Sound Absorbing Characteristics of Granular Material Multi-divided by Membranes supported by Rigid Frame

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Summary

This paper investigated techniques to control the sound absorbing characteristics of granular materials without changing thickness. The multi-divided structure of granular materials was proposed, which is granular materials multi-divided by membranes that are supported by a rigid frame. This structure was designed to apply no static load of the upper layer to the lower layer. The normal incident sound absorption coefficients of two types of specimen, namely non- and multi-divided structure of hollow glass beads, were measured using a cylindrical acoustic tube. For the non-divided structure, the first peak frequency of the sound absorption coefficient shifted toward a lower frequency side as the thickness increased. When the thickness further increased, the shift of first peak frequency became smaller. The first peak frequency of the multi-divided structure appeared at a lower frequency than that of the non-divided structure of the same thickness. In addition, the first peak frequency shifted toward a lower frequency side as the number of division increased. The first peak frequency was calculated from the effective mass and the apparent dynamic stiffness for the granular materials. The effective mass was evaluated by the effective axial stress inside the granular materials filled in a container. The apparent dynamic stiffness of the multi-divided structure was evaluated as a series connection of the dynamic stiffness of each layer. The calculation of the first peak frequency was almost in a good agreement with the experimental results with respect to the multi-divided structure.

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1. Introduction

There are machines that generate low-frequency noise, such as transformers and large rotating equipment [1]. Low-frequency sound absorbers are generally required to suppress such noise. In terms of architectural application, it is desired to reduce the thickness of the sound absorbing layer as much as possible so as to increase the effective space in a room.

Porous materials are widely used as sound absorbers in the architectural field. A lot of studies have been conducted on sound absorbing characteristics of porous materials on a theoretical or experimental basis [2]. Many of these deal with models that only consider sound propagation through the air in a rigid porous frame [2,3,4 for instance]. Included in the category of these models are rock wool [4] and dense glass beads [5] as examples of fibrous and granular materials. Low-frequency sound absorption using these porous materials requires thicker materials or a larger air space behind the material. On the other hand, it is reported that there are several granular materials that show sound absorbing characteristics different from rock-wool and dense glass beads. Z. Hong et al. measured the normal incident sound absorption coefficients of multi-porous hollow polymer micro-spheres [6]. Y. Okudaira et al. measured the normal incident sound absorption coefficients of six kinds of granular materials including the granulated silica [7]. These granular materials showed the sound absorbing characteristics with distinct peaks at specific frequencies. The first peak of the normal incident sound absorption coefficient of those materials appeared at a lower frequency than that of rock wool of the same thickness. Hence, the granular materials have a possibility of being used as low-frequency sound absorbers, if it is possible to control the peak frequency of the sound absorption coefficient. In addition, it is possible that the thickness of sound absorbing layer can be reduced by using the granular materials compared with rock wool.

It was found that the peak frequencies of the normal incident sound absorption coefficient correspond to the mode frequencies of one-dimensional vibration of the particle layer for the granular materials showing the sound absorbing characteristics with peaks at specific frequencies [8]. Y. Okudaira et al. measured the vibration acceleration with respect to the sound propagation direction at every depth in the granular materials filled in a cylindrical container as well as the normal incident sound absorption coefficients when sound waves were incident perpendicularly to the granular materials. Then, it was confirmed that the one-dimensional vibration mode was excited with the bottom as a fixed end in the sound propagation direction. From this, it is considered that adjusting the vibration-mode leads to control of the sound absorbing characteristics for the granular materials. A. J. Matchett and T. Yanagida studied on the vibration-mode of granular materials [9]. They presented the model to predict the first-order mode frequency of vibration and the apparent dynamic stiffness for granular materials filled in a cylindrical container that vibrates in one direction. According to the formula derived by A. J. Matchett and T. Yanagida, it is necessary to increase the thickness when shifting the first-order mode frequency toward a lower frequency side. However, they indicated from their experimental results that the first-order mode frequency of the granular materials filled in a container might become a constant value when the thickness further increases.

The purpose of this study is to investigate techniques to control the first peak frequency of sound absorption coefficients for the granular materials which show the sound absorbing characteristics with peaks at specific frequencies without changing thickness. The multi-divided structure of granular materials, which is granular materials divided by membranes that are supported by a rigid frame, (hereinafter the multi-divided structure) is proposed to control the first peak frequency. The multi-divided structure is designed to decrease the total dynamic stiffness by applying no static load of the upper layer to the lower layer. The second section describes the calculation procedure of the first peak frequency of the normal incident sound absorption coefficient for the multi-divided structure. The third section shows the measurement condition for determining the normal incident sound absorption coefficient of granular materials and the composition of the multi-divided structure. The calculated values and the experimental results of the first peak frequency of normal incident sound absorption coefficient for the multi-divided structure are shown in the last section.

2. Calculation of first peak frequency

This paper assumes one-dimensional sound propagation in granular materials. According to the knowledge in the reference [8], the first peak frequency of the normal incident sound absorption coefficient corresponds to the first-order mode frequency of vibration in one-dimensional sound propagation for several granular materials. It is assumed that the granular materials in this paper also satisfy this condition. The first-order mode frequency of vibration is expressed by Eq. (1) [9], so it is considered that the first peak frequency of sound absorption f_0 is also given by this equation.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{M_{eff}}} \tag{1}$$

where k is the apparent dynamic stiffness, and M_{eff} is the effective mass.

The apparent dynamic stiffness of granular materials filled in a container is expressed by the following equation [9].

$$k = S\beta E_0 (P - \frac{\rho g}{\beta})(n-1) \times \left[(\frac{\rho g}{\beta} + (P - \frac{\rho g}{\beta})e^{-\beta h})^{1-n} - P^{1-n} \right]^{-1} \tag{2}$$

where ρ is bulk density, g is gravity acceleration, P is external force applied to the surface of the material in the sound propagation direction, h is thickness of granular materials, S is the cross-sectional area of a container, and E_0 is proportionality constant. Since it is experimentally confirmed that n takes the value of 1/3 in many granular materials [9,10], n in this paper also takes the same value. β is called the Janssen coefficient, and in the case of a cylindrical container, it is given as follows [11]:

$$\beta = \frac{4K\mu_W}{d} \tag{3}$$

K is called the redirection coefficient, which is defined as the ratio of horizontal stress toward the wall to vertical stress in sound propagation direction. μ_w is the friction coefficient between wall and granular materials, and d is inner diameter of a container.

If the external force applied to the surface of the material in the sound propagation direction is small enough to establish $\rho g/\beta - P \approx \rho g/\beta$, Eq. (2) is expressed by Eq. (4).

$$k = SE_0(1-n)(\rho g)^n (\frac{1-e^{-\beta h}}{\beta})^{n-1} \quad (4)$$

Two approaches are conceivable for the effective mass of the granular materials.

One is the approach that the effective mass is evaluated by the Rayleigh method [12]. In the Rayleigh method, a homogeneous elastic body is replaced with spring-mass systems, and the effective mass per direction is calculated by kinetic energy conservation law. Since this study focuses on sound propagation in a single direction, the effective mass M_{eff} is one third of the actual mass. That is:

$$M_{eff} = \frac{1}{3}\rho h S \quad (5)$$

The other approach is to evaluate from the effective axial stress. The effective axial stress σ inside granular materials filled in a container is given by the following equation [13].

$$\sigma = \frac{\rho g}{\beta}(1-e^{-\beta x}) \quad (6)$$

The effective mass is obtained by substituting σ in Eq. (6) into Newton's law, $\sigma S = M_{eff}\, g$.

$$M_{eff} = \frac{\rho}{\beta} S(1-e^{-\beta h}) \quad (7)$$

The first peak frequency of the non-divided structure is determined from Eq. (1) by substituting k in Eq. (4) and M_{eff} in Eq. (5) or Eq. (7).

The multi-divided structure is designed to apply no static load of the upper layer to the lower layer. In this composition, the dynamic stiffness k_i of i-th layer divided by the membranes is expressed by Eq. (4) by substituting the thickness h_i of each layer into h in Eq. (4). It is assumed that the total apparent dynamic stiffness of the multi-divided structure is expressed by a series connection of the dynamic stiffness of each layer.

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2} + \cdots + \frac{1}{k_i} + \cdots + \frac{1}{k_m} \quad (8)$$

The subscript "m" indicates the number of divided layers.

The first peak frequency of the multi-divided structure is determined from Eq. (1) by substituting k in Eq. (8) and M_{eff} in Eq. (5) or Eq. (7).

3. Measurements

The normal incident sound absorption coefficients were determined by the transfer-function method according to ISO10534-2:1998 [14]. Fig. 1 illustrates the measuring apparatus. The measurements were made using a steel cylindrical acoustic tube of 100 mm in inner diameter. The acoustic tube was set to make its axial direction perpendicular to the ground. The loud speaker is set at the upper end and the specimen was installed at the lower end which is the ground side. A pseudo random noise was used as a sound source. Hollow glass beads(Qcel5020 made by Potters-Ballotini Co. Ltd.) were used as a granular specimen. The physical properties of the specimen are given in Table 1. The specimen was poured with light tapping into a cylindrical container made of PLA (polylactic acid) resin. The surface of the specimen was leveled smoothly after pouring. The frame of container was attached to the wall of the acoustic tube, and the contact gap between the container and the tube was sealed by petrolatum. The sound absorption coefficient with an empty container was about 0.01 in the frequency range from 40 to 2k Hz. It was confirmed that the effect of container itself and the contact gap on sound absorption coefficients was small. The membranes were films made of PP (polypropylene) of 0.2mm in the thickness. The area density of the films is 0.18 kg/m^2. Fig. 2 shows a schematic diagram of the multi-divided structure of granular materials. The membranes were bonded to the wall of the container to apply no static load of the upper layer to the lower layer. The sound absorption coefficients were measured for three specimens under each condition, and the sound absorption coefficients were determined from averaging these three experimental results. The difference of the sound absorption coefficients among the three specimens under each condition was less than 0.01.

Table 1. The physical properties of hollow glass beads used in the measurements.

Granular material	hollow glass beads
Mean Particle Diameter (μm)	60
Bulk Density (g/cm^3)	0.20
True Density (g/cm^3)	0.11
Porosity	0.45

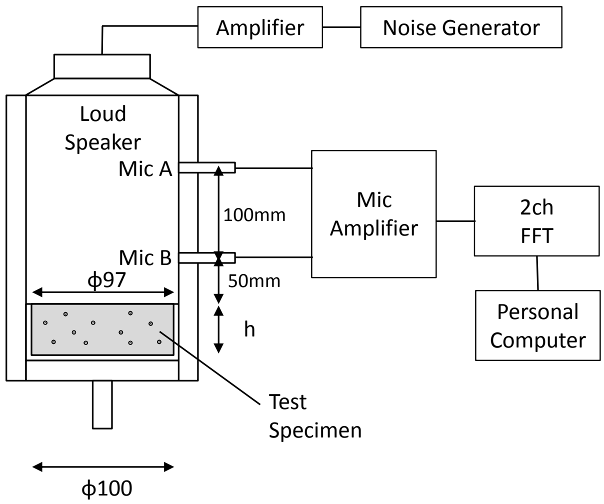

Fig. 1. The measuring apparatus for determining the normal incident sound absorption coefficient of granular materials.

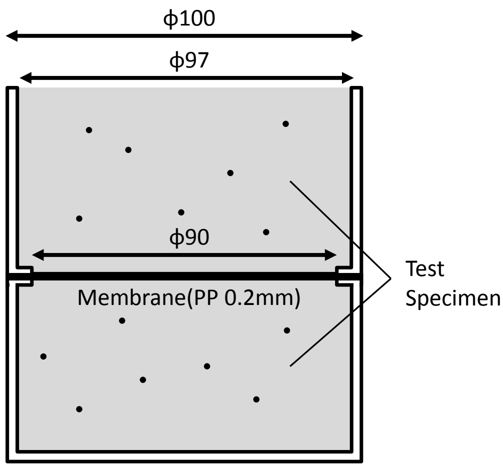

Fig. 2. The composition of multi-divided structure of granular materials. The granular materials are divided by membranes, and the membranes are supported by a frame of cylindrical container.

4. Results and discussion

Fig. 3 shows the experimental results of the normal incident sound absorption coefficient of the non-divided structure of hollow glass beads. Measurements were made with the thickness varying in the range from 20 mm to 550 mm. The first peak frequency of sound absorption coefficient shifted toward a lower frequency side as the thickness increased. The shift of first peak frequency became smaller when the thickness exceeded around 160 mm. The parameters E_0 in Eq. (4) and $K\mu_w$ in Eq. (3) were estimated from the experimental results. The experimental results of the first peak frequencies $f_{0,\text{meas}}$ in Fig. 3 are plotted as a function of thickness in Fig. 4. The calculated curves using Eq. (1) were fitted to the experimental results in Fig. 4 by the least-squares method to estimate the parameters. Table 2 shows the estimated values in the case that Eq. (5) and Eq. (7) are applied as the effective mass, respectively. Though $K\mu_w$ is physically in the range of, $0 \leqq K\mu_w \leqq 1$, it exceeded this range when Eq. (5) was applied. Fig. 4 shows the calculation of the first peak frequency $f_{0,\text{calc}}$ applying Eq. (5) or Eq. (7) to the effective mass. The estimated values in Table 2 were substituted for E_0 and $K\mu_w$, respectively. The difference between the calculation and the experimental results was smaller in the case of applying Eq. (7) to the effective mass than applying Eq. (5), especially with the thickness exceeding over 160 mm. From this result, it is presumed that the effective mass is proportional to the effective axial stress when the sound wave propagates in one direction inside the granular materials. When Eq. (7) is applied as the effective mass, the calculation of the first peak frequency shows the tendency of converging to a specific value as the thickness increases. This tendency is consistent with the suggestion by A. J. Matchett and T. Yanagida [9] that the peak frequency of vibration become a constant value as the thickness increases.

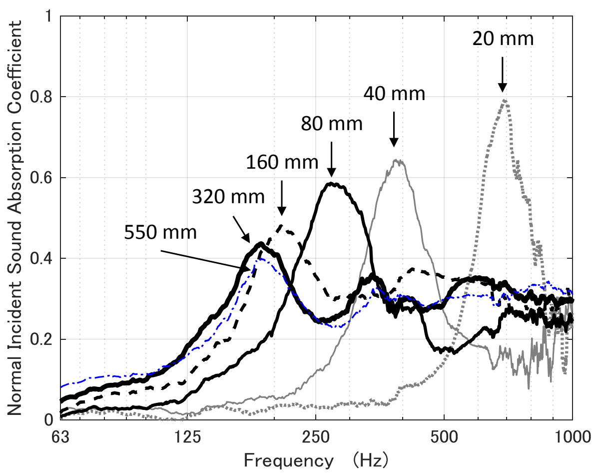

Fig. 3. The experimental results of the normal incident sound absorption coefficient for the non-divided structure of hollow glass beads with varying thickness.

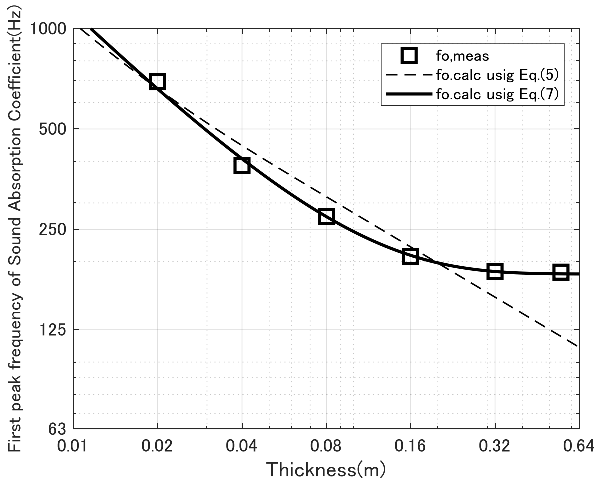

Fig. 4. The calculations using Eq. (5) and Eq. (7) as the effective mass, and experimental results of the first peak frequency of normal incident sound absorption coefficient for the non-divided structure of hollow glass beads as a function of thickness.

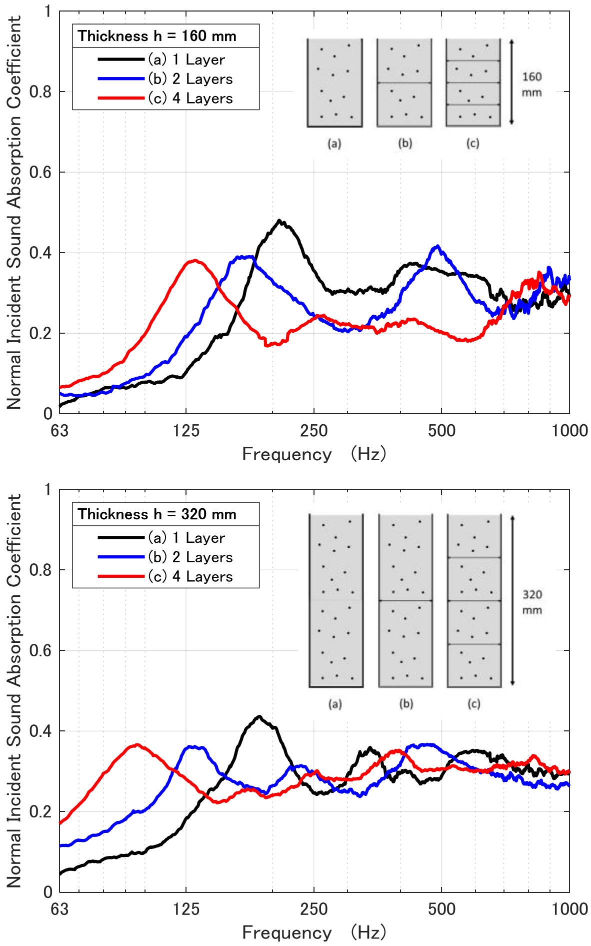

Fig. 5. The experimental results of the normal incident sound absorption coefficient for the multi-divided structure of hollow glass beads (Top:160mm in total thickness, Bottom:320mm in total thickness). The multi-divided structures were equally divided to two and four layers.

Table 2. The estimated values of E_0 and $K\mu_w$ by applying Eq. (5) and Eq. (7) to the effective mass.

	using Eq.(5) $M_{eff} = \rho h S \dfrac{1}{3}$	using Eq.(7) $M_{eff} = \dfrac{\rho}{\beta} S(1-e^{-\beta h})$
E_0	8.43×10^4	35.39×10^4
$K\mu_w$	2.31	0.29

The experimental results of the normal incident sound absorption for the multi-divided structure of hollow glass beads with the total thickness of 160 and 320 mm are shown in Fig. 5. The multi-divided structures with each total thickness were equally divided to two and four layers, respectively. The first peak frequency of the multi-divided structure appeared at a lower frequency than that of the non-divided structure. When the number of division increased, the first peak frequency shifted further downward. The calculations are compared with the experimental results with respect to the first peak frequency. The calculations and experimental results of the multi-divided structure are plotted as a function of thickness in Fig. 6. This figure shows the experimental results for the case of two divisions with a total thickness of 80 mm in addition to the results in Fig. 5. The calculations are obtained by applying Eq. (7) to the effective mass. The parameters E_0 and $K\mu_w$ in the calculation are the estimated values in Table 2. As shown in Fig. 6, the calculations are in a good agreement with the experimental results of the multi-divided structure. Thus, the assumption of Eq. (8) is considered appropriate in this composition. Furthermore, according to the calculations, the peak frequency of the multi-divided structure may take a value smaller than the lowest frequency of the non-divided structure. The first peak frequency in the calculation is slightly higher than that in the measurements in the case of the divided structure into four layers. As one of the reasons, it is considered that the mass and the tension of the membranes may be attributed to the difference. Detailed examination of these effects will be a future task and will not be discussed further in this paper.

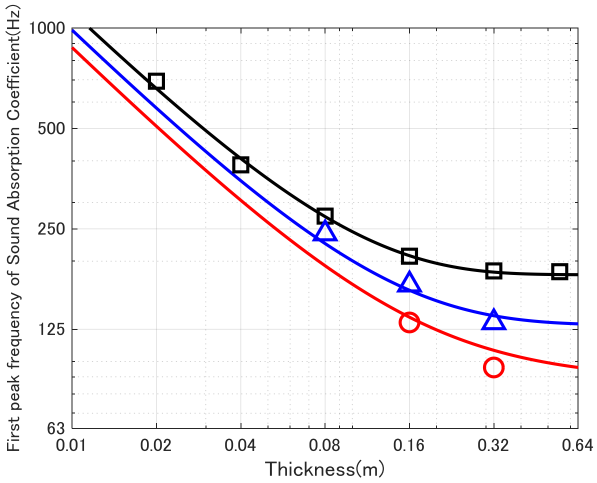

Fig. 6. The experimental results and calculations of the first peak frequency of the normal incident sound absorption coefficients for the non- and multi-divided structure of hollow glass beads as a function of thickness. （Measurements- □:1 layer; △:2 layers; ○:4 layers, Calculation using Eq. (7)- —:1 layer; —:2 layers; —:4 layers）

5. Conclusion

This paper proposed the multi-divided structure of granular materials, which was granular materials divided by membranes that were supported by a rigid frame, as a technique to control the sound absorbing characteristics of granular materials without changing thickness. The first peak of the sound absorption coefficient for the non-divided structure shifted to a lower frequency side as the thickness increased. When the thickness further increased, the first peak frequency showed the tendency of converging to a specific value. The first peak of the multi-divided structure appeared at a lower frequency than that of the non-divided structure of the same total thickness. As the number of division increased, the first peak frequency shifted to a lower frequency side. It was assumed that the effective mass was proportional to the effective axial stress and that the apparent dynamic stiffness of the multi-divided structure was evaluated as a series connection of the dynamic stiffness of each division. The experimental results confirmed that these assumptions were appropriate. Consequently, it is considered that the multi-divided structure of granular materials is effective in controlling the first peak frequency of sound absorption coefficient without changing the thickness. The multi-divided structure also has a possibility of accomplishing a lower first peak frequency of sound absorption than the lower limitation of the non-divided structure.

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