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Absorption performance optimization of perforated plate using multiple-sized holes and a porous separating partition

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ABSTRACT

This research proposes a new type of sound absorptive perforated plate with multiple-sized holes and a porous separating partition in an attempt to extend the sound absorption bandwidth. Separating different sized holes with a porous partition instead of a conventional rigid partition is an unprecedented idea. However, existence of a porous separating partition makes it hard to use theoretical surface impedance models to predict absorption performance. So we introduce appropriate finite element simulation method using the effective density of hole. To consider the end correction effects for hole length and viscosity length of a perforated plate, the effective density of the Johnson-Champoux-Allard model is modified and the end correction lengths of the modified effective density are corrected again in connection with finite element simulation. Material property of a porous separating partition is modeled by the Delany-Bazley material model. After constructing the finite element model, we analyzed the absorption coefficient graphs of perforated plates with two-sized holes and four-sized holes according to the separating partition types: no partition, rigid partition and porous partition. To enhance the wide-band absorption performance, flow resistivity value and thickness of a porous separating partition as well as hole sizes are optimized. From the analysis and design examples, we confirmed that the perforated plate using multiple-sized holes and a porous separating partition can make a continuous frequency range of high absorption coefficient compared to the perforated plate with a conventional rigid partition.

1. Introduction

This research presents a new type of perforated plate consisting of various-sized holes and a porous separating partition to extend the frequency region of high sound absorption coefficient. In several relevant researches, a variety of novel ideas, such as multi-layer perforated plates, different cavity depths with separating partitions, and internal porous layers, have been investigated based on theoretical and experimental approaches in attempts to improve the wide-band absorption performance [1–9]. Other types of perforated plate systems have also been devised and investigated [10–20]. One of the advantages of the present perforated plate system compared to the previous absorbers is that it shows higher absorption coefficients for a wide frequency range without using a large number of different sized holes. This aspect is vital in case of some area or space limitations. Also it does not increase the required space between the perforated plate and the rigid wall.

1.1. Previous perforated plate models for wide-band absorption performance

An important research topic related to the performance of perforated plates is to investigate the method to widen the frequency range of high absorption coefficient. To achieve this, various types of perforated plates have been proposed, as shown in Fig. 1. In [1–5], multi-layers of perforated plates with different-sized holes were proposed (Fig. 1a). For the theoretical prediction of the absorption performance of multi-layer absorbers, some analytical models were proposed and compared with experimental results. Using case studies, researchers have shown significantly improved absorption effects in a wide-band frequency region with some peak frequencies. Other researchers have utilized parallel arrangement of perforated plate modules with different cavity depths that are separated by a rigid partition, as shown in Fig. 1b [6–9]. The idea of different cavity depths can be simply explained by the fact that it utilizes multiple Helmholtz resonance frequencies to widen the high absorption frequency region. However, the designs in Fig. 1a and b are novel with sufficient spaces behind the perforated plates to widen the frequency range over which the plates are most effective. With spatial limitation in the cavity depth behind the

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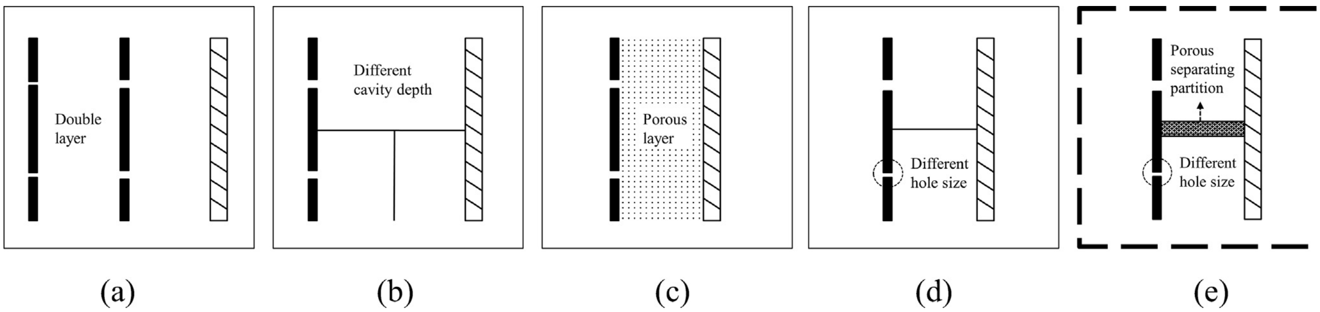

Fig. 1. Existing perforated plate models and our suggested perforated plate model. (a) Perforated plate with multi-layers [1–5], (b) perforated plate with different cavity depths separated by a rigid partition [6–9], (c) perforated plate with an internal porous layer [1,10–13], (d) perforated plate with multiple hole sizes separated by a rigid partition (resonator array panel) [14,15], and (e) the suggested perforated plate with multiple hole sizes separated by a porous partition.

plates, it is challenging to realize effective absorption performance in a wide frequency range.

To improve the absorptivity without increasing the space behind the perforated plate, an internal porous layer can be inserted behind the perforated plate, as shown in Fig. 1c [1,10–13]. This is one of the simplest methods that can be used to enhance the sound absorptivity without increasing the thickness of the entire perforated plate structure. However, from an engineering point of view, this method only increases the amplitude of absorption coefficient; it does not adjust the effective frequency range of high absorptivity.

As a different way to avoid the increased entire thickness of a perforated plate structure, a perforated plate with a rigid separator between different-sized holes was proposed in Fig. 1d [14,15]. In [15], a perforated plate with multiple-sized holes, but without a partition, was also proposed. And it was discussed that a perforated plate with multiple-sized holes without a partition performs similarly to a perforated plate with single-sized holes; this is also re-investigated in the present study. In those papers, a specific explanation about the properties of the separating partition was not mentioned. However, by guessing the context, it can be known that the partition is rigid (it is not a porous partition surely). Because one perforated plate module (with single-sized holes) is a single resonator, the parallel arrangement of each module with different-sized holes separated by rigid partitions is a combination of multiple Helmholtz resonators with different resonance frequencies. Therefore, this perforated plate model shows wide-band frequency noise attenuation characteristics of a resonator array panel. Nevertheless, if there is insufficient area to utilize a large number of resonators with different resonance frequencies, it is difficult to obtain wide-band frequency absorption characteristics because each resonator is effective near its resonance frequency.

1.2. New perforated plate model with multiple-sized holes and a porous separating partition

To contribute to the wide-band absorption issue of a perforated plate, we propose to use a porous separating partition rather than a rigid separating partition, as shown in Fig. 1e; specifically, we suggest a perforated plate with multiple-sized holes and a porous separating partition. To our knowledge, no previous research has been conducted that predicts the noise attenuation performance of a porous separating partition behind a perforated plate. Using a porous separating partition can lead to effects that are similar to those obtained by using many resonators with different resonance frequencies. The remaining parts of this paper are as follows.

In Section 2, to evaluate the absorption characteristics of a perforated plate with various-sized holes and a porous separating partition, we developed the acoustic finite element (FE) simulation method based on the Johnson-Champoux-Allard model (JCA model) [21–23] and the Beranek-Ingard model [21,24,25]. To consider the physical phenomenon around holes, we modified the totuosity in the effective density formulation of the original JCA model and it is validated in connection with the end correction lengths around holes in the FE simulation environment.

In Section 3, using the developed FE simulation method, we investigated the absorption bandwidth-extending effect of using a porous separating partition between different sized holes. To reflect the material properties of a porous separating partition in the simulation, the Delany-Bazley material model is employed [26–28]. We compared the absorption coefficient graph of a perforated plate with a porous separating partition and that of a perforated plate with a rigid separating partition (under the same conditions) in two cases of two-sized-holes and four-sized holes, respectively.

In Section 4, based on the simulation results, we applied optimization techniques to the design problem of our new perforated plate model. So we optimized the hole sizes, flow resistivity value of porous separating partition and partition thickness to maximize the sum of absorption coefficients in a target frequency region. Finally, our findings and conclusions are summarized in Section 5.

2. Finite element analysis method for absorption performance of a perforated plate

Most previous research related to the absorption performance of perforated plates was conducted by theoretical analysis method and experiment. Thanks to the previous research, quite precise theoretical surface impedance models for a perforated plate have been developed. And the surface impedance can be used to calculate the absorption coefficient. Although there exist some papers that use theoretical approaches [5,7,8,12,17,29,30], it is not easy to derive the surface impedance when the structure behind the perforated plate becomes complex (like when the perforated plate has multiple hole sizes and a porous separating partition, as suggested by this paper). Therefore, we used a finite element method to effectively analyze the performance of the perforated plate suggested in this paper.

To reflect the absorption phenomena occurring in the holes of a perforated plate in FE simulation, we modified the effective density of the original Johnson-Champoux-Allard (JCA) model. The modified effective density substitutes the air density of holes in the present FE model. From [22], it was presented that the effective density of the JCA model can be used to derive surface impedance models of a perforated plate by considering the end correction length of hole for the tortuosity parameter. Although the Beranek-Ingard model was retrieved from the JCA model with some assumption in [22], we modified the JCA model so that the surface impedance by the JCA model is exactly same to the