Applied Acoustics 126 (2017) 114–119

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical note

Micro-perforated absorbers with incompletely partitioned cavities

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A R T I C L E I N F O

Article history:
Received 7 March 2017
Received in revised form 12 May 2017
Accepted 15 May 2017
Available online 29 May 2017

Keywords:
Micro-perforated panel
Incomplete partitioning
Sound absorption

A B S T R A C T

Acoustic performance of a micro-perforated panel with an incompletely partitioned cavity (MPPIPC) is investigated. A MPPIPC is achieved by inserting separators, which are shorter than the depth of the cavity, periodically behind the micro-perforated panel (MPP). Due to these separators, the sound field in the cavity is significantly changed. This paper reveals these unique sound reflection modes among the separators, based on which a theoretical model is proposed to calculate the absorption coefficient of a MPPIPC in the diffusion field. Experiments verified the theoretical predictions. These results indicate that the appropriately arranged insertion can improve the performance of a MPP absorber effectively at low frequencies.

1. Introduction

Compared to noise at middle and high frequencies, the adverse effects of low-frequency noise are of particular concern due to its pervasiveness of numerous sources, efficient propagation, and reduced efficacy of many structures (walls, noise barriers, and hearing-protection devices). A work on low-frequency noise has indicated that it causes great subjective reactions and to some extent physiological reactions on human beings [1]. Among those sound absorbers working at low frequencies, micro-perforated panels which possess excellent properties including fiber free, non-combustible, as well as aesthetically pleasing, are widely used in noise control engineering [2].

According to Maa's theory [3,4], the cavity depth plays an important role in determining the MPPs' sound absorption band. Aiming for improving sound absorption at lower frequencies, an increased cavity depth is required. However, in the case where space for the backed cavity is limited, conventional MPP absorbers cannot provide sufficient sound absorption at low frequencies. Therefore, various strategies treating the air cavity have been proposed. Yairi et al. [5] concluded that completely partitioning the air cavity with subwavelength interval was especially effective. This observation was further confirmed by Toyoda et al. [6] and Liu et al. [7,8]. To enhance low frequency absorption, flexible tube bundles [9,10] and mechanical impedance plates [11] were also incorporated into a MPP absorber.

In this paper, an incomplete partition technique is proposed and applied to a MPP to improve its sound absorption at low frequencies. With appropriately arranged insertion, these separators could significantly elongate the equivalent depth of the air cavity. In this paper, Maa's theory of MPPs in the diffusion field is discussed in Section 2. Section 3 reveals those unique sound reflection modes among the separators of MPPIPCs. In Section 4, theoretical predictions are compared with experiment results. Finally, conclusions are made in Section 5.

2. Maa's theory of MPPs in the diffusion field

The MPPs were initially proposed by Maa [3,4]. For normal incidence, the absorption coefficient is derived by

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \cot(\omega D/c))^2}, \tag{1}$$

where r is the normalized specific acoustic resistance of the MPP, m is the normalized acoustic mass of the MPP, ω is the angular frequency of incident wave, c is the speed of sound, and D is the cavity depth behind the MPP.

For oblique incidence, a MPP itself provides a motion-constraint condition to the particles, leading to a one-dimensional sound field in each of MPP's holes, which is also known as "locally reacting surface". Then the acoustic wave can only propagate normally to the MPP, resulting in an unaltered specific normal acoustic impedance independent of the incident angle. According to Huygens principle, the sound wave transmitted through MPP's holes will propagate in the same direction with the incident wave [3]. And for the air cavity, path difference between the incident and the

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http://dx.doi.org/10.1016/j.apacoust.2017.05.016

reflected waves plays an important role in determining the transfer impedance. Proposed a plane wave impinges obliquely on the MPP's surface, the specific normal transfer impedance can be derived by

$$Z_n = \frac{p}{v_n} = \frac{p_i + p_r}{v_i \cos\theta_i + v_r \cos\theta_r} \tag{2}$$

where p_i is the incident wave, p_r is the reflected wave, v_i and v_r are the particle velocity of air generated by incident and reflected waves respectively, θ_i and θ_r denote the angles of incidence and reflection.

The analytical model for calculating cavity's specific transfer impedance is shown in Fig. 1(a). Assume that point **A** is the origin, point **E** located at $(-X_0, 0)$, the cavity wall is rigid, and the cavity depth $D = D_0$. Hence, substituting these coordinates into Eq. (2), finally the specific normal transfer impedance of the air cavity can be expressed as

$$Z_{cn} = -j\frac{\rho c}{\cos\theta_i}\cot(\omega D_0 \cdot \cos\theta_i / c). \tag{3}$$

Notice that the difference of air cavity's specific transfer impedance between normal and oblique incidences is that the cavity depth D_0 is replaced by $D_0 \cos\theta_i$ in the cotangent function. As illustrated in Fig. 1(a), points **E** and **C** belong to the same wave front. Then for the incident and reflected waves at **E**, the sound path difference is CD + DE. Since BC = EF = EF′, this path difference equals to BD + DF′ (=$2D_0 \cos\theta_i$). In another word, the term $D_0 \cos\theta_i$ is half of the path difference between incident and reflected waves at **E**, which is regarded as the "equivalent depth" of the cavity. Herein, the "equivalent depth" of the cavity is used to calculate the specific normal transfer impedance of air cavity under oblique incidence.

With the obtained specific normal acoustic impedance of the MPP and its backed cavity, the absorption coefficient of MPPs can be calculated by

$$\alpha_{\theta_i} = 1 - \left|\frac{Z_{n,\theta_i}\cos\theta_i - \rho c}{Z_{n,\theta_i}\cos\theta_i + \rho c}\right|^2, \tag{4}$$

where

$$Z_{n,\theta_i} = \rho c(r + j\omega m) - j \cdot \frac{\rho c}{\cos\theta_i}\cot\left(\frac{\omega D_0 \cos\theta_i}{c}\right). \tag{5}$$

Here $Z_{n,\theta i}$ is the specific normal acoustic impedance of MPPs at incident angle θ_i. Substituting Eq. (5) into Eq. (4) yields

$$\alpha_{\theta_i} = \frac{4r\cos\theta_i}{(1 + r\cos\theta_i)^2 + (\omega m \cos\theta_i - \cot(\omega D_0 \cos\theta_i / c))^2}. \tag{6}$$

This result is accord with Maa's theory. Furthermore, considering a diffusion field where waves impinge on a MPP from all angles, then the random incident sound absorption coefficient α_s is given by

$$\alpha_s = \int_0^{\pi/2} \alpha_{\theta_i} \sin 2\theta_i d\theta_i. \tag{7}$$

3. Sound reflection modes among the separators of a MPPIPC

In Section 2, the Maa's theory of MPPs in the diffusion field has been introduced, and the sound absorption coefficient at incident angle θ_i has been deduced. Herein, by inserting short separators behind the MPP periodically to partition the cavity incompletely, the original ways that sound rays undergo behind the MPP will be altered drastically. Accordingly, path differences of these rays will be changed and hence result in a variety of the normal acoustic impedance of a MPPIPC. To obtain the sound path differences, those sound reflection modes among the separators of a MPPIPC should be investigated systematically. As discussed above, according to the relation between the sound path difference and the "equivalent depth" of air cavity, the specific normal acoustic impedance of the proposed MPPIPCs can be calculated.

In this section, the possible sound reflection modes in the cavity of a MPPIPC are analysed and classified into five categories. Those modes between two separators (the left panel I and the right panel II) are illustrated in Fig. 1(b)–(e). Fig. 1(b) represents the most simple mode that all the rays avoid the separators, leading to the same path difference with the case of a non-partitioned cavity. Fig. 1(c) represents the rays that first hit the bottom of the cavity and then are reflected by the separator II before leaving the MPPIPC. Fig. 1(d) represents the rays which first hit the separator panel II and then are reflected by the cavity bottom before leaving the MPPIPC. While Fig. 1(e) represents the rays that hit, in turn, separator II, cavity bottom, separator I, and finally leave the MPPIPC. Actually these four modes account for the majority proportion of incident rays. Only in the case with an incident angle greater than a

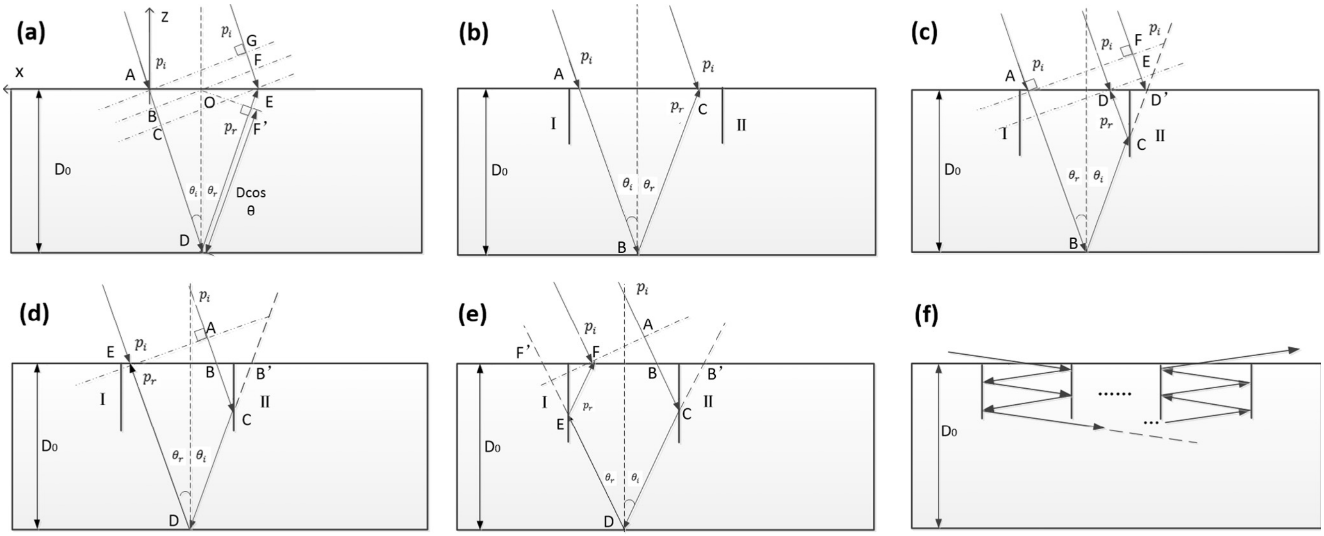

Fig. 1. (a): Analytical diagram to calculate the specific normal transfer impedance of the cavity; (b)–(e): demonstration of sound reflection modes between two separators; (f): demonstration of the reflection mode under large-angle incidence.