



# Effect of a honeycomb on the sound absorption characteristics of panel-type absorbers

Toyoda, Masahiro  
Sakagami, Kimihiro  
Takahashi, Daiji  
Morimoto, Masayuki

---

(Citation)

Applied Acoustics, 72(12):943-948

(Issue Date)

2011-12

(Resource Type)

journal article

(Version)

Accepted Manuscript

(URL)

<https://hdl.handle.net/20.500.14094/90001612>



# Effect of a honeycomb on the sound absorption characteristics of panel-type absorbers

Masahiro Toyoda<sup>a</sup>, Kimihiro Sakagami<sup>b</sup>, Daiji Takahashi<sup>c</sup>, Masayuki Morimoto<sup>b</sup>

<sup>a</sup>*Department of Architecture, Faculty of Environmental and Urban Engineering, Kansai University,*

*3-3-35, Yamate-cho, Suita-shi, Osaka 564-8680, Japan*

<sup>b</sup>*Environmental Acoustics Laboratory, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe, 657-8501 Japan*

<sup>c</sup>*Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University,*

*C1-4-385, Kyoto Univ. Katsura, Nishikyo-ku, Kyoto, 615-8540 Japan*

---

## Abstract

Panel-type sound absorbers are commonly used to absorb low-frequency sounds. Recently, a new type of panel/membrane absorbers has been proposed as a next-generation sound absorber free from environmental problems. On the other hand, it is known that placing a honeycomb structure behind a porous layer can improve sound absorption performance and a similar effect can be obtained for microperforated-panel absorbers. Herein, the sound absorption characteristics of a panel sound absorber with a honeycomb in its back cavity are theoretically analyzed. The numerical results are used to discuss the variations in the sound absorption characteristics due to the honeycomb as well as the mechanism for sound absorption.

*Keywords:* Panel-type absorber, Honeycomb, Sound absorption, Sound transmission

---

## 1. Introduction

Panel- and membrane-type sound absorbers have long been used for sound absorption, especially at low frequencies. They are also employed recently for

---

*Email address:* toyoda@kansai-u.ac.jp (Masahiro Toyoda)

various purposes as substitute materials for porous sound absorbers with environmental problems. Therefore, a new type of panel/membrane absorbers has been proposed as a next generation sound absorber [1].

Brueel's pioneering work [2] initiated studies on the absorption characteristics and mechanisms of panel and membrane sound absorbers. Kimura has conducted comprehensive experimental studies [3], and his results have been included in many textbooks. Ford and McCormick [4], Hiraizumi et al. [5], etc. have also performed theoretical studies. Additionally, our series of theoretical studies, which assumed the panel extends infinitely [6, 7, 8], have contained detailed discussions, including the effect of the backing structure. Along with Bosmans et al. [9], etc., we have theoretically analyzed membrane-type absorbers [10].

Additionally, the acoustical effect of honeycombs in the back cavity of sound absorbing systems has been studied, particularly for porous absorbent materials [11]. Placing a honeycomb structure behind a porous layer can improve the sound absorption performance, especially low frequencies. Consequently, a honeycomb structure can broaden the absorption frequency range. With regard to other sound absorption materials, the authors have studied MPP (microperforated panel) absorbers with a honeycomb structure attached behind them [12, 13]. All of these studies have observed a similar effect. Although the honeycomb structure itself is typically used to reinforce a room interior surface, its acoustical effect is noteworthy. This acoustical effect is attributed to its properties that force the sound wave in the honeycomb cells to propagate normal to the absorbing surface. When the honeycomb divides a cavity into narrow cells, the sound field in each cell can be assumed to be locally one-dimensional. This assumption is valid if the cell width is less than one-half wavelength of air [13, 14, 15]. The sound wave impinging on the honeycomb surface is forced to propagate inside the honeycomb layer in the direction normal to the surface. Consequently, the sound wave is inferred to be similar to the case of normal incidence [12]. Therefore, a honeycomb should show a similar effect on different types of sound absorbing materials. As introduced above, there have been some studies showing that honeycombs can improve the absorption performance of porous materials and MPP absorbers. However, the effect of honeycombs on panel-type absorbers has not yet been studied. Although a similar effect to those on porous materials and MPP absorbers can be expected by controlling the sound wave propagation in the back cavity, different phenomena and behaviors could be observed because the absorption mechanism of a panel-type absorber is ob-

viously different from those of porous materials and MPP absorbers. Therefore, a possibility of honeycombs for improving the performance of panel-type absorbers should be investigated in detail.

Panel/membrane-type sound absorbers are usually composed of an interior wall and its back space, except in cases where they are designed and installed for a specific purpose. Thus, the interior surfaces must be reinforced and supported by a structural element such as a frame, joist, etc. Honeycombs can also serve as reinforcement. However, when the panel is intended to absorb sound, the vibration of the panel can be disturbed and sound absorption may deteriorate if the panel is tightly bonded to the honeycomb. Furthermore, honeycombs can be used for acoustical purposes if the surface or structure is sufficiently strong, which can improve the sound absorption performance.

In this study the sound absorption characteristics of a panel sound absorber with a honeycomb in its back cavity is theoretically analyzed. The numerical results are used to discuss the effect of the honeycomb on the sound absorption characteristics and the honeycomb mechanism. The theoretical analysis assumes the panel extends infinitely. Both the vibration of the panel and the sound field are expressed by the standard form of a standing wave. The discussion herein focuses on the influence of the honeycomb on the sound absorption characteristics.

## 2. Theoretical consideration

Figure 1 shows a model of a panel sound absorber with an air-backed cavity. The panel is a thin plate that extends infinitely and is located at  $z = 0$  with density  $\rho$ , thickness  $h$ , Young's modulus  $E$ , loss factor  $\eta$ , Poisson's ratio  $\nu$ , and complex flexural rigidity  $D = E(1 - i\eta)h^3/\{12(1 - \nu^2)\}$ . The specific acoustic admittance of its illuminated surface is  $A_1$ , and that of the back side (transmitted side) is  $A_2$ . The back cavity is divided into two layers with depths  $d_1$  and  $d_2$ . A honeycomb can be inserted into one or both of these layers. However, this study assumes the panel and the honeycomb are not in mechanical contact (i.e., they do not have a force transmission). The back wall located at  $z = d_1 + d_2$  is rigid with surface specific acoustic admittance  $A_b$ . The time factor  $e^{-i\omega t}$  is suppressed throughout, and  $i$  is an imaginary unit,  $\omega$  is the angular frequency, and  $t$  is time.

In this case, the equation of motion for the panel displacement  $w(x)$  can

be written as

$$D \frac{\partial^4 w(x)}{\partial x^4} - \rho h \omega^2 w(x) = p_1(x, 0) - p_2(x, 0), \quad (1)$$

where  $p_j(x, z)$  ( $j=1,2,3$ ) is the sound pressures of  $j$ th layer. Assuming an incident plane wave with a unit pressure amplitude upon the panel with an angle of incidence  $\theta$ ,  $w(x)$ ,  $p_j(x, z)$ , and the particle velocities  $v_j(x, z)$  can be expressed in terms of unknown quantities  $W$  and  $P_j^\pm$  as

$$w(x) = W e^{ik_0 x \sin \theta}, \quad (2)$$

$$p_j(x, z) = (P_j^+ e^{ik_0 z \cos \theta} + P_j^- e^{-ik_0 z \cos \theta}) e^{ik_0 x \sin \theta}, \quad (3)$$

$$v_j(x, z) = \frac{\cos \theta}{\rho_0 c_0} (P_j^+ e^{ik_0 z \cos \theta} - P_j^- e^{-ik_0 z \cos \theta}) e^{ik_0 x \sin \theta}, \quad (4)$$

where  $\rho_0$  is the density of air,  $c_0$  is the speed of sound,  $k_0 = \omega/c_0$  is the wavenumber of air, and  $P_1^+ = 1$ . In the case of a layer with a honeycomb,  $\theta = 0$  can be substituted into cosines in Eqs. (3) and (4). The sines in the equations remain even in the honeycomb layer. This condition means the cell width of the honeycomb is infinitely small and the surface of a cell wall is perfectly smooth. The former assumption is valid if the cell width is less than one-half wavelength of air [13, 14, 15]. Although the latter assumption would be also ideal, the treatment of a honeycomb layer is on the safe side; when the surface is not smooth, additional sound absorption due to energy loss at the surface can occur especially at high frequencies.

Allowing for admittances of the panel and the back wall, the boundary conditions can be written as

$$v_1(x, 0) = -i\omega w(x) + A_1 p_1(x, 0), \quad (5)$$

$$v_2(x, 0) = -i\omega w(x) - A_2 p_2(x, 0), \quad (6)$$

$$p_2(x, d_1) = p_3(x, d_1), \quad (7)$$

$$v_2(x, d_1) = v_3(x, d_1), \quad (8)$$

$$v_3(x, d_1 + d_2) = A_b p_3(x, d_1 + d_2). \quad (9)$$

By substituting Eqs. (2)–(4) into Eqs. (1) and (5)–(9), the solutions for unknown quantities  $W$  and  $P_j^\pm$  can be obtained. Then the oblique incidence absorption coefficient  $\alpha_\theta = 1 - |P_1^-|^2$  can be calculated, and the sound-field-averaged absorption coefficient is determined by taking the average from 0 to 78 degrees for the angle of incidence  $\theta$  over the half space.

### 3. Numerical Examples and Discussion

#### 3.1. Effect of honeycomb: normal and oblique incidences

Figure 2 shows numerical examples of the normal and oblique ( $\theta=30, 60, 75$  degrees) absorption coefficients relative to the field-incidence-averaged absorption coefficient. Herein the back cavity is assumed to be completely filled with the honeycomb by setting  $d_1=0.045$  m and  $d_2=0$  m (therefore, the thickness of the honeycomb is also  $d_1$ ). The specific acoustic admittance  $A_b$  is set to zero, and the specific acoustic admittances  $A_1$  and  $A_2$  are set to 0.026. The admittance of 0.026 means absorption coefficient of 0.1 without phase shift, which is considered herein as the mean value of sound absorption coefficients due to the surface roughness of plywood. As a matter of course, the sound absorption characteristics of plywood surface depend on frequency. We however give the constant value of 0.026 at all frequencies in order to abstract the effect of surface absorption. Figures 2(a) and (b) show those without and with a honeycomb, respectively.

For the normal and oblique incidence cases, the peak frequencies drastically change with the angle of incidence as well as the presence of a honeycomb (Fig. 2(a)). Without a honeycomb, the peak frequency increases as the angle of incidence increases. Additionally, the peak value varies with the angle. In this example, the peak is highest for  $\theta=60$  degrees. In contrast, the peak frequency does not change with the angle of incidence upon applying a honeycomb (Fig. 2(b)). (It should be noted that the peak frequency changes more than two octaves without a honeycomb.) Therefore, in the case of a honeycomb-inserted absorber, the peak frequency is independent of the angle of incidence. Attaching a honeycomb causes the peak frequency characteristics to become similar to those in the case of normal incidence. However, the peak value for the honeycomb case is similar to the case without a honeycomb, except where  $\theta=75$  degrees and a significant peak is not present (compare Figs. 2 (a) and (b)).

In the field-incidence-averaged case, the characteristics are the results of the average of the characteristics for each angle of incidence. Thus, the peak becomes sharper and higher with a honeycomb (Fig. 2(b)). The peak frequency remains nearly constant in the normal incidence case, but is lower than the peak frequency of the field-incidence-averaged case without a honeycomb. Thus, the honeycomb shifts the peak frequency to a lower frequency and increases the peak value, effectively improving the sound absorption performance of panel absorbers. Although the peak becomes narrower, which

means the effective absorption frequency range decreases, the reduction is not very significant. However, because the honeycomb increases the peak value, the honeycomb may be effectively used as a frequency-selective sound absorption system with a specific purpose.

### 3.2. Deterioration due to the honeycomb

Figure 3 shows the numerical results for different honeycomb thickness within a cavity, which has a total depth of  $d_1+d_2=0.05$  m. In this case, placing the honeycomb behind the panel or in front of the back wall does not affect the results. Thus, the example shows the results when the honeycomb is situated just behind the panel.

As the peak thickness increases, the peak frequency decreases. The peak becomes sharper until it reaches its maximum when the honeycomb thickness is half the total cavity depth, and then the peak diffuses. Although the previous section states that the honeycomb increases the peak value, the aforementioned value is not the maximum.

For a larger cavity depth, this tendency appears to be more drastic. Figure 4 shows the results for the total cavity depth of  $d_1+d_2=0.2$  m. In this case the peak frequency decreases as the honeycomb thickness increases, but the peak does not become sharper. Actually, the peak becomes more diffuse. Hence, inserting a honeycomb in the cavity is ineffective. Thus, inserting a honeycomb into the back cavity does not necessarily improve the acoustic performance of a panel absorber.

Figure 5 shows the influence of the angle of incidence on the oblique incidence absorption coefficient of the absorber with the same parameters. In the case without a honeycomb (Fig. 5(a)), the peak absorption coefficient increases with the angle. However in the case with a honeycomb (Figs. 5(b)–(d)), the absorption coefficient decreases for a large angle of incidence. Hence, if these characteristics are averaged, the overall field-incidence-averaged absorption coefficient with a honeycomb decreases.

## 4. Mechanism

The phenomenon where peak absorption decreases with honeycomb thickness, which is described in the previous section, can be interpreted from the previous results by the authors [15]. In studies on the sound transmission through a single wall, transmission loss increases when honeycombs divide the back side of the wall. In the case of a panel sound absorber, acoustical

damping in a cavity that absorbs the sound energy transmitted through the panel via the vibration by the incidence sound is large. Therefore, when the transmitted energy through the panel decreases due to the honeycomb, the energy in the cavity itself becomes smaller. Consequently, the sound absorption efficiency is reduced. To clarify the mechanism for the variation of the absorption coefficient by a honeycomb, herein we discuss sound reflection from the viewpoints of the honeycomb itself and sound transmission through a single panel attached to a honeycomb.

Equations (3), (4), (7), and (8) can model a honeycomb located in free air where  $P_3^- = 0$  with the boundary conditions  $p_1(x, 0) = p_2(x, 0)$  and  $v_1(x, 0) = v_2(x, 0)$ . The second layer of the honeycomb is modeled by substituting  $\theta = 0$  into cosines in Eqs. (3) and (4). Then the reflection ratio of the honeycomb  $R_\theta = |P_1^-|^2$  can be obtained by solving the simultaneous equations. Figure 6 shows the effect of the angle of incidence on the reflection ratio when the honeycomb is 0.1 m thick. Considering the treatment of a honeycomb, the reflection ratio under a normal incidence is naturally zero. However for oblique incidences, the peak reflection ratio increases when the angle is large, but the reflection ratio for all angles reaches zero around 1.7 kHz and 3.4 kHz due to  $z$ -directional resonances inside the honeycomb cells. Figure 7 shows the effect of honeycomb thickness for  $\theta=75$  degrees. The reflection ratio at low frequencies increases when the honeycomb thickness is large, except at resonance frequencies. Hence, the honeycomb layer reflects sound according to its thickness and the angle of incidence.

Placing a honeycomb on the back side of a panel causes the honeycomb to reflect the transmitted sound through the panel. Consequently, the transmission loss of the panel increases [15]. Equations (1)–(8) can model a single panel with a honeycomb where  $P_3^- = 0$ . The transmission loss  $TL_\theta = 20 \log_{10}(1/|P_3^+|)$  can be obtained by the same manner as above. Figure 8 shows the numerical results for different honeycomb thicknesses when the honeycomb is placed just behind the panel and the panel parameters are the same as those in the preceding section. The transmission loss generally increases due to the reflection characteristics of the honeycomb. However, the increase in the transmission loss with thickness is not monotonic. Figure 9 is an enlargement of the variations in the transmission loss around 125 Hz and 250 Hz. As honeycomb thickness increases from 0 m, the transmission loss initially decreases slightly, but then increases. These turning points of thickness are between 0.05 and 0.15 m for 125 Hz and between 0.025 and 0.05 m for 250 Hz. Therefore, it can be inferred that the turning point for



thickness becomes thinner at higher frequencies.

From the above investigations and considering that a smaller transmitted energy into the back cavity leads to a lower sound-absorption efficiency, factors that influence the variation in the absorption characteristics by the honeycomb into a panel-type absorber can be summarized as follows.

1. As the honeycomb thickness increases, the fluctuation in the peak frequency due to the angle of incidence decreases.
2. As the honeycomb thickness increases, the transmitted energy into the back cavity slightly increases, but then decreases.
3. The turning point for thickness is thinner at higher frequencies.

The absorption coefficient is determined by these factors, and depends on both frequency and honeycomb thickness. Consequently, the following variations due to honeycomb thickness are observed.

1. Inserting a very thin honeycomb slightly increases the absorption peak value.
2. As the honeycomb thickness increases, the peak sharpens and the peak value increases.
3. However, beyond a certain point, increasing the thickness decreases the peak value because the transmitted energy starts to decrease.
4. If the total back cavity is sufficiently deep, the absorption peak vanishes as the honeycomb becomes thicker because surface absorption on the illuminated side becomes predominant compared to absorption due to multireflections in the back cavity.

## 5. Conclusion

In this study, the sound absorption characteristics of a panel sound absorber with a honeycomb structure in its back cavity are theoretically analyzed, particularly the effect of the honeycomb on the sound absorption characteristics and its mechanism. Inserting a honeycomb generally decreases the absorption peak value due to multireflections in the back cavity because the honeycomb reflects the transmitted sound through the panel, reducing the sound energy absorbed in the back cavity. However, the peak value can increase, and the peak frequency decreases with a thin honeycomb under certain limited configurations. Thus, the honeycomb must be carefully selected to improve the absorption characteristics of a panel-type absorber.

## Acknowledgments

This study was partially supported by the Program for the Improvement of Research Environment for Young Researchers from the Special Coordination Funds for Promoting Science and Technology (SCF) commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan. Additionally, this study was partly supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, Grant-in-Aid for Scientific Research (C), 20560550, 2010.

## References

- [1] H. V. Fuchs, Alternative fiberless absorbers - New tools and materials for noise control and acoustic comfort, *Acustica/Acta Acustica* 87 (2001) 414-422.
- [2] P. V. Bruel, Sound insulation and room acoustics, Chapman and Hall, London, 1951, Chap. 4.
- [3] S. Kimura, Experimental studies on the sound absorbing characteristics of acoustic materials, *Rep. Inst. Indust. Sci. Univ. Tokyo* 10(5) (1961) 1-48 (in Japanese).
- [4] R. D. Ford, M. A. McCormick, Panel sound absorbers, *J. Sound Vib.*, 10 (1969) 411-423.
- [5] M. Hiraizumi, K. Takahashi, T. Sone, T. Nimura, Study on the sound absorption by panel vibration - Analysis in the model of circular panel with clamped boundary -, *J. Acoust. Soc. Japan* 30 (1974) 276-284.
- [6] K. Sakagami, D. Takahashi, H. Gen, M. Morimoto, Acoustic properties of an infinite elastic plate with a back cavity, *Acustica* 78 (1993) 288-295.
- [7] K. Sakagami, H. Gen, M. Morimoto, D. Takahashi, Acoustic properties of an infinite elastic plate backed by multiple layers, *Acustica/Acta Acustica* 82 (1996) 45-53.
- [8] K. Sakagami, H. Gen, M. Morimoto, D. Takahashi, Acoustic reflection of an elastic plate with periodic ribs and a back cavity, *Acustica/Acta Acustica* 85 (1999) 1-11.

- [9] I. Bosmans, W. Lauriks, G. Lombaert, J. Mermans, G. Vermeir, Sound absorption of stretched ceilings with an impervious synthetic membrane, *J. Acoust. Soc. Am.* 106 (1999) 233-239.
- [10] K. Sakagami, M. Kiyama, M. Morimoto, D. Takahashi, Sound absorption of a cavity-backed membrane: A step towards design method for membrane-type absorbers, *Appl. Acoust.* 49 (1996) 237-247.
- [11] K. Attenborough, Sound absorbing materials and sound absorbers in Noise and vibration control engineering, 2nd Ed. (Ver IL, Beranek LL, eds.), Wiley, New York, 2005.
- [12] K. Sakagami, M. Morimoto, M. Yairi, Application of microperforated panel absorbers to room interior surfaces, *Int. J. Acoust. Vib.* 13 (2008) 120-124.
- [13] K. Sakagami, I. Yamashita, M. Yairi, M. Morimoto, Sound absorption characteristics of a honeycomb-backed microperforated panel absorber: Revised theory and experimental validation, *Noise Contr. Eng. J.* 58 (2010) 157-162.
- [14] M. Toyoda, D. Takahashi, Sound transmission through a microperforated-panel structure with subdivided air cavities, *J. Acoust. Soc. Am.* 124 (2008) 3594-3603.
- [15] M. Toyoda, H. Kugo, T. Shimizu, D. Takahashi, Effects of an air-layer-subdivision technique on the sound transmission through a single plate, *J. Acoust. Soc. Am.* 123 (2008) 825-831.

## Figure captions

**FIG. 1.** Geometry of the analytical model for a panel absorber backed by two air layers and a rigid wall.

**FIG. 2.** Effect of sound incident conditions on the absorption characteristics: (a) without a honeycomb, (b) with a honeycomb completely filled in the back cavity. Parameters of the panel are as follows:  $E=6\times 10^9$  Pa,  $\rho=610$  kg/m<sup>3</sup>,  $h=0.002$  m,  $\eta=0.01$ ,  $\nu=0.3$ ,  $d_1=0.045$  m,  $d_2=0$  m,  $A_1=A_2=0.026$ ,  $A_b=0$ .

**FIG. 3.** Effect of honeycomb thickness  $d_1$  on the sound-field-averaged absorption coefficient.  $d_1+d_2=0.05$  m. Other parameters are the same as in Fig. 2.

**FIG. 4.** Effect of honeycomb thickness  $d_1$  on the sound-field-averaged absorption coefficient.  $d_1+d_2=0.2$  m. Other parameters are the same as in Fig. 2.

**FIG. 5.** Angle dependence of the absorptivity of the honeycomb-backed panel absorbers.  $d_1+d_2=0.2$  m.  $d_1$ =(a) 0, (b) 0.05, (c) 0.1, (d) 0.2 m. Other parameters are the same as in Fig. 2.

**FIG. 6.** Angle dependence of the reflection ratio of a honeycomb itself.

**FIG. 7.** Effect of honeycomb thickness  $d_1$  on the reflection ratio under an oblique incidence of  $\theta=75$  degrees.

**FIG. 8.** Effect of honeycomb thickness  $d_1$  on the field-incidence-averaged transmission loss of the panel with a honeycomb. Parameters of the panel are the same as in Fig. 2.

**FIG. 9.** Effect of honeycomb thickness  $d_1$  on the field-incidence-averaged transmission loss of the panel with a honeycomb: (a) around 125 Hz, (b) around 250 Hz. Parameters of the panel are the same as in Fig. 2.

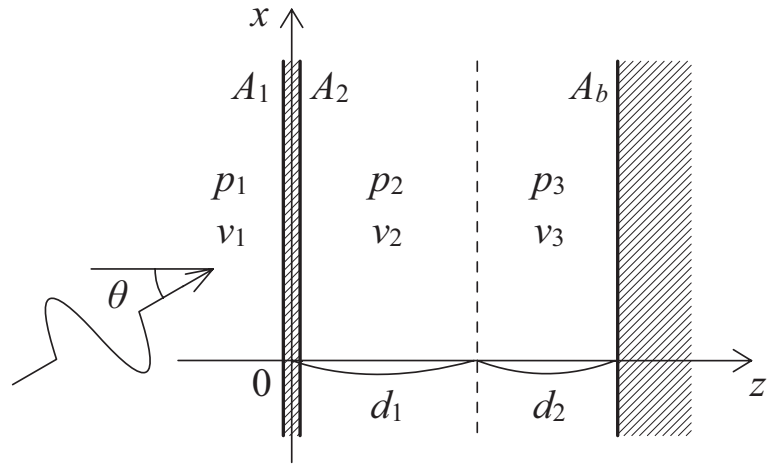


Figure 1: Geometry of the analytical model for a panel absorber backed by two air layers and a rigid wall.

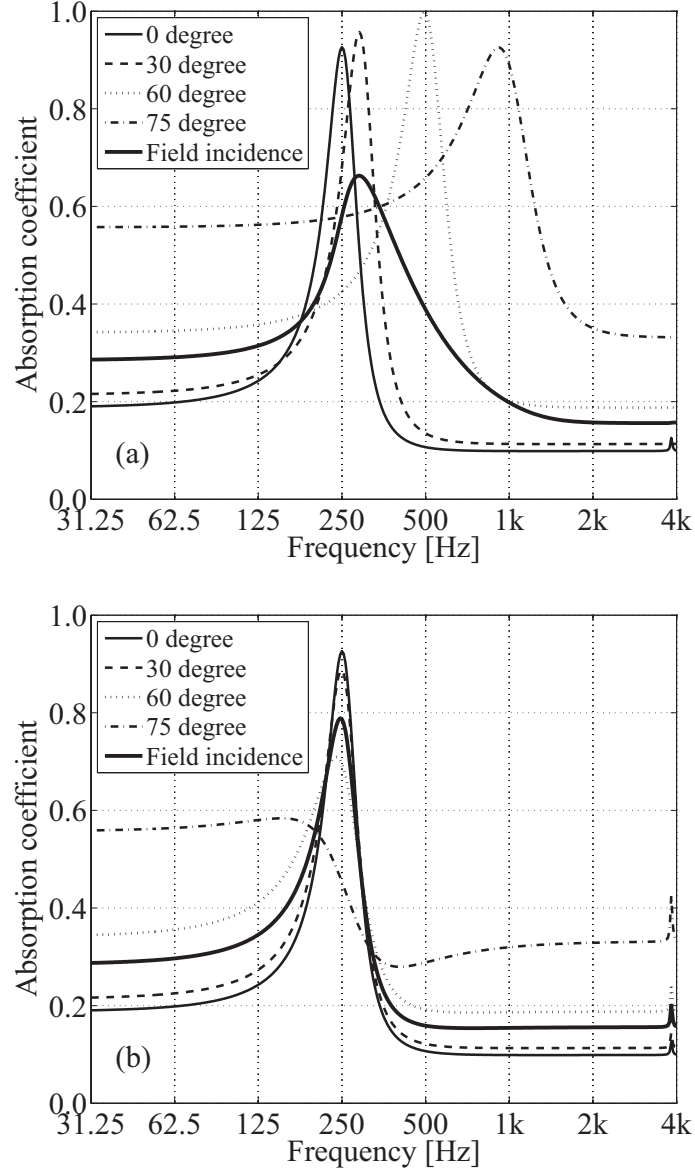


Figure 2: Effect of sound incident conditions on the absorption characteristics: (a) without a honeycomb, (b) with a honeycomb completely filled in the back cavity. Oblique incidence: (1) 0, (2) 30, (3) 60, (4) 75 degrees, and (5) field-incidence averaged.  $E=6 \times 10^9$  Pa,  $\rho=610$  kg/m<sup>3</sup>,  $h=0.002$  m,  $\eta=0.01$ ,  $\nu=0.3$ ,  $d_1=0.045$  m,  $d_2=0$  m,  $A_1=A_2=0.026$ ,  $A_b=0$ .

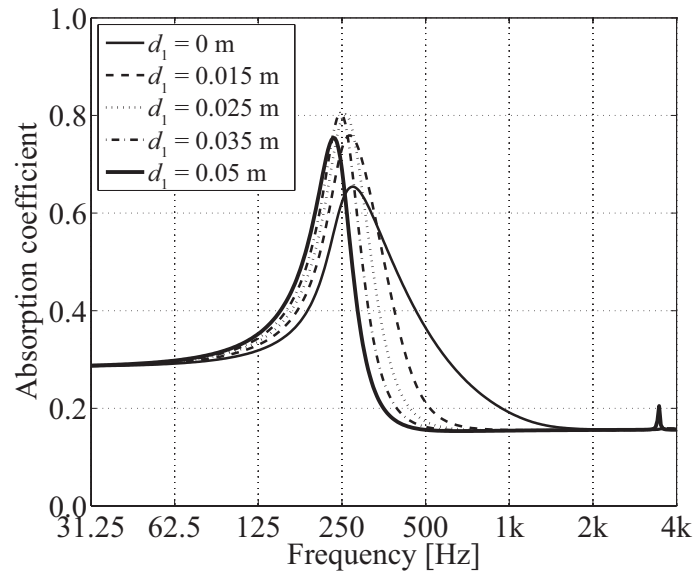


Figure 3: Effect of honeycomb thickness  $d_1$  on the sound-field-averaged absorption coefficient.  $d_1+d_2=0.05$  m.  $d_1=(1)$  0, (2) 0.015, (3) 0.025, (4) 0.035, (5) 0.05 m. Other parameters are the same as in Fig. 2.

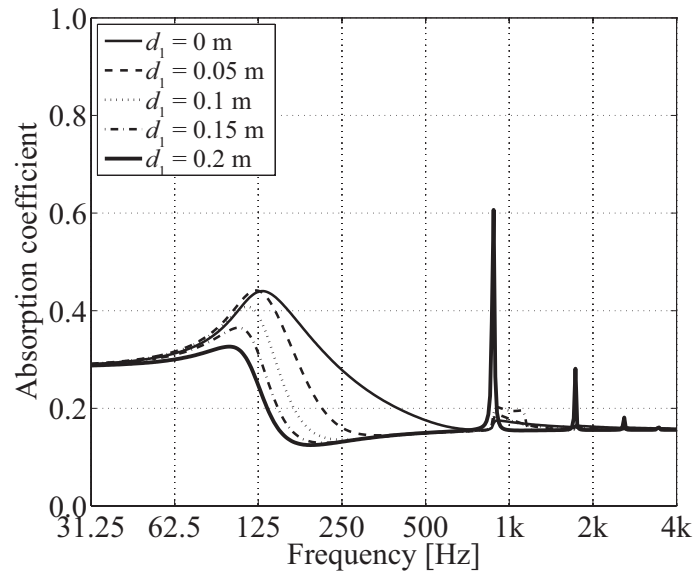


Figure 4: Effect of honeycomb thickness  $d_1$  on the sound-field-averaged absorption coefficient.  $d_1 + d_2 = 0.2$  m.  $d_1 = (1) 0$ , (2) 0.05, (3) 0.1, (4) 0.15, (5) 0.2 m. Other parameters are the same as in Fig. 2.



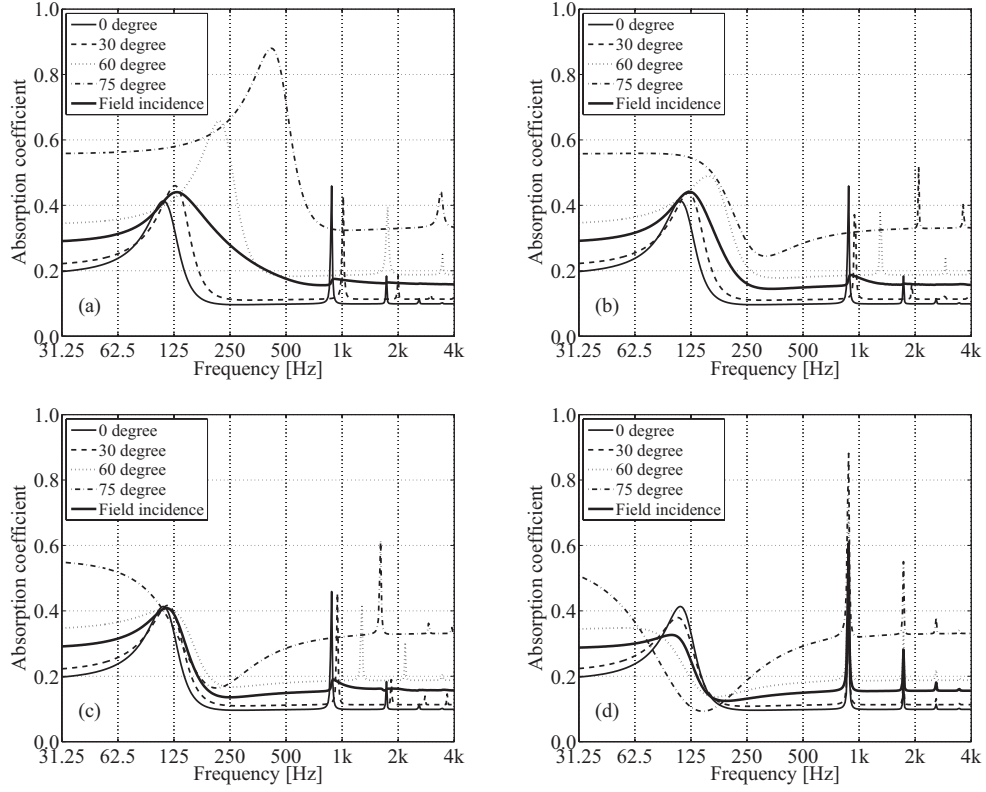


Figure 5: Angle dependence of the absorptivity of the honeycomb-backed panel absorbers.  $d_1+d_2=0.2$  m.  $d_1$ =(a) 0, (b) 0.05, (c) 0.1, (d) 0.2 m. Oblique incidence: (1) 0, (2) 30, (3) 60, (4) 75 degrees, and (5) field-incidence averaged. Other parameters are the same as in Fig. 2.

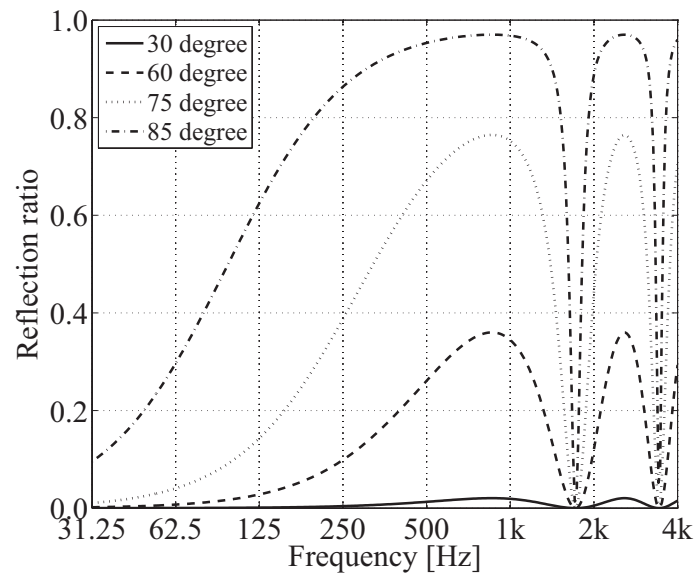


Figure 6: Angle dependence of the reflection ratio of a honeycomb itself. Oblique incidence: (1) 30, (2) 60, (3) 75, (4) 85 degrees.

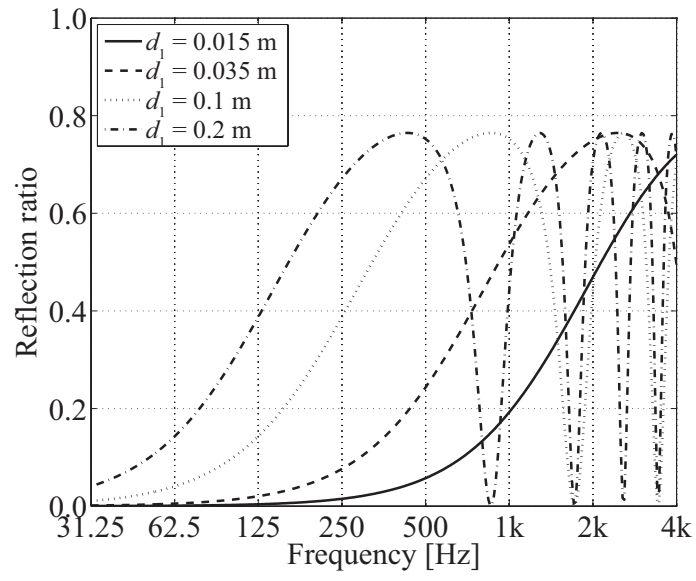


Figure 7: Effect of honeycomb thickness  $d_1$  on the reflection ratio under an oblique incidence of  $\theta=75$  degrees.  $d_1=(1)$  0.015, (2) 0.035, (3) 0.1, (4) 0.2 m.

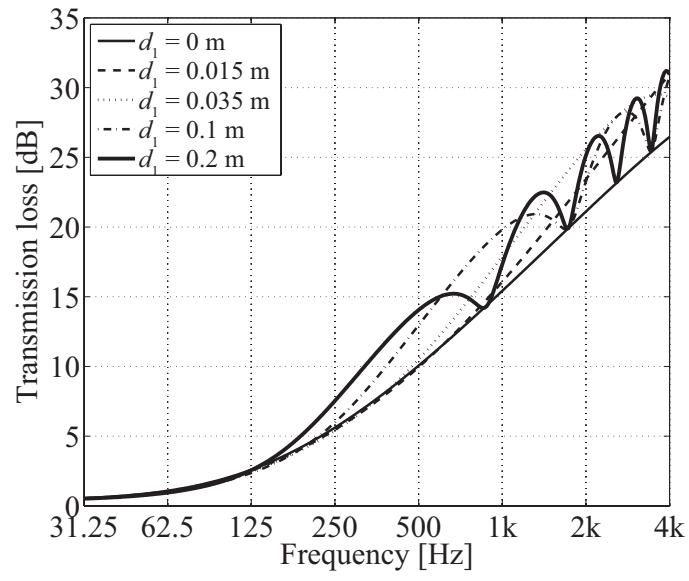


Figure 8: Effect of honeycomb thickness  $d_1$  on the field-incidence-averaged transmission loss of the panel with a honeycomb.  $d_1$ =(1) 0, (2) 0.015, (3) 0.035, (4) 0.1, (5) 0.2 m. Parameters of the panel are the same as in Fig. 2.

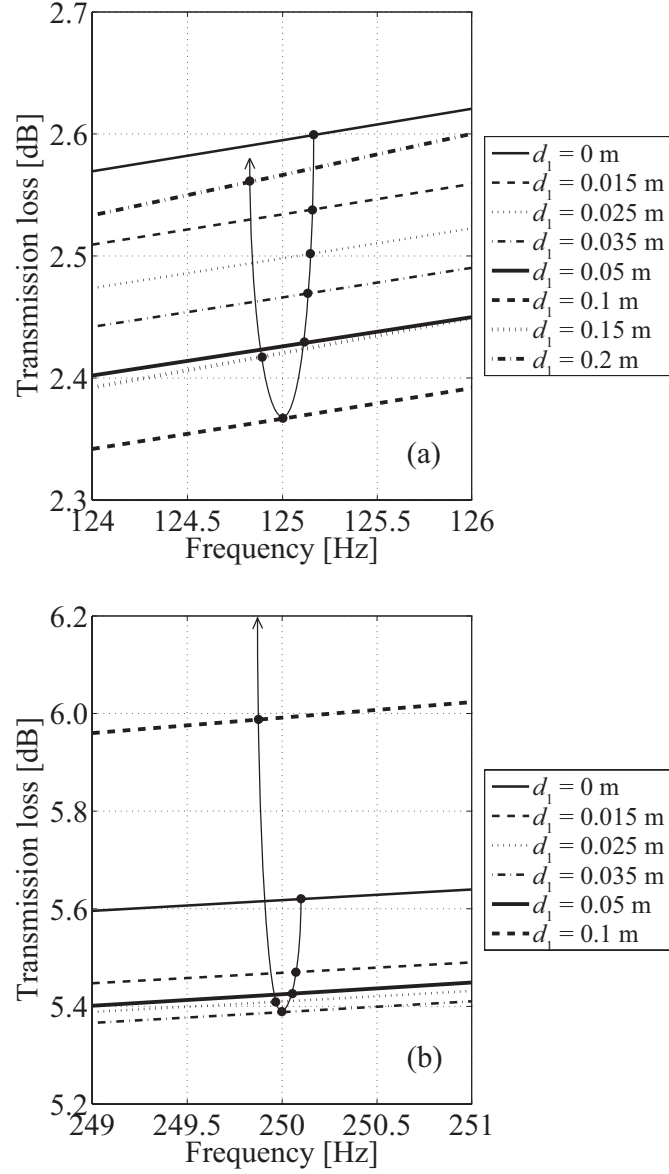


Figure 9: Effect of honeycomb thickness  $d_1$  on the field-incidence-averaged transmission loss of the panel with a honeycomb: (a) around 125 Hz, (b) around 250 Hz.  $d_1$ =(1) 0, (2) 0.015, (3) 0.025, (4) 0.035, (5) 0.05, (6) 0.1, (7) 0.15, (8) 0.2 m. Parameters of the panel are the same as in Fig. 2.