*Materials Transactions*, Vol. 49, No. 2 (2008) pp. 345 to 351


# Relationship between Sound Absorption Property and Microscopic Structure Determined by X-ray Computed Tomography in Urethane Foam Used as Sound Absorption Material for Automobiles

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Recently, the application of porous soundproof materials to automobiles is changing from the use of sound insulation materials to the use of sound absorption materials. A method for attaining high absorption performance in the low-frequency region without increasing the material weight is thus needed. We investigated the use of X-ray computed tomography (CT) scanning for investigating the microscopic structure of soft urethane foam, a low specific gravity resin material, in a nondestructive manner. Our testing reveals that it is an effective tool for observing the microscopic organizational structure of a low specific gravity resin material and that the cell size of urethane foam, as measured by X-ray CT, affects the sound absorption characteristics. It also shows that reducing cell size shifts the peak frequency of the sound absorption coefficient downward. [doi:10.2320/matertrans.MRA2007234]

(Received October 3, 2007; Accepted November 5, 2007; Published January 25, 2008)

***Keywords:*** *sound absorption, soundproof material, X-ray computed tomography, microstructure, urethane foam*

## 1. Introduction

The growing demand for environmental protection in the face of global warming is affecting automobile development. In particular, technologies are needed for reducing fuel consumption so that $CO_2$ emissions are reduced. One way to reduce fuel consumption is to reduce the weight of automobiles, particularly the weight of the car body.

On the other hand, quietness in the car cabin is required from the viewpoint of enhanced comfort, and quietness is improved by using soundproof materials. There are two types of soundproof materials, insulating and absorbing. Insulation materials generally have a double-layered structure accompanied with a mass layer, so they are disadvantageous in terms of weight reduction. Absorption materials have a single-layered structure and do not have a mass layer, so they are lighter. Their automotive application is thus increasing.

However, their acoustic performance when used in automobiles is problematic because they do not have good absorption at low frequencies. This is because the limited application space limits their thickness.

One way to improve the absorption performance of single-layer sound absorbing material at low frequencies range is to increase the density and thickness of the material. However, this approach is not compatible with the need to reduce the weight of the acoustic materials used in automobiles.

There have been few reports on the relationship between the internal structures of porous materials and their sound absorption performance.[1–4] We have investigated the relationship between the microscopically observed internal structure of polyurethane foam and its sound absorption characteristics. Our objective is to improve its sound absorption performance in the low frequency range without increasing its weight by controlling its internal structure.

Generally, optical and/or electron microscopes are used to observe the internal microscopic organization of materials. However, with these methods, the observed materials are destroyed in the process, and it is difficult to observe various internal cross sections. Because the material is destroyed, it is impossible to analyse its other characteristics continuously. A method is thus needed for observing the microscopic structure of materials without destroying them.

Two ways to observe the microscopic structure of a material without destroying it are to use X-ray computed tomography (CT) and to use neutron radiography. The former is widely used in the fields of medicine, biology, and pharmacology.[5–9] It is also used in industry to observe the internal structure of developed products and identify internal defects; that is, it is used for quality control. Another industrial application is penetration examination to quantitatively measure the residual stress in metals due to welding. The research on such applications has generally been for such materials as iron and resin, which have a large specific gravity, and has focused on the relationship between X-ray wavelength and penetration. There have not been studies on the use of X-ray CT for analyzing soundproof materials, particularly acoustical absorption materials.

In this paper, we report on our testing of the use of X-ray CT scanning to examine the microscopic structure of soft urethane foam, a low specific gravity resin material, in a nondestructive manner. Comparison of the relationship between the microscopic structure and sound absorption performance showed that the cell size of the foam affects the absorption frequency.

## 2. Materials and Methods

### 2.1 Materials

We used ether soft urethane foam, which is used for automobile soundproofing. The test samples were molded to have the same density ($0.08\,g/cm^3$) as when the material is used for in automobiles in order to eliminate the effect of weight. The microscopic structures (cell size) of the samples were varied to enable us to clarify the effect of the microscopic organization.

The injection molding was done at 45, 55, or 60°C. The

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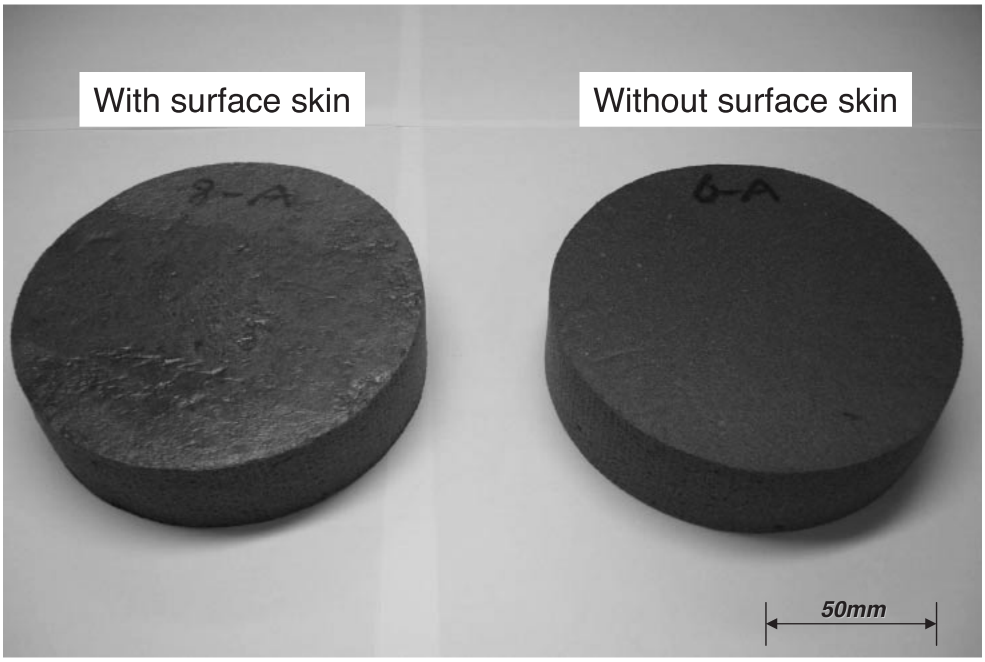


Fig. 1 External appearance of samples: a thin skin is evident on the lower temperature sample (left) but not on the higher temperature sample (right).

upper and lower molding dies were used so that the urethane foam size is 1 m long and 25 mm thick. The undiluted urethane solution was injected into dies, and it turned into foam. The two types of test samples were 100 and 29 mm in diameter and 25 mm thick. The 29-mm samples were mainly used for our research because the absorption properties at this thickness mainly account for the differences in performance at high frequency.

### 2.2 Methods

The normal incidence acoustic absorption coefficient was measured using a sound impedance tube (Brüel & Kjær, Type 4206 made in accordance with ISO 10534-2). To clarify the characteristics of the material itself, we measured the absorption coefficient without a back air cavity close to a rigid wall. The 100-mm samples were used for measuring the characteristics in the low-frequency region, and the 29-mm samples were used for measuring them in the high-frequency region.

X-ray CT was used to investigate the microscopic organization of the material. The samples were rotated between an X-ray tube and inspection machine. The X-rays penetrated the sample from various directions, and the amount of X-ray absorption for each direction in the target section was measured. A section image was composed by calculating the arrangement of the amount of X-ray absorption in the section on the basis of the X-ray absorption data.

Two different X-ray CT devices were used. One, with a high-voltage X-ray tube (Shimadzu, SMX-225CT-SV), was used for macroscopic observation at a magnification power of 2 times. The other, with a low-voltage tube (Shimadzu, SMX-100CT-SV), was used for microscopic observation at a magnification power of 35 times.

The reason two types of devices were used is that the ability to observe the internal structure of a material depends on the penetration ability of the X-rays. And the penetration ability of X-rays depends on their wavelength and the specific gravity of the material. That is, the shorter the wavelength, the better the penetration ability, and the larger the specific density and the larger the absorption coefficient, the worse the penetration ability. Therefore, it is necessary to use X-rays that have a wavelength suitable for the density and specific gravity of the material, and it is necessary to apply voltage for generating the X-rays. Moreover, it is necessary to place the material an appropriate distance from the detector and to use a light source focused to obtain a clear image.

Urethane foam can be microscopically observed with good resolution by using an X-ray observation device suitable for the low-density materials, a low applied voltage, and a low current. Therefore, we used a device suitable for observing the microscopic structure and one suitable for observing the macroscopic structure. For the macroscopic observations, a 60 kV was applied to the X-ray tube, the current of the X-ray tube was 200 μA, and observation scan distance was 0.028 mm. For the microscopic observation, 40 kV was applied, the current as 80 μA, and the distance was 0.0054 mm.

## 3. Results

### 3.1 Surface observation

The urethane foam samples had different types of surfaces depending on the die temperature. A thin film skin (the "surface skin") was generated on the surface of the samples made at lower temperatures (45 and 55°C). There was no surface skin on the higher temperature samples (65°C). The appearance of typical samples is shown in Fig. 1, and the results of a visual inspection of the sample surfaces are summarized in Table 1.

Table 1 Molding temperature and presence of surface skin.

| Test specimen | Molding temperature | Surface skin ○; observed ×; not observed |
|---|---|---|
| 45-1 | 45°C | ○ |
| 45-2 | | ○ |
| 45-3 | | ○ |
| 55-1 | 55°C | × |
| 55-2 | | ○ |
| 55-3 | | ○ |
| 65-1 | 65°C | ○ |
| 65-2 | | × |
| 65-3 | | × |
| 65-4 | | × |
| 65-5 | | × |
| 65-6 | | × |

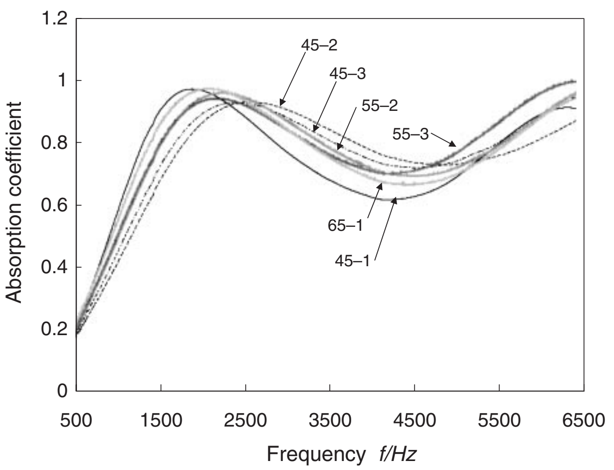


Fig. 2 Measured normal incidence acoustic absorption coefficient for samples with surface skin.

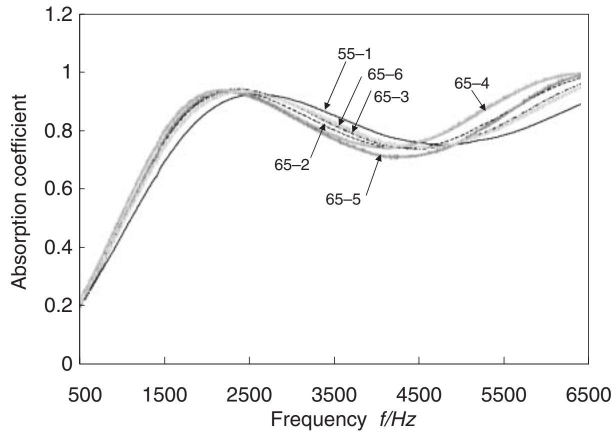


Fig. 3 Measured normal incidence acoustic absorption coefficient for samples without surface skin.

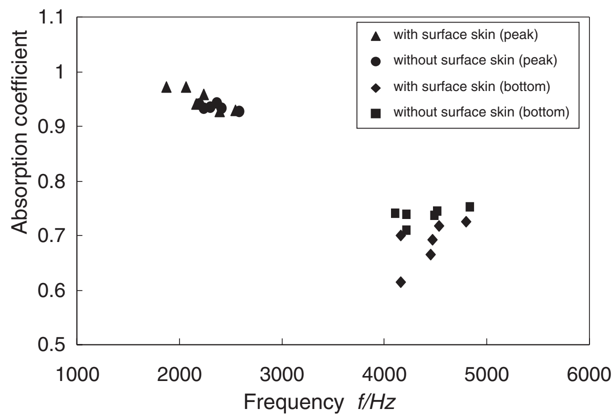


Fig. 4 Relationships between peak absorption coefficient and peak frequency and between bottom absorption coefficient and bottom frequency for samples with and without surface skin.

## 3.2 Normal absorption coefficient

The measured normal incidence acoustic absorption coefficient for the samples with surface skin is shown in Fig. 2, and that for the samples without a surface skin is shown in Fig. 3. In both cases, the sound absorption had a frequency range in which the acoustic absorption coefficient initially reached a maximum value (the "peak absorption coefficient") and the peak frequency between about 1500 and 2600 Hz. The acoustic absorption coefficient reached a minimum value in both cases due to interference between the wave incident to the material and the wave reflected from the rigid back wall (the "bottom absorption coefficient") and the bottom frequency between about 4000 and 5000 Hz. These results indicate that the dispersion of the absorption characteristics for the samples with a surface skin was larger than that for those without one even though the materials had the same density.

Figure 4 shows the relationships between the peak absorption coefficient and peak frequency and between the bottom absorption coefficient and bottom frequency. The samples without a surface skin had higher peak absorption coefficients (0.92 to 0.95). Furthermore, their bottom absorption coefficients existed between 0.70 and 0.75, the dispersion of their bottom absorption coefficients was within 0.05 and smaller than that of samples with surface skin. Thus the performance of the samples without skin is steadier than that of the samples with skin. However, the results for the samples with a surface skin shows that the bottom absorption coefficient decreased when the bottom frequency decreased.

As shown in Fig. 5, the higher the peak absorption coefficient, the lower the bottom absorption. This means that the presence of a surface skin is not compatible with maintaining a high absorption coefficient.

The relationship between the peak and bottom frequencies is illustrated in Fig. 6. There is a positive correlation between them: the bottom frequency decreased with the peak frequency. While this relationship did not depend on the presence of a surface skin, it was stronger for the samples without a surface skin. The dispersion of the frequencies was small and was particularly linear for the samples without a surface skin.

These results show that the presence of a surface skin causes differences in the acoustic absorption properties and their dispersion even though the density and composition of

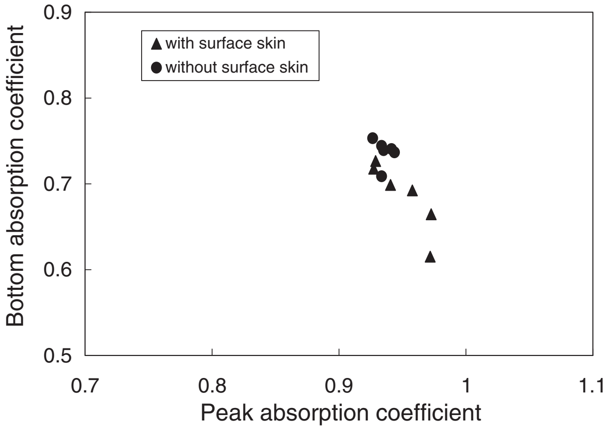


Fig. 5 Relationship between absorption coefficients of bottom (minimum) and peak (maximum).

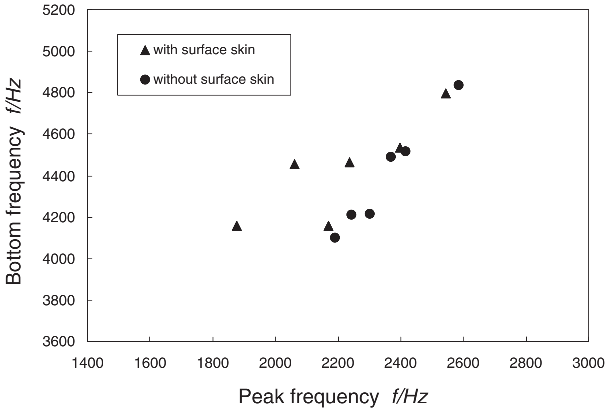


Fig. 6 Relationship between frequencies at bottom (minimum) and peak (maximum) absorption coefficient.

the molded urethane foam were the same. The absorption coefficients of the samples without a surface skin were almost the same; moreover, the changes of the samples without skin in the peak and bottom frequencies were smaller and steadier than those of the samples with a surface skin.

It is well-known that the existence of the peak and bottom frequencies can be clearly seen in the material which has comparatively small sound propagation attenuation. They are caused by periodic changes in the frequency response of the acoustic absorption coefficient in accordance with the periodic properties of the trigonometric function in the expression for the acoustic impedance of the porous material. This relates to wavelength of the sound waves passing through the material, *i.e.* to the speed of sound.

To clarify the relationships between the microscopic structure of the material related to the passing of sound waves and the peak and bottom frequencies, we used X-ray CT scanning to investigate the internal structure for the samples without a surface skin, which affects the peak and bottom frequencies remarkably. The results are presented in the next section.

## 3.3 Internal structure

### 3.3.1 Macroscopic observation and absorption characteristics

The observed cross sections for a sample are shown in Fig. 7. From X-ray CT macroscopic observation in the depth direction, we recognized that a few rough pores ("macroscopic circular cavities") dotted. They had average diameters of 0.8 to 1.4 mm. They were mainly found in area approximately 7 mm below the upper surface. Microscopic observation in a matrix section revealed a porous structure consisting of minute cells ("microscopic cells") that were 310 to 370 μm in average diameter.

The results shown in Fig. 7 demonstrate that it is possible to carry out macroscopic and microscopic observations of the

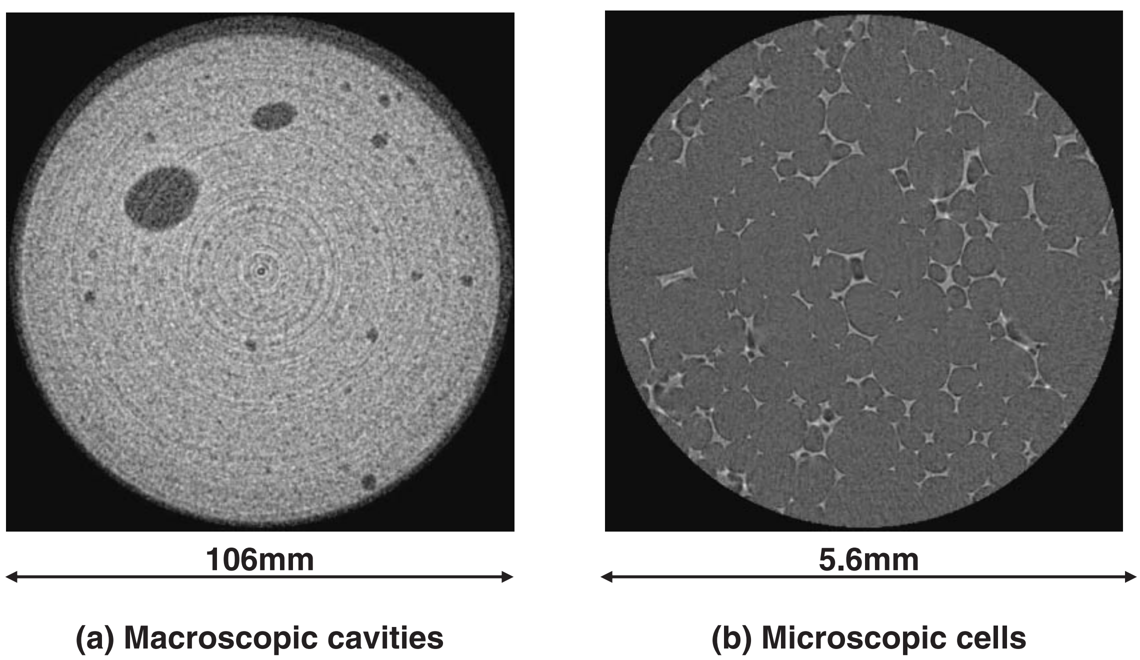


Fig. 7 Two observed cross sections by X-ray CT.

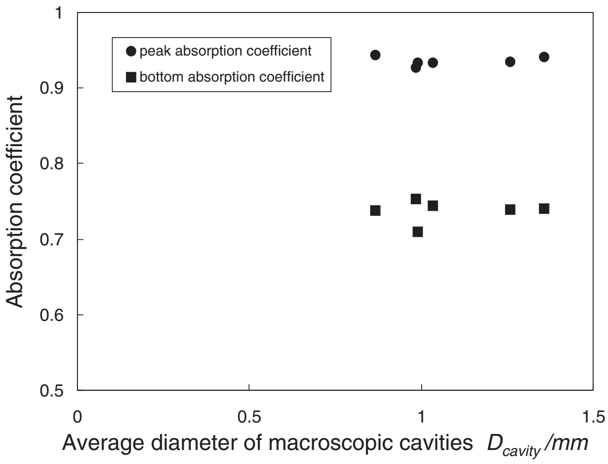


Fig. 8 Relationship between absorption coefficient and average diameter of macroscopic cavities.

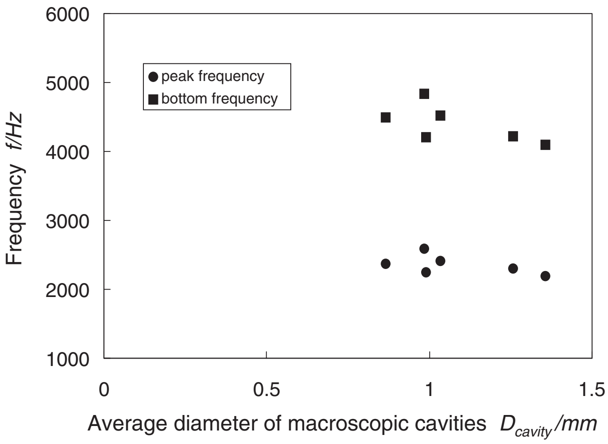


Fig. 9 Relationship between frequency and average diameter of macroscopic cavity.

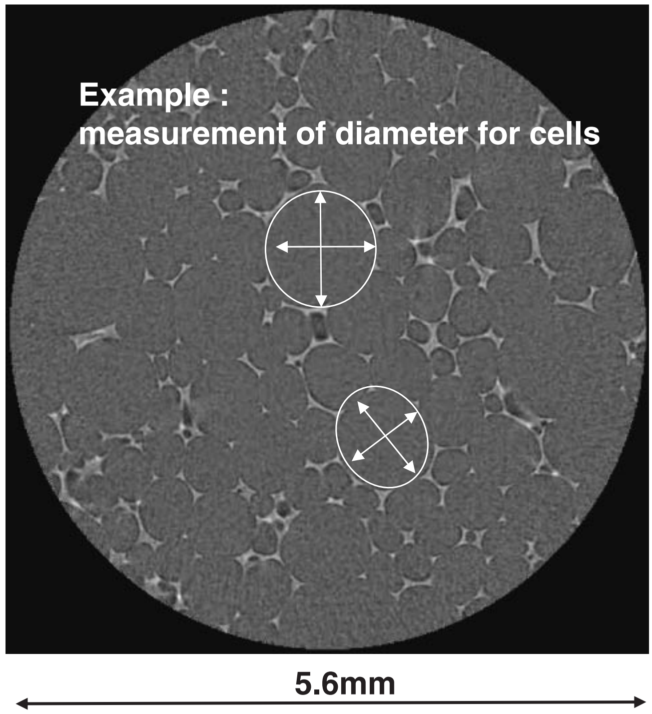


Fig. 10 Definition of evaluation value for cell structure of urethane foam based on X-ray CT photograph.

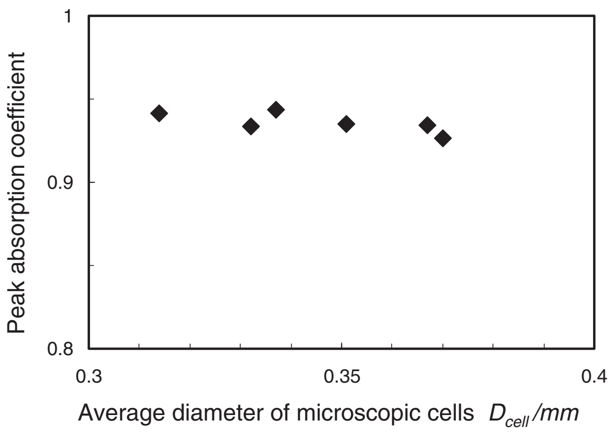


Fig. 11 Relationships between peak and bottom absorption coefficients and urethane foam cell diameter.

internal structure of an acoustic absorption material without destroying it by using two types of X-ray CT scanning devices properly. This method is thus a powerful tool for grasping the microscopic structure of acoustic absorption materials.

To clarify the influence of macroscopic cavities on absorption performance, we examined the relationships among the diameter of the macroscopic circular cavities and the peak and bottom acoustic absorption coefficients. As shown in Fig. 8, an almost steady acoustic absorption coefficient was obtained regardless of the size of the macroscopic cavities.

The relationships among the diameter of the macroscopic circular cavity and the peak and bottom frequencies are shown in Fig. 9. There was no correlation among them because of the large dispersion of the results. These results show that the presence of such cavities in the upper area of urethane foam does not significantly affect absorption performance.

### 3.3.2 Microscopic observation and absorption characteristics

To determine the relationship between the size of the cells in the urethane foam and sound absorption, we conducted detailed microscopic observation using X-ray CT in the 12.5-mm deep area of a test sample (the sample centre), where the state is steady state.

To enable us to evaluate the results quantitatively, we defined the average diameter of the cells as the evaluation value, as illustrated in Fig. 10. The diameters in the long and short directions of each cell, which exists in photograph of X-ray CT scanning (5.6 mm in diameter), were measured, and their average was calculated.

Figure 11 and 12 show the relationships between the peak and bottom acoustic absorptions and the average cell diameter. This shows that the absorption coefficient does not depend on the cell diameter and stays fairly constant.

Figure 13 and 14 show the relationships between the peak and bottom frequencies and the average cell diameter. There

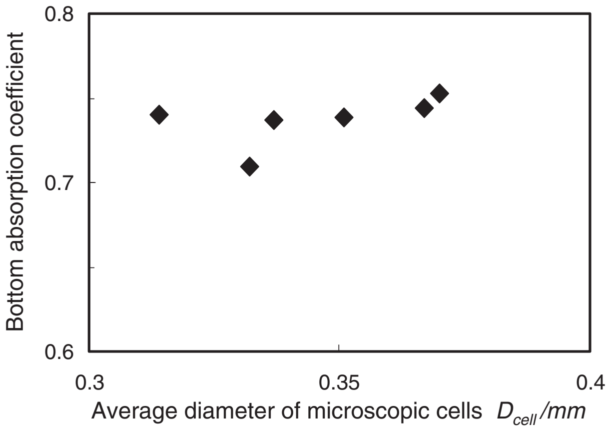


Fig. 12 Relationships between bottom absorption coefficients and urethane foam cell diameter.

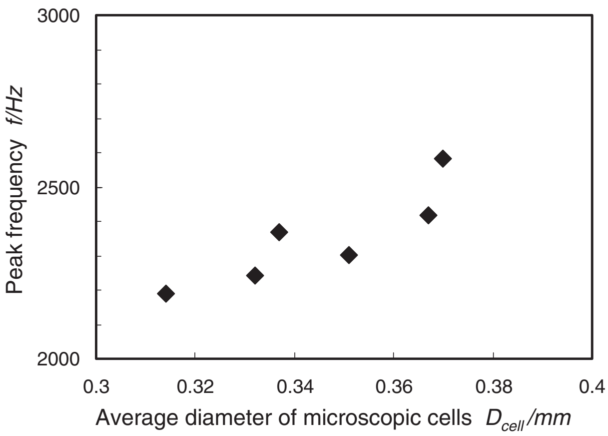


Fig. 13 Relationships between peak frequencies and urethane foam cell diameter.

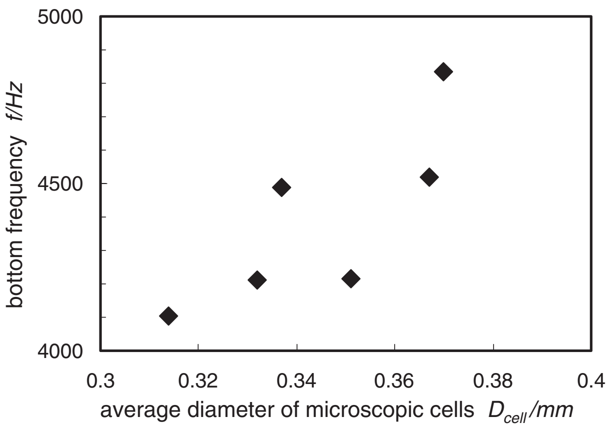


Fig. 14 Relationships between bottom frequencies and urethane foam cell diameter.

is a positive correlation between the average cell diameter and both frequencies.

These results show that the peak and bottom frequencies can be shifted down by reducing the diameter of the cells. However, exponential correlation between cell size and frequency indicates that a needlessly small cell diameter does not contribute to reducing the peak and bottom frequencies.

## 4. Discussion

The results of our experiments indicate that the microscopic cell size affects the peak and bottom frequencies of the normal incidence absorption coefficient. In this section, we theoretically discuss the relationship between cell size and frequency.

The normal incidence absorption for porous materials is related to the normal acoustic impedance, and the normal sound impedance, Zn, without an air cavity behind the material is given by

$$\mathrm{Zn} = -j\mathrm{Zc}\cot(k'd) \tag{1}$$

$d$: material thickness
$k'$: ($k' = \beta - j\gamma$) complex transmission constant
$\beta$: phase constant ($= \omega/C_{\mathrm{M}}$; $\omega$: circular frequency
$C_{\mathrm{M}}$: sound velocity in material)
$d$: attenuation coefficient.

The periodicity of a normal incidence acoustic absorption coefficient is related to the periodic properties of the trigonometric function of this impedance. The maximum value of the acoustic absorption coefficient (the "peak absorption") appears when $\beta$d is an odd number multiple of $\pi/2$.[10–14)]

Since we used a constant thickness of 25 mm, the change in the periodic properties of the frequency was related to $\beta$, that is, sound velocity $C_{\mathrm{M}}$ in the material. Therefore, the correlations between the average diameter of the cells and the peak and bottom frequencies of the acoustic absorption coefficients suggest that cell size affects the speed of sound passing through the air inside the material.

The relationship between frequency and sound velocity is given by

$$f = C_{\mathrm{M}}/\lambda_{\mathrm{M}}, \tag{2}$$

where $_{\mathrm{M}}$ means propagation in the material.

Therefore, our finding that reducing the cell size of the urethane foam reduces the peak frequency of the normal absorption coefficient means that reducing the cell size reduces the velocity of sound in the material, which is given by

$$C_{\mathrm{M}} = (K/\rho)^{1/2} \tag{3}$$

where $\rho$ is the effective density of air in the material, and K is the bulk modulus.

Johnson *et al.* showed that this effective density can be expressed using the following equation.[15,16)]

$$\begin{aligned} \rho &= \rho_0 k_{\mathrm{s}}[1 + \sigma\phi/\mathrm{j}\omega\rho_0 k_{\mathrm{s}} \cdot Gc(S)] \\ &= \rho_0 k_{\mathrm{s}} + \sigma\phi/\mathrm{j}\omega \cdot Gc(S) \end{aligned} \tag{4}$$

where

$$\begin{aligned} Gc(S) = -3/4 \cdot \sqrt{\phantom{x}} - j \cdot J_1(s\sqrt{\phantom{x}} - j)/J_0(s\sqrt{\phantom{x}} - j) \\ /[1 - 2/s\sqrt{\phantom{x}} - j \cdot J_1(s\sqrt{\phantom{x}} - j)/J_0(s\sqrt{\phantom{x}} - j)] \end{aligned}$$

and $\rho_0$ is air density, $k_{\mathrm{s}}$ is the structure factor (tortuosity), $s = c(8\omega\rho_0/\sigma\phi)^{1/2}$, $\phi$ is porosity, $\sigma$ is flow resistivity, c is a parameter depending on the shape of the cross section, and $J$ is a Bessel function.

This structure factor $k_{\mathrm{s}}$ is defined so that it does not depends on fluid in the material and is based on the inside frame structure of the material. Therefore, a decrease in sound velocity, that is, an increase in the effective air density, is related to the structure factor.

Since the cell size of urethane foam affects the frame structure inside the material, that is, the structure factor, an increase in the effective density of air in the material is related to a decrease in the cell size of urethane foam. Therefore, a decrease in cell size of urethane foam increases the complexity of the sound transmission path and increases the structure factor. Furthermore, it increases the effective density of the fluid in the material, which reduces the sound velocity. As a result, the peak frequency of the sound absorption coefficient shifts downward.

## 5. Conclusion

To attain high absorption performance in the low-frequency region without increasing the material weight, we investigated the relationship between the microscopic structure and sound absorption properties of soft urethane foam. The structure was observed using X-ray CT scanning. The molded urethane foam had a density of $0.08\,g/cm^3$ and a thickness 25 mm, the same as when it is used as a soundproof material for automobiles. Several interesting results were obtained.

(1) The characteristics of the normal incident absorption coefficient of the urethane foam differed between samples molded at different temperatures but with the same density.
(2) The presence of a surface skin affected the sound absorption characteristics. When there was no surface skin, the dispersion of the acoustic absorption coefficients was smaller and the sound absorption was steady.
(3) A surface skin was generated more easily when the foam was molded at a lower temperature.
Macro- and microscopic observations of samples without a surface skin by X-ray CT to identify the differences in the internal structure that affects the normal incident absorption properties also resulted in several interesting findings.
(4) The average diameter of the cells in the samples effectively explained the sound absorption properties of the polyurethane foam material.
(5) Continuous observation of the internal structure in the thickness direction revealed the existence of macroscopic cavities and of a region with a steady state cell structure.
(6) These macroscopic cavities were not related to sound absorption.
(7) The frequency can be shifted downward while still maintaining peak acoustic absorption performance by controlling the size of the cells. Reducing the cell size increases the structure factor, shifting the peak frequency downward.

## Acknowledgement

This research is supported by Parker Corporation for supply of materials, and by Fukushima technology center and Shimadzu Corporation for X-ray CT measurement.

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