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Inclined sound radiator using flexural wave in honeycomb

ハニカムサンドイッチパネル中の屈曲波を用いる傾斜音波ラジエータ

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1. Introduction

Auditory way-finding system in public spaces has been getting broad attention lately because people can perceive sound direction intuitively.[1)] In order to lead pedestrians using sound more accurately, we attempt to propose a sound radiator which indicates the right direction regardless of position in guidance path. We focused on sound radiation with inclined angle from flexural wave propagating in elastic plate.[2)] The mechanism is the same as that of leaky Lamb wave. The inclined sound is radiated in air when phase velocity of the flexural wave is larger than sound velocity in air. Therefore, vibration plate requires high stiffness and low density like beryllium in order to achieve sound radiation with inclined angle in audio frequency. In addition, in the case of homogeneous elastic plate, phase velocity of the flexural wave has dispersion which cause dispersive group delay and radiation angle variance with frequency, therefore, the proposed sound radiator is still challenging.[3)] On the other hand, sandwich plate which consists of two face plates and interjacent honeycomb core layer is well known material with its hardness and lightness. Furthermore, the dispersion of the phase velocity becomes small as frequency gets higher in auditory frequency.[4)] The characteristics are attractive to generate voice-guided navigation, hence, this study aims to construct the sound radiator using honeycomb sandwich panel.

Dynamic behavior of honeycomb sandwich panel has been analyzed by simulation using 3-D finite element method (FEM) in recent studies,[5, 6)] however, the computational effort of 3-D FEM increases due to its complex structure. Therefore, the prediction of the behavior of the sandwich panel by theoretical equation is attractive to optimize by varying the parameters; the thickness of the core wall or the face plate. In order to confirm availability of the honeycomb sandwich panel and its theoretical equation, we calculate the phase velocity dispersion of flexural wave in the sandwich panel and compare results of the equation with that of 3-D FEM simulation.

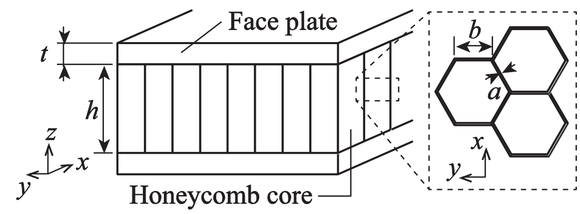

Fig. 1. Schematic representation of honeycomb sandwich panel and geometrical properties.

2. Theoretical equation using plate theory for simplified model of honeycomb sandwich panel

Figure 1 shows a sandwich panel which is modeled by a three-layered structure composed of two face plates and a core layer between the face plates. The core layer has a honeycomb structure and assumed to be orthotropic continuum. An adhesive layer bonding the face plate and the core is ignored for simplicity. Thompson *et al.* indicated the phase velocity v_p of flexural wave propagating in sandwich panel by solving the plate equations as following equation [4],

$$v_\mathrm{p}^2 = \frac{\omega^2(DM+IK) - \omega\sqrt{\omega^2(DM+KI)^2 - 4MDK(\omega^2 I - K)}}{2M(\omega^2 I - K)}, \quad (1)$$

where

$$D = \left(c_{\mathrm{f}11} + \frac{c_{\mathrm{f}13}c_{\mathrm{f}31}}{c_{\mathrm{f}33}}\right)\left(L_\mathrm{f}^3 - L_\mathrm{c}^3\right) + \left(c_{\mathrm{c}11} + \frac{c_{\mathrm{c}13}c_{\mathrm{c}31}}{c_{\mathrm{c}33}}\right)L_\mathrm{c}^3, \quad (2)$$

$$K = I\omega_\mathrm{TS}^2, \quad (3)$$

$$I = \rho_\mathrm{f}\left(L_\mathrm{f}^3 - L_\mathrm{c}^3\right) + \rho_\mathrm{c}L_\mathrm{c}^3, \quad (4)$$

$$M = 2\{\rho_\mathrm{f}(L_\mathrm{f} - L_\mathrm{c}) + \rho_\mathrm{C}L_\mathrm{C}\}, \quad (5)$$

where D and K are the stiffness as for flexural and shearing deformations, respectively. The parameter I is rotary inertia and M is mass. The stiffness coefficients of the face plate c_f and of the core c_c are given by the physical property of the material and by the wall thickness and length of honeycomb cell, respectively.[7)] The density of the face plate and the apparent density of the core are expressed as ρ_f and ρ_c. The parameter ω_TS in K is determined by the resonant frequency of fundamental thickness-shear mode. The face plate thickness t and the core height h give L_f and L_c; $L_\mathrm{f} = t + h/2$ and $L_\mathrm{c} = h/2$.

3. Comparison of phase velocity dispersion of flexural wave propagating in honeycomb sandwich panel

3.1 Calculation of phase and group velocities

First, the theoretical value was calculated by substituting these parameters into eq. (1). **Table 1** shows the parameters of a honeycomb sandwich panel (3A Composites, ALUCORE), and the material of the face plate and the core are used aluminum 5754-H22 and aluminum A3003, respectively. The wall thickness and length of the core are defined a and b as shown in Fig. 1.

Second, the honeycomb sandwich panel was modeled by 2-D shell elements using simulation software (COMSOL Multiphysics 4.4) based on FEM. **Figure 2** shows mesh shape of the panel used in the simulation. The length L in x direction of the panels is 1,000 mm, and the width W in y direction is 12.8 mm (157 × 2 cells). Natural frequencies f_n of flexural wave in x direction were simulated, and frequency dependency of the phase velocity v_p was given by general expression $v_\mathrm{p} = 2Lf_n/n$, where n is the number of half wavelengths in the panels.

In addition, it is difficult to calculate ω_{TS} for calculation of the theoretical values because it needs apparent rigidity modulus and density of the whole panels. Therefore, we simulated thickness-shear mode using small model with 2 × 2 cells to obtain ω_{TS}.

3.2 Results and discussion

Figure 3 shows frequency characteristics of phase velocity of flexural wave in the panels. Thick solid line and dotted line indicate the phase velocity v_{p} and the group velocity v_{g} of the theoretical value, respectively. Solid-circle and dotted-circle mark also indicate v_{p} and v_{g} of the FEM. Here, in order to find the difference between the honeycomb sandwich panel and the homogeneous plate in the dispersion, v_{p} and v_{g}, a homogeneous plate that has 20 mm thickness and the same material properties as the face plate is also calculated by classical beam theory. These velocities are represented as thin solid line and dotted line, respectively.

The phase velocity and the group velocity of the theoretical value well accorded with the simulation results. It is found that dispersion of v_{p} became small in over 2 kHz. Due to the result, the dispersion in v_{g} is approximately resolved in the theoretical and the simulation values, which means that the radiated sound from the honeycomb panel would not have group delay difference with frequency in over 2 kHz. On the other hand, in the case of a homogeneous plate, both velocities increase with increasing frequency.

In the case of the honeycomb sandwich panel, it is confirmed that v_{p} is enough larger than the sound velocity 340 m/s at over 0.3 kHz, in which the condition of radiating inclined sound was met, and human voice can be radiated. In contrast, the homogeneous plate needs enough thickness to meet the condition, therefore, the vibration plate of the sound radiator becomes too heavy and has difficulty for driving. According to these results, the honeycomb sandwich plate has useful characteristics to realize the inclined sound radiator for auditory way-finding system. In addition, it is clarified that the parameters of honeycomb panel can be determined by the theoretical equation.

4. Conclusions

In this study, we focused on a sound radiator using a honeycomb sandwich panel for inclined sound. In order to confirm availability of the honeycomb sandwich panel and its theoretical equation, we calculated the phase velocity dispersion of flexural wave in the sandwich panel and compared results of the equation with that of 3-D FEM simulation. It was confirmed that the theoretical equation can determine the parameters of honeycomb sandwich panel, and the panel has useful characteristics to realize the proposed sound radiator. As further study, we will measure the phase velocity by experimental investigation.

References

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Table I. Parameters of honeycomb sandwich panel used for theoretical equations.

a (μm)	70
b (mm)	3.67
h (mm)	23
t (mm)	1
$c_{\mathrm{f}\,11}$, $c_{\mathrm{f}\,13}$, $c_{\mathrm{f}\,33}$ (GPa)	200, 49.72, 200
$c_{\mathrm{c}\,11}$, $c_{\mathrm{c}\,13}$, $c_{\mathrm{c}\,33}$ (GPa)	3.13×10^{-3}, 1.86×10^{-3}, 1.55
ρ_{f} (kg/m^3)	2660
ρ_{c} (kg/m^3)	89.20
ω_{TS} (rad/s)	7.93×10^{4}
D (kg m^2/s^2)	3.3×10^{4}
K (kg m^2/s^2)	810
I (kg)	1.29×10^{-3}
M (kg/m^2)	7.37

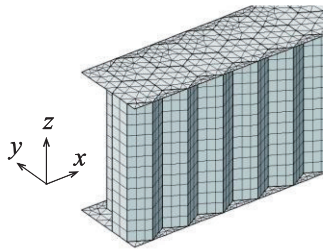

Fig. 2. Finite element division of a honeycomb sandwich panel in FEM simulation.

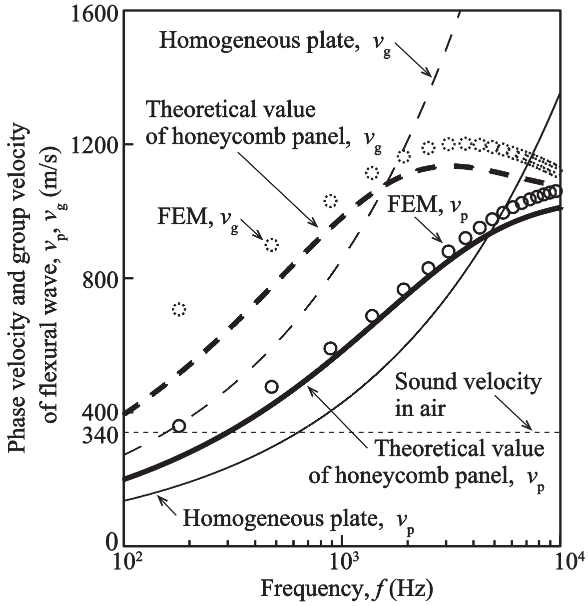

Fig. 3. Frequency characteristics of phase velocity and group velocity of theoretical values, simulation results, and homogeneous plate.