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Technical note

A strategy for extending the effective application of micro-perforated panel absorbers to high sound intensity

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A R T I C L E I N F O

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A B S T R A C T

Micro-perforated panel (MPP) absorbers are simple to construct, can be used in a variety of applications, show good absorption properties and allow relatively accurate prediction and design under linear conditions. However, when the sound intensity is high, the sound pressure level (SPL) under which the MPP is effective is limited due to the nonlinear effect. To solve this problem, we investigated the suppression of the nonlinear effect through design parameters. In this case, the linear response of an MPP with increasing SPL is enhanced; thus, the advantages of MPPs under linear conditions can be attained. First, the concept of a transition SPL is proposed to quantify the effect of the suppression. Then, the rules controlling the influence of the parameters on the transition SPL are investigated via a parameter study. Finally, the validity of the findings is confirmed using experimental data published in the literature. The obtained results can provide guidance for the design of MPP absorbers for high SPL applications.

1. Introduction

Micro-perforated panel (MPP) absorbers have many advantages, such as a simple structure, low weight, high-temperature performance, and environmental friendliness, and are therefore regarded as the most promising green sound-absorbing materials in the 21st century for many different applications [1–4]. An MPP is a thin flat panel perforated with numerous sub-millimeter orifices. By reducing the perforations to sub-millimeter size, the acoustic resistance and low acoustic mass reactance necessary for wideband sound absorption can be achieved without the use of any fibrous or porous materials. The typical structure of an MPP absorber consists of an MPP fitted in front of a rigid backing wall separated by a constant air cavity, as shown in Fig. 1. The basic theory of the MPP absorber was first presented by Maa in 1975 [5] and was further improved in 1998 [6]. Following several decades of development of Maa's pioneering work, the absorption characteristics of MPP absorbers have been optimized and MPP absorbers now constitute a mature technology with properties that can be predicted exactly and are completely determined by the hole diameter d, panel thickness t, air cavity depth D and perforation ratio σ (total area of the perforation on a unit area of panel). However, at high sound intensities, MPP absorbers exhibit nonlinear impedance characteristics that are usually parameterized as a function of the sound pressure level (SPL). As a result, the linear impedance model is no longer applicable, and the MPP absorbers exhibit poor absorption performance [7–9].

According to Maa, the perforations themselves, which are short narrow tubes, are only slightly affected. In other words, the linear parts remain almost unchanged at high sound intensity, whereas the acoustic resistance of the end corrections will increase substantially, and the acoustic mass will decrease only slightly due to jet-formation at the ends of the perforations. Maa noted that these phenomena limit the range of intensities under which the MPP absorbers are effective. This is because, as mentioned above, the perforations in the MPPs themselves can provide the necessary acoustic resistance, and thus, if the resistance continues to increase as the SPL increases, the absorption performance of MPP absorbers will be greatly degraded or even completely lost [10,11]. To solve this problem, Maa proposed extending the range of application by utilizing nonlinear effects. Specifically, this can be realized by reducing the linear resistance and making the nonlinear resistance play the dominant role in sound absorption; as a result, the SPL range under which MPP absorbers are applicable increases. However, although this approach may overcome the application limitations of MPP absorbers due to the nonlinear effects under high SPL, its disadvantages cannot be neglected. MPP absorbers are tailored to suppress noise by providing appropriate impedance boundary conditions over a broad frequency range. On the one hand, unlike the case of linear impedance, the nonlinear impedance varies with SPL, which changes constantly; thus, the possibility of obtaining an appropriate impedance that is effective over a wide frequency band is greatly reduced. On the other hand, while the linear characteristics of MPP absorbers are well

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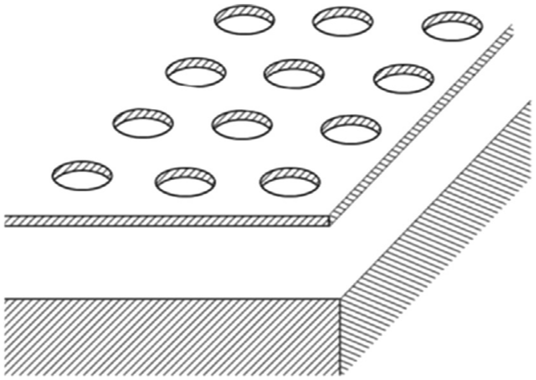

Fig. 1. Schematic diagram of an MPP absorber.

understood, the nonlinear aspects are not, despite decades of effort dedicated to elucidating the complex flow physics and absorption mechanism under high SPL. Therefore, the performance prediction is less reliable than that required by the designers. Last but not least, this approach can severely degrade the absorption ability of MPP absorbers at relatively low levels of sound intensity. Hence, more effective methods are necessary.

2. The strategy

We note that the acoustic impedance under high sound intensity includes two contributions: the linear acoustic impedance and the nonlinear acoustic impedance. As the SPL increases, a threshold SPL is reached, which implies the transition of the acoustic impedance from the linear regime to the non-linear one, and more specifically, below which the linear resistance due to viscous dissipation tends to dominate the nonlinear effects; otherwise, the nonlinear effects begin to have an impact. Therefore, this paper presents a more direct and effective approach that suppresses the nonlinear effect by increasing the critical SPL (or transition SPL), thereby enhancing the linear response of an MPP with increasing SPL. Consequently, an MPP that exhibits linear performance over a wide range of SPL and its potential benefits under linear conditions can be obtained. In fact, a linear sound absorber is always more favorable for practical applications [12,13]. However, achieving such an increase in the transition SPL is a key challenge. Either the linear impedance or the nonlinear impedance is mainly dependent on the structural parameters. The transition SPL described above is also affected by structural parameters. Hence, this work investigates the rules governing the influence of structural parameters on the transition SPL and the possible approaches for improving the transition SPL. A preliminary study conducted by Chandrasekharan et al. explored the orifice aspect ratio (i.e., the panel thickness-to-diameter ratio [t/d]) [14] without strictly excluding other variables that could influence the transition SPL. In addition, their study did not explicitly evaluate other key parameters, such as the diameter d and perforation ratio σ. Therefore, a thorough parameter study is conducted in this work.

3. Parameter study

3.1. Impedance model

The nonlinear effects are mainly of hydrodynamical origin. When the sound intensity is high at the exit of the holes, a jet is formed. In other words, the acoustic energy is converted into vortex shedding at inflow/outflow from the opening and is lost. This dissipation creates an increase in the resistance as a function of SPL. Several prediction models relating the normalized specific acoustic impedance of micro-perforated resonators to the SPL have been developed [15–17]. In this section, Hersh's model is used to conduct a parameter study because it is more accurate for large orifice aspect ratios than other models. The derivation of Hersh's model is based on the application of the conservation of unsteady mass and vertical momentum for a single isolated orifice. The model is then extended to an MPP with multiple orifices via a perforation ratio assuming a constant volume velocity. Another two important assumptions of Hersh's model are that the hole interaction effect is negligible and that all dimensions of interest are small compared to the acoustic wavelength. With these assumptions, the expression for the normalized specific acoustic impedance of an MPP absorber is given as

$$z = \sqrt{[(1-C_D)/C_D](P_i/\rho_0^2 c_0^2) + (R_L/2\rho_0 c_0)^2} + R_L/2\rho_0 c_0 + \mathrm{j}(X/\rho_0 c_0) \quad (1)$$

where

$$R_L/\rho_0 c_0 = (1/\sigma)(\nu/c_0 d)(t/d)[K_{SS} + \sqrt{(\omega d^2/\nu)}K_{ac}] \quad (2)$$

$$X/\rho_0 c_0 = \omega H/\sigma c_0 - \cot(\omega L_c/c_0) \quad (3)$$

In the above formulas, R_L is the linear resistive loss, X is the specific acoustic reactance, P_i is the driving sound pressure at the orifice entrance, ρ_0 is the air density, c_0 is the speed of sound, L_c is the cavity depth, $\omega = 2\pi f$ is the angular frequency with f the frequency of incident acoustic wave, ν is the kinematic viscosity, C_D is the acoustic discharge coefficient, K_{ac} is the acoustic viscous loss parameter, K_{ss} is the steady-state viscous loss parameter, and H is the orifice nonlinear inertial length parameter. Note that the values of C_D, K_{ac}, K_{ss} and H are all obtained by empirical curve fitting of these parameters; the detailed procedure for obtaining these parameters is described by Hersh et al. [15]. Although quantitative agreement between the experiments and the theoretical predictions is lacking in this semi-empirical model, it can qualitatively reflect the changing trend of the normalized specific acoustic resistance with increasing SPL and is, therefore, sufficient for defining the transition SPL.

3.2. Effects of structural parameters on the transition SPL

The influences of three structural parameters—the orifice diameter d, the panel thickness t, and the perforation ratio σ—on the transition SPL are investigated. Note that a basic principle of this work is that when a parameter is studied, the other parameters are held constant to exclude their influence. Another fundamental principal is that the resonant frequency of an MPP absorber where the total reactance $x = 0$ is used to conduct the parameter study because it is well known that the nonlinear effects are strongest when resonance occurs. For convenience, the resonant frequency is kept constant at 2500 Hz. According to Maa [5,6], when the other structural parameters are given, the cavity depth L_c can be adjusted to produce the required resonant frequency when $x = 0$. Here, the SPL varied from 100 to 160 dB.

3.2.1. Orifice diameter

Note that for all cases, when a parameter's effect is studied, the other relevant parameters are selected randomly. In this subsection, the rules governing the influence of the orifice diameter d on the transition SPL are studied. First, t and σ are randomly fixed at 0.5 mm and 5%, respectively. The orifice diameter d is varied from 0.04 to 0.3 mm. Fig. 2 presents the normalized specific acoustic impedance as a function of the SPL with different values of the orifice diameter d. This figure shows that the MPP has transition SPLs of 142 dB for $d = 0.05$ mm, 136 dB for $d = 0.07$ mm, 132 dB for $d = 0.10$ mm, 128 dB for $d = 0.15$ mm, 120 dB for $d = 0.30$ mm, and 116 dB for $d = 0.50$ mm. Clearly, the transition SPL increases as the orifice diameter decreases, while the other two structural parameters remain unchanged. This finding is reasonable because, on the one hand, the linear acoustic resistance due to viscous dissipation is proportional to d^{-2}, and thus, it tends to dominate the nonlinear impedance in small-diameter orifices.