^- - M^+} \cdot \frac{\beta}{\alpha} \cdot \rho c. \tag{9}$$

Hence, we can get the surface impedance and absorption coefficient from Eqs. (4), (5), (6), and (9).

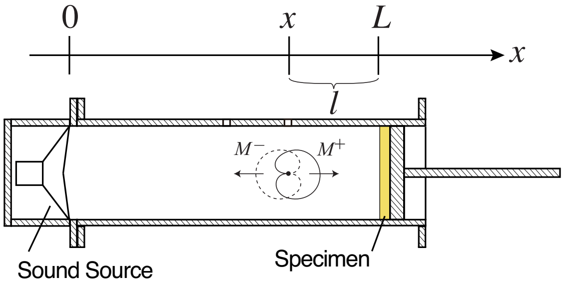


Figure 2. Acoustic impedance measurement schematic diagram using one cardioid microphone and recording twice at x.

4 EFFECT OF THE BARANCE OF BOTH SOUND PRESSURE AND VELOCITY ON THE SPECIFIC IMPEDANCE

The previous section, we can obtain a sound pressure and velocity from one or two cardioid micrphone, and can also obtain the specific impedance at measureing position. However, the real microphone has several detecitive barance of the sound pressure and velocity. In this section, when we use one cardioid microhne, the effect of the ratio β/α in Equaiton (9) is examined numerically.

4.1 Effect of the barance of both sound pressure and velocity included in a cardioid microhone

The even barance of both pressure and velocity mixing siganl can be obtaine dby an ideal cardioid microphone. The ideal microphone has the ratio $\beta/\alpha = 1/2 + 0j$. Where j is imaginary unit. When we use the ideal cardioid microphone, the measured specific impedance $Z_t(x)$ is given by

$$Z_t(x) = \frac{M^+(x) + M^-(x)}{M^-(x) - M^+(x)} \rho c. \tag{10}$$

Therefore, when we define the specific impedance $Z_m(x)$ measured by a real cardioid microhone, the relation of $Z_m(x)$ and $Z_t(x)$ is expressed as:

$$Z_m(x) = \frac{\beta}{\alpha} Z_t(x). \tag{11}$$

Equation (16) express that the ratio of both sound pressure and vecity included in a cardioid micphone gives the error to the specific impedance.

When, We express $\varepsilon = \beta/\alpha$, r_t and r_m are respectively given by

$$r_t = \frac{Z_t(x) - \rho c}{Z_t(x) + \rho c} e^{2jkl}, \tag{12}$$

$$r_m = \frac{\varepsilon Z_t(x) - \rho c}{\varepsilon Z_t(x) + \rho c} e^{2jkl}. \tag{13}$$

4.2 Numerical examination for revealing the effect of the retio of sound pressure and velocity

The numerical examination of specific impedance measurement using Delany-Bazlay model[15]. The simulated porus material has 32 $\mathrm{kg/m^3}$, 80,000 $\mathrm{Ns/m^4}$ flow registance and 50 mm thick. In this exmamination, the error factors (1) the ratio of amplitute between pressure and velocity, (2) the difference of phase (degree.) is given to receiving signals. Additionally, (3) the distance l from the specimen to receiving postion aloso assumes to become the error factor, l is changed stepwisely.

The examnination ressults of phace difference are shown in Figure 3. A little bit of error in $Z(x)$ can be seen in the left figure, however the errors become bigger in surface impdedance $Z(L)$ and absorption coefficient α. When the periodical peaks shown in $Z(x)$ are made to flat to calculate $Z(L)$. In this procedeure, the error could make bigger. So that, These errors has periodical flactuation not to depend on the phase difference. The exmamination results of amplitude difference are shown in Figure 4. These errors also become bigger in surface

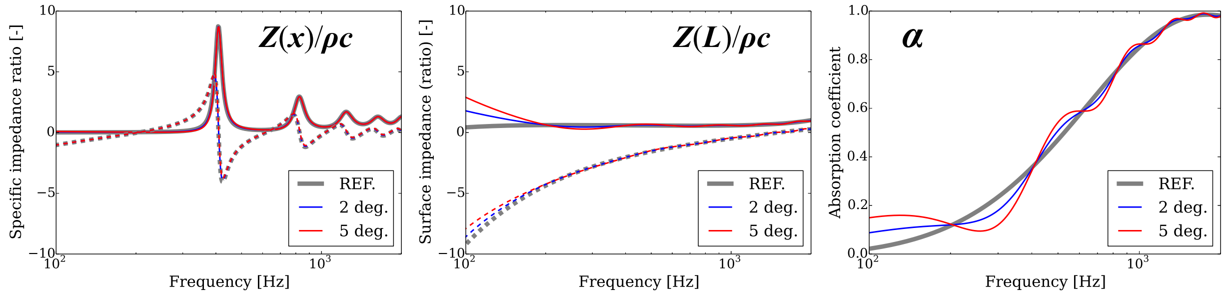


Figure 3. Effect of phase difference of sound pressure p and velocity u inherent in a cardioid macrophone on specific impedance at x, surface impedane and absorption coefficient (l = 36 cm).

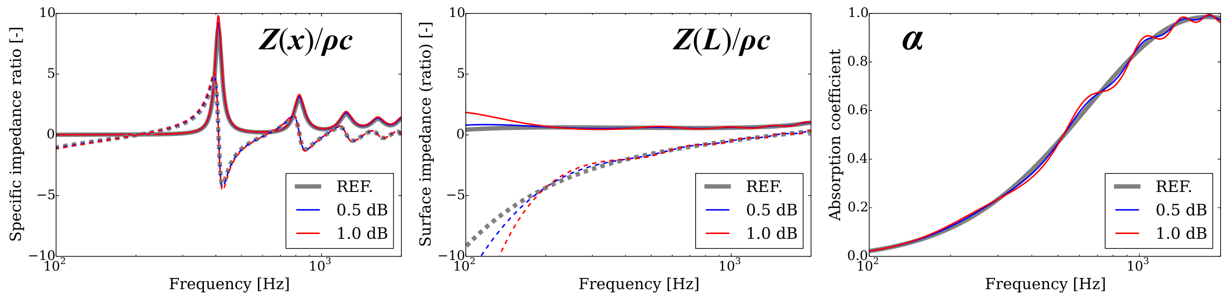


Figure 4. Effect of amplitude difference of pressure p and sound velocity u inherent in a cardioid microphone on specific impedance at x, surface impedane and absorption coefficient (l = 36 cm).

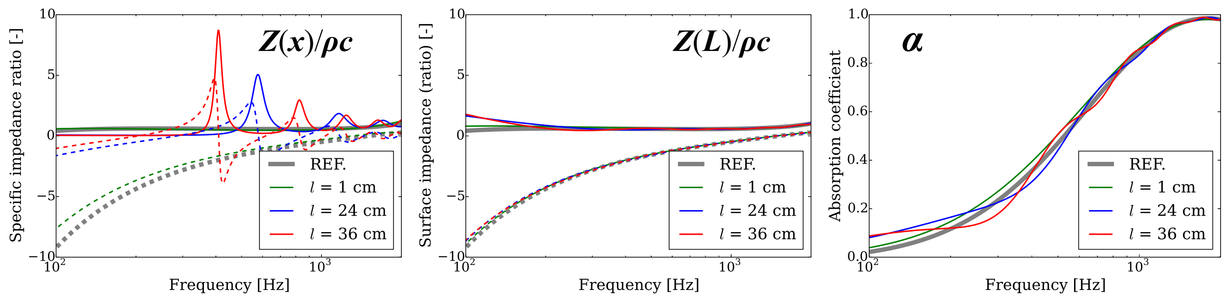


Figure 5. Effect of distance between measurement position and material on specific impedance at x, surface impedane and absorption coefficient when phase difference of pressure p and sound velocity u inherent in a cardioid microphone is 2 degrees.

impdedance $Z(L)$ and absorption coefficient α. The exmamination results also has periodical flactuation and this peroid is same as the previous examination of phase difference. The examination results of the difference of distance from receiving position to the specimen are shown in Figure **??**. The longer distance, the period of flactuation becomes longer. Hence, the flacuation depends on the distance, which is only 1 cm from the specimen, the distance affects on the measument result. This error occur not only using cardioid microphone, but also using P-U sensor, because the difference between pressure and velocity causes this error. This problem has been also indicated by Jacobsen[14].

5 ESTIMATION METHOD OF THE COMPLEX RATIO OF PRESSURE TO VELOCITY INHERENT IN A CARDIOID MICROPHONE

In previous section, the numerical experiments clarified that the ratio of pressure and velocity inherent in a cardioid microhone affects on the specific impedance measurement in a tube. Therefore, The ratio called ε have to be measued before a impedance measurement. In this section, the mesurement technique of ε of a cardioid microhone using an impedance tube will be discussed.

When a rigid boundary is installed at $x = L$, the Eqs. (1) and (2) become

$$p(x) = A\left(e^{-jkx} + e^{jk(x-2L)}\right), \tag{14}$$

$$u_x(x) = \frac{A}{\rho c}\left(e^{-jkx} - e^{jk(x-2L)}\right), \tag{15}$$

so that, the ideal specific impedance $Z_t(x)$ also becomes

$$Z_t(x) = \frac{p(x)}{u_x(x)} = -j\rho c\,\frac{\cos(kl)}{\sin(kl)}. \tag{16}$$

On the other hand, when the measured specific impedance $Z_m(x)$ using one cardioid microphone in a tube, theese impedances $Z_t(x)$ and $Z_m(x)$ are corresponded ideally, hence, the ε is given from Eqs. (9) and (16),

$$\varepsilon = \frac{\beta}{\alpha} = -j\,\frac{(M^- - M^+)}{(M^+ + M^-)}\frac{\cos(kl)}{\sin(kl)}. \tag{17}$$

Equaiton (22) tells us that we can measure ε of a cardioid microphne using a impedance tube, however, this equaiton consist of the ratio cos to sin, so that the upper limit frequency is decided by $l < \lambda/4$.

6 EXAMINATION FOR VERIFICATION

The possivility of mesurement about the surface impedance using both a cardioid microphone recorded twice and an impedance tube is verified.

6.1 conditions for surface impedance measurement

A impedance tube made from 15 mm thick MDF wooden boards is ready for measurement. The section diagram is drawn in Figure 6. A grasswool that has 50 mm thick, 32 $\mathrm{kg/m^3}$ density is ready for specimen. The measurement technique which uses one cardioid microphone and receiving signals twice is adopted. Two different manifucture's cardioid microhpnes are ready for the measurement. One is ISOMAX II-C (Countryman Co. Ltd.), the other is one 4188 (DPA). Two ISOMAX II-C and one 4188 are ready for comparison. The same pinknoise is exposed twice from the loudspeaker for one minute respectively. The directivity of cardioid microhone heads for the specimen and head for the loudspeaker in each recording with 48 kHz sampling rate. The distance l from receiving position to the specimen is 24 cm and 36 cm for the possibility of measurement at any position. The measuremnt using two omnidirecitional microphone is also examined for obtaining reference data with transfer function method.

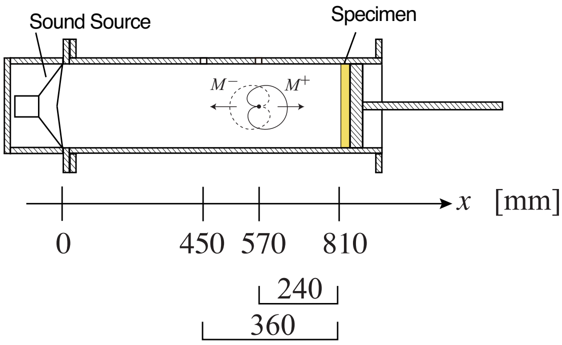


Figure 6. Section diagram of an acoustic impedance tube and measurement positions for verifying tests.

6.2 Measuring the ratio of puressure to velocity inherent in cardioid microhone

Before impedance measurement, the ratios $\beta/\alpha = \varepsilon$ of pressure to velocity inherent in the three cardiod microphones are measured using the same impedance tube and rigid surface end. In these measurements, the distance l of microphone to rigid wall is ajusted 1.5 cm and 24 cm respectively. The same pinknoise are exposed from the loudspeaker for 1 minitute and we recorded twice when the directivity of the microphone heads to the loudspeaker and to the rigid wall at each position. The ε is calculated step by 16384 data (8192 data overlapping) and averaged with Eq. (17). We chose the ε measured with l = 24 cm under 240 Hz, and that measure with l = 1.5 more than 240 Hz. The phase values of ε for 240 to 800 Hz are not enable to be obtained suitable value, these values are generated through liner interpolation.

6.3 Analysis procedure

After recording for impedance mesurement, we conducted following calclulations. Due to check the effect of ε, the specific impedance $Z(x)$ at x is calculated two patterns. One is no correcting with ε, $Z(x)$is calculated as $Z(x) = \rho c(M^+ + M^-)/(M^- - M^+)$. The other is corrected with ε, $Z(x)$ is calculated as $Z(x) = (\rho c/\varepsilon) \cdot (M^+ + M^-)/(M^- - M^+)$. The $Z(x)$ is calculated step by 16384 data (8192 data overlapping) and averaged in the both calculations procedure. Reflection coefficent r and absorpotion coefficient α are calculated with Eqs. (8) and (9).

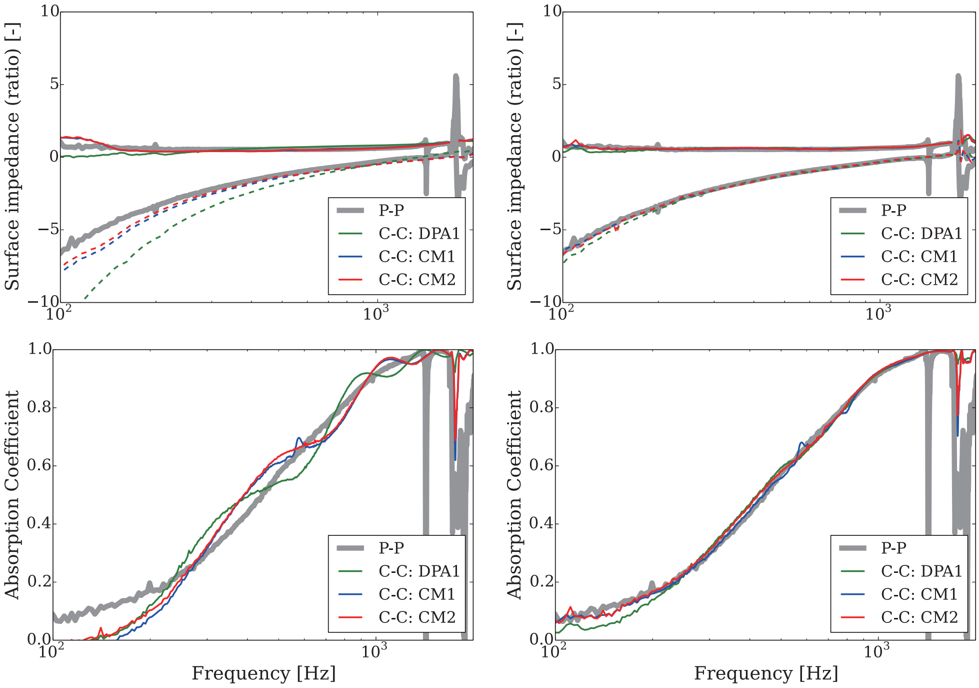
6.4 Results

The result of l = 24 cm shows in Figure 7 and that of l = 36 cm shows in Figure 8. The upper graph shows surface impedance and the lower graph shows absorption coeffient in each figure. Focusing on (a) original of absorption coefficient in Figure 7 and 8, we can see the periodical flactuation in measured any cardioid microphone. The period of flactuation is decided by the distance l and the phase of fractuation differ from microphone type. These flactuations occur from the ratio of pressure to velocity inherent in cardioid microphone own. The errors result in microphone type, and do that the indivitual difference is very small.

Hence, let us focus on the results of absorption coefficient (b) corrected by ε. The all of values measured by cardioid microphone correspond to measured by P-P method (transfer function method) at all frequencies. These results clearly show that the amplitude and phase both of corrected cardioid microphone can use for impedance measurement. It was founded that the ε is unique value in each microphone because the ε can use in any distance l.

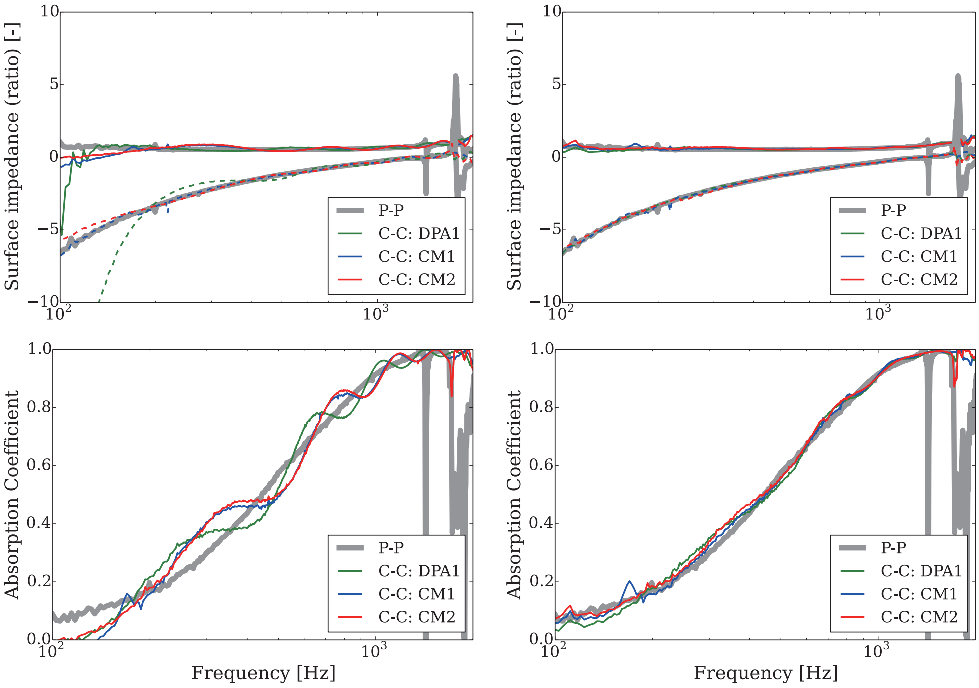
7 CONCLUSION

We trid to measure surface impedance of a material using one or two cardioid microhone and a impedance tube. As a result, we found that the cardioid microphone has the error of balance between pressure and velocity, and



(a) original　　(b) corrected

Figure 7. Measurement results of surface impedance and absorption coefficient in an impedance tube (l = 24 cm). The results (a) directedly calculated from receiving signals. The results (b) derived from corrected data by ε



(a) original　　(b) corrected

Figure 8. Measurement results of surface impedance and absorption coefficient in an impedance tube (l = 36 cm). The results (a) directedly calculated from receiving signals. The results (b) are calculated from corrected data by ε

if the error is corrected we can measure the impedance with the cardioid microphone in the tube. In this trial we chose the technique using one cardioid microphone and recoding twice. Next, we will try to use two cardioid microhone and recording simaltaneously.

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