Acoustical Characteristics of Newly Developed Perforated Plates

Takayoshi Nakai(1), Fukushi Kawakami (1), Keiichiro Wada(2) and Takayuki Sano(2)

(1) Facuty of Engineering, Shizuoka University, 3-5-1 Johoku, Naka-ku, Hamamatsu, 432-8561, JAPAN
(2) Tomoegawa Co. , Ltd., 3-1 Mochimunetomoe-cho, Suruga-ku, Shizuoka, 421-0192, JAPAN

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ABSTRACT

We search materials which are hard but can absorb sound quite a bit, or are hard and do not affect the sound transmission. For this aim, we measured normal incident absorption coefficient of perforated plates with/without glass wool absorption materials by transfer function method. The perforated plates include commercial aluminum perforated plates with 22.6% and 8.2% perforation rate, and aluminum plates with 1% perforation rate. The thickness of the plates is 0.5 mm to 2 mm. The diameter of the holes in the plate is 0.5 mm or 1 mm. For comparison, the plates with a single hole of 22.6%, 8.2% and 1% perforation rate were measured. From the results, it is implied that the perforated plates act as low pass filters and, their cut-off frequency is due to the perforation rate and the thickness of the plates. If the perforation rate is the same, the cut-off frequency of the perforated plate is higher than that of the plate with a single hole. For simulations of this phenomenon, we analyzed using both FEM and electrical equivalent circuit model of the tube. It is shown that the particle velocity in the holes of the plate is higher than the other part. It is shown that for the perforated plate, wave front passing through the plate is not largely changed by way of comparison of that for the plate with a single hole.

INTRODUCTION

We search materials which are hard but can absorb sound quite a bit. Plates with high perforation rate are well known as having the almost same absorption characteristics as ones of absorption materials behind the plates. But it is not known how absorption characteristics the plate have if changed perforation rate and how to transmit through perforated-plates. Therefore, we measure normal incident absorption coefficient of perforated-plates with/without glass wool absorption materials by transfer function method. Then, we analyze acoustical characteristics of the perforated-plates using both FEM and equivalent electrical circuit model of the tube.

MEASUREMENT METHOD

Measurement method of normal incident absorption coefficients

There are two systems. One, for Tube A, is available as measuring 200 to 2 kHz as shown as Figure 1. The diameter of the tube is 44.8 mm. The two microphones used here are 1/2 inch condenser ones, B&K 4133, and are set as 70 mm distance between them. A loudspeaker is inputed octave-noise with the center frequencies 500, 1 k, 2 k, and 4 kHz from the noise generator.

Sound velocity in the tube is calculated from the room temperature. The outputs of the microphones are amplified by the amplifier and are taken for 20 seconds in a personal computer through an A/D converter. Sampling frequencies are 1024, 2048, 4096, 8192, and 16384 Hz against the center frequency 250, 500, 1 k, 2 k, and 4 kHz of the noise generator. The normal incident absorption coefficients are calculated from the transfer functions of the values obtained by the two microphones.

Figure 1 Measurement system of normal incident absorption coefficients from 200 to 2 kHz. (Tube A)
The normal incident absorption coefficients, $\alpha$, are calculated as follows. At first, 0.5 second data obtained from microphones 1 and 2 are multiplied by hanning window. Their FFTs are carried out. Autocorrelation of microphone 1 and cross-correlation between microphones 1 and 2 are calculated from their FFTs. The transfer function, $H_{12}$, is calculated from their 20 times average values. $\alpha$ is given as

$$\alpha = 1 - \frac{|H_{12} - H_i|}{|H_r - H_{12}|}$$

where $H_i = \exp(-jk_s)$, $H_r = \exp(jk_s)$, $k$ is the wave number, and $s$ is the distance between microphones 1 and 2, 70mm or 20mm.

The perforated-plates are set as A-A side as shown in Figure 1, and as 36 mm distance from the right microphone as shown in Figure 2. We measure $\alpha$ for the perforated-plates with/without 96 kg/m$^3$ glasswool absorption materials when the tube lengths from the right end are 50 mm, 70mm, and 90mm.

**Measured perforated-planes**

There are four kinds of perforated-plates as follows.

1. Commercial aluminium perforated-plate with 22.6% perforation rate and 0.5 mm thickness and ones pasting two from four planes together. The diameter of holes is 0.5mm, and partially 1.5mm.

2. Commercial aluminium perforated-plate with 8.2% perforation rate and 1 mm thickness. The diameter of holes is 1 mm.

3. Aluminium perforated-plate with about 1% perforation rate, and 0.5 and 1 mm thickness. The diameter of holes is 1 mm.

4. Aluminium plates with single hole, 1mm thickness, and 22.6%, 8.2% and 1% perforation rate.

**MEASUREMENT RESULTS**

**Results using Tube A**

1. Commercial aluminium perforated-plate with 22.6% perforation rate and 0.5 mm thickness

There is a 20mm air space between the perforated-plate and the glass-wool absorption materials. The normal incident absorption coefficients are little changed, even when the thickness of the plate changes. So, Figure 3 shows normal incident absorption coefficients for perforated-plates with 2 mm thickness. The normal incident absorption coefficients for 0.5mm diameter of holes are almost the same as for 1.5 mm diameter of holes and similar to for only glasswool absorption materials.

![Figure 3](image-url)
(3) Aluminium perforated-plate with about 1% perforation rate

Figures 5 and 6 show the normal incident absorption coefficients of the plate with 0.5 mm and 1 mm thickness, respectively. In cases of only the plate, the normal incident absorption coefficients have peaks, and the values of the peaks are 0.6 to 0.8. These results are different from the plate with 8.2% perforation rate. The peak frequency is lower, when the length of backward tube is longer. These results are known as microperforated panel, or mpp [1], [2]. For no air space between the plate and glass-wool, the normal incident absorption coefficients have a broader band up to 0.7. For 2 cm air space between the plate and glass-wool, the normal incident absorption coefficients have up to 1 and its upper limit frequency, when it becomes 0.7, is more than 1 kHz. The peak frequency of the plate with 0.5 mm thickness is higher than that of the plate with 1 mm thickness.

(4) In the cases of single hole

Figures 7 and 8 show the normal incident absorption coefficients for the plates with 4.4 mm, about 1% perforation rate, and 12.5 mm, about 8.2% perforation rate, in diameter of single hole, respectively. For only the plates with 1% perforation rate, the normal incident absorption coefficients have a peak, and the peak frequency is lower than for multi holes. For only the plate with 8.2% perforation rate, the normal incident absorption coefficients have a low peak and the peak frequency is lower than for multi holes. For no air space between the plate and glass-wool, the normal incident absorption coefficients have a low peak in the case of 1% perforation rate and have a peak in the case of 8.2% perforation rate. For both cases, the peak frequencies are lower than for multi holes. For 2 cm air space between the plate and glass-wool the normal incident absorption coefficients have a peak or a broad band peak, but the peak frequencies are exactly lower than for multi holes.
Results using Tube B

Figures 9 and 10 show the normal incident absorption coefficients for 10 mm and 20 mm air spaces between the plates and glass-wool, respectively. For the perforated plate with 0.5 mm diameter of holes, 0.5 mm thickness, and 22.6% perforation rate, the normal incident absorption coefficients are almost the same up to 5.6 kHz as for only glass-wool, when air spaces are 10 mm and 20 mm. For the perforated plate with 1 mm diameter of holes, 1 mm thickness, and 8.2% perforation rate, upper limit frequencies when the coefficient becomes 0.7, are 5 kHz in the case of 1 cm air space, and 3.7 kHz in the case of 2 cm air space. It is seen that the upper limit frequency changes due to the length of the air space. For the single hole, every the upper limit frequency is lower than for the multi holes and for 1 cm air space is higher than for 2 cm air space.

SIMULATION USING FINITE ELEMENT METHOD

We analyse a tube with the plate and absorption wall using FEM by Sysnoise version5.5, LMS Co..

2-D models

2-D models are a rectangle shape, 151 mm long and 45 mm wide. Every element is 1 mm long and 1 mm wide. There is an aluminium plate with 1 mm thickness at a distance of 100 mm from the left end. Density of aluminium is 2.7g/cm$^3$ and sound velocity in aluminium is 3150 m/s. There are four kinds of hole(s): first is a 5 mm single hole (11.1% perforation rate), second is a 11 mm single hole (24.4% perforation rate), third is 5 holes equally spaced with 1 mm wide, fourth is 11 holes equally spaced with 1 mm wide. As boundary conditions, impedance of the left and right ends is $\rho c$, where the density of air, $\rho$, is 1.4kg/m$^3$ and the sound velocity is 340m/s. The sound pressure at the left end is given 1 Pa. The upper and lower wall is rigid.

3-D models

For 3-D models, a rectangular box is x-directional and y-directional symmetry because input pressure is uniform in the tube. The box is 21 mm wide, 21 mm high, and 151 mm long; the real size is 42 mm wide, 42 mm high, and 151 mm long. There is an aluminium plate with 1 mm thickness at a distance of 100 mm from the left end. There are two kinds of hole(s): first is a 7 mm wide and 7 mm high single hole (11.1% perforation rate, the real hole is a 14 mm wide and 14 mm high and centerally-placed on the plate), and second is 49 holes equally spaced with 1 mm wide and 1 mm high. As boundary conditions, impedance of the left and right ends is $\rho c$, where the density of air, $\rho$, is 1.4kg/m$^3$ and the sound velocity is 340m/s. The sound pressure at the left end is given 1 Pa. The other walls are rigid.

Analysis frequencies are 100, 300, 500, 1 k, 2 k, 5 kHz (partially 7 kHz).

Calculation of normal incident absorption coefficient

The normal incident absorption coefficient, $\alpha$, is given as follows. From sound pressure, $P_1$ and $P_2$, on the wall obtained from FEM analysis, the transfer function, $H_{12}=P_2/P_1$. The reflection coefficient, $R$, is given as follows.

$$ R = \frac{H_{12} - \exp(-jkd)}{\exp(jkd) - H_{12}} $$

$$ \alpha = 1 - |R|^2 $$
where the locations obtaining $P_1$ and $P_2$ are at 30mm and 87 mm distance from the left side at less than 2 kHz, and are at 30 mm and 50 mm distance from the left side at 5 kHz. The distance between them is $d$, and $k$ is the wave number.

**Results and discussion**

Figure 11 shows pressure distribution of 2-D models. For single hole, (a) and (c), it is seen that sound pressure contours are not perpendicular on the left side of the hole. For 5 holes and 11 holes, (b) and (d), sound pressure contours are almost perpendicular on the left side of the hole. Figure 12 shows distributions of x-directional particle velocity. The particle velocity is large in the holes. When the absorption coefficients are nearly 1, the particle velocity in the holes varies inversely with perforation rate.

(a) Single hole(5mm), 500Hz, 88.7dB(blue)-91.2dB(red)

(b) 5 holes, 500Hz, 90.3dB(blue)-91.0dB(red)

(c) Single hole(11mm), 500Hz, 89.8dB(blue)-91.1dB(red)

(d) 11 holes, 5kHz, 88.5dB(blue)-92.9dB(red)

Figure 11 Pressure distributions of 2-D models. Broken line: position of aluminum plate.

Figure 13 shows pressure distribution of 3-D models. It is seen that even for single hole, sound pressure contours are more perpendicular against propagation direction on the left side of the hole than for 2-D models. For multi-holes, sound pressure contours in front of and behind the plate are perpendicular, and are the almost same as in the case that the plate do not exist. Figure 14 shows distributions of z-directional particle velocity. The z-directional particle velocity is large in the holes as same as in 2-D models. For multi-holes, the z-directional particle velocity is larger than in 2-D model.

(a) Single hole(11mm), 500Hz, 0.08mm/s(blue)-9.1mm/s(red)

(b) 11 holes, 500Hz, 0.31mm/s(blue)-4.6mm/s(red)

Figure 12 X-directional particle velocity distributions of 2-D models.

(a) Single hole, 1kHz, 91.0dB(blue)-99.5dB(red)

(b) 49 holes, 1kHz, 91.0dB(blue)-92.3dB(red)

Figure 13 Pressure distributions of 3-D models.
**ANALYSIS USING EQUIVALENT ELECTRICAL CIRCUIT MODEL OF TUBE**

We assume that sound in the tube propagates as planar wave. From this assumption, propagating sound in the tube is described as equivalent electrical circuit model. The normal incident absorption coefficients of glass-wool are frequency-dependent, however we assume that they are 1, or are equal to impedance of air, $\rho \cdot c$. The inductance, $L$, and the capacitance, $C$, of each section of the tube are given as

$$L = \left(\frac{\rho}{A}\right) \Delta L, \quad C = \left(\frac{\rho \cdot c^2}{A}\right) \Delta L$$

where density of air, $\rho$, is 1.14kg/m$^3$, sound velocity in air, $c$, is 340m/s, $A$ is a cross-sectional area [m$^2$], and $\Delta L$ is a length of the tube [m]. For the equivalent electrical circuit model, cross-sectional area is relative, so the cross-sectional area of the tube except the perforated-plate is 1 m$^2$ and that of the perforated-plate is $P/100$ m$^2$, where $P$ is perforation rate [%]. $\Delta L$ [m] is the length of the tube. If $\Delta L$ is 1 mm, upper computable frequency is 20 kHz.

The normal incident absorption coefficient is given as the ratio of effective power, $V_0 \cos \theta$, to $V^2/\rho \cdot c$, where $V$ is a voltage of both end of the perforated-plate, $I$ is a current in the perforated-plate, and $\theta$ is phase difference between $V$ and $I$. Figure 16 shows normal incident absorption coefficients of the perforated-plate with 8.2% perforation rate and 2 mm thickness. This characteristics is a LPF, or lowpass filter. The normal incident absorption coefficient is 0.9 at 1.5 kHz, and is 0.7 at 3 kHz. The frequency of the absorption coefficient 0.9 is a half of the frequency of absorption coefficient 0.7. This frequency is proportional to

$$\text{perforation rate(%) / thickness (mm)}.$$

The proportionality factor is 0.72 in the case of the absorption coefficient 0.7. This result is somewhat different to the results of Figures 9 and 10. This is due to that the absorption coefficient of glass-wool is 1.

We analyze equivalent electrical circuit model in the case that the absorption coefficient of glass-wool is 0.9. Figure 17 shows the results. If the air space between the plate and glass-wool changes, the absorption coefficient changes, and results of equivalent electrical circuit model close in results of measuring.

**CONCLUSIONS**

We measured the normal incident absorption coefficients of some kinds of perforated-plates with/without glass-wool. From the results with glass-wool, it is implied that the perforated plates act as low pass filters and their cut-off frequency is due to the perforation rate and the thickness of the plates. If the perforation rate is the same, the cut-off frequency of the perforated plate is higher than that of the plate with a single hole. It is shown that the particle velocity in the
holes of the plate is higher than the other part from FEM. It is shown that for the perforated plate, wave front passing through the plate is not largely changed by way of comparison of that for the plate with a single hole from FEM. From analysis using equivalent electrical circuit model of the tube, it is shown that upper cut-off frequency is proportional to

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\text{perforation rate(\%) / thickness (mm)}.
\]

We showed the reason why the normal incident absorption coefficients are changed by the air space between the plate and glass-wool.

The future works will be to simulate the perforated plates without glass-wool.

![Figure 17](image1.png)

**Figure 17** Normal incident absorption coefficients of simulation in the case that absorption coefficient of glass-wool is 0.9. Upper: 10 mm air space, and lower: 20 mm air space.

**REFERENCES**