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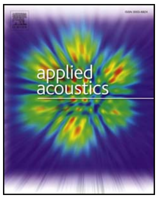

Technical note

Engineering-oriented design strategy to obtain linear micro-perforated panel absorbers at high sound pressure environment

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ABSTRACT

The nonlinear effect at high sound intensity not only degrades the absorption performance of a micro-perforated panel (MPP) absorber, but also makes its performance prediction and structure design become difficult and unreliable due to the absence of accurate nonlinear impedance models. Hence, it is desirable to develop a linear MPP absorber. Based on this, this paper presents an investigation on an engineering-oriented design method of a linear absorber according to practical needs for a specific high sound pressure level (SPL) application. The strategy actually involves a reverse design method and process and the output is a set of structure parameters that uniquely determine an MPP absorber. The input is the characteristic parameters of an MPP absorber which are associated with environment parameters, such as the most undesirable frequency and the maximum SPL. Firstly, the detailed process of design for a linear MPP absorber is expatiated in this study. Then a concrete design example based on the current approach is present and finally, the reliability of the design results is validated by experiment. This study provides a new thought and method for the effective application of MPP absorbers in high SPL environments.

1. Introduction

Micro-perforated panel (MPP) sound absorber is regarded as a new generation of green sound-absorbing materials since it is fire proof, lightweight, simple in construction, and friendly to environments which makes it suitable to be used in tough conditions like acoustic shield in engine enclosures [1,2], inside mufflers [3], and acoustic liners [4]. Under linear condition, a significant advantage of an MPP absorber is its flexibility in design reflected in two aspects: on one hand, the construction parameters can be precisely designed and optimized according to the actual demand; on the other hand, the acoustic performance affords accurate prediction by using exact linear impedance models. However, as the sound pressure level (SPL) increases, this advantage becomes weak since the MPP exhibit nonlinear impedance characteristics that are usually parameterized as a function of SPL [5,6]. Although through several decades of development, the linear characteristics of such MPPs are well understood, while the nonlinear aspects are not. This renders the MPPs' performance predictions and reverse design less reliable than required by designers at high SPL environments. Moreover, as at high sound intensity the SPL becomes a variable that affects the impedance of MPPs beyond the structure parameters, which has indeed exacerbated the possibility to design an optimal impedance that is suitable for a variety of SPLs due to the fact that the SPL of the noise environment is undergoing constant change. For these reasons, the design of an MPP absorber in a high sound pressure environment is always more challenging. Soon-Hong PARK explores a design method of MPP absorber at high sound pressure environment in launcher fairings [7]. In his study, firstly an empirical impedance model of an MPP absorber is specially developed for the launcher fairing application. Then based on this model, the geometric parameters of the MPP absorber are designed with a given incident sound pressure. Apparently, this design method doesn't address the limitations resulted from the nonlinear effect at high sound intensity. Also, this method implies that a nonlinear impedance model, whether it is empirical or semi-empirical, needed to be developed for each different high sound pressure noise environment. So this method inevitably involves a time-consuming and uneconomic process. Teresa Bravo et al., propose an optimization procedure of micro-perforated silencers in linear and nonlinear regimes separately [8]. In their research, a multi-modal propagation method has been proposed to predict nonlinear effects of micro-perforated silencers. As we know, the numerical method may be good at forward prediction, but it may become inefficient when it comes to the reverse design of an MPP structure according to the need of the application. In fact, to the best knowledge, almost all of the published literature on the design method of MPP absorber under high SPLs has tended to accept and utilize the

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nonlinear effect rather than suppress or eliminate it so far. Therefore either the design efficiency or the reliability of these methods is always limited by the nonlinear effects. Accordingly, a more efficient and reliable design method of MPP absorber at high sound pressure levels is needed. A previous study revealed that the linear response of MPP absorbers with increasing SPL can be enhanced by either reducing the orifice diameter or increasing the orifice thickness/diameter aspect ratio [5]. Based on this, in order to substantiate the potential benefits of micro-perforated panels (MPP) i.e., greater SPL independence with deceasing orifice diameter or increasing aspect ratio, an engineering-oriented design approach aims to design a linear MPP absorber at high sound pressure levels is proposed and investigated in this paper. A linear MPP absorber has no or very little nonlinear effects that can almost be ignored, therefore the mature linear impedance models can be used to carry out its performance prediction and reverse design. As a result, the efficiency and reliability of the design method is ensured. Moreover, a linear MPP absorber usually has greater SPL independence to some extent, thus it possesses more stable performance and is more favorable at high SPL noise environments [9].

2. Design process

2.1. Parameters determination

This article explores on how to design a linear MPP absorber under given conditions. As we know, not only the construction but also the acoustic performance of such a device can be completely determined by the parameters of the orifice diameter d, the panel thickness t, the perforation ratio σ and the air cavity depth D. So it's clear that the output result of the design method is a set of structure parameters that uniquely determine a linear MPP absorber whose acoustic characteristics meet the actual noise reduction requirements. From the view of engineering, firstly it is important to determine appropriate input parameters. Note that our design principle is to design a linear MPP absorber based on the actual demand. In this sense, the acoustic property parameters of an MPP absorber should be linked up with the environment parameters correctly. For traditional MPP absorbers, the resonance frequency f_0 and its corresponding resonance or maximum absorption coefficient a_0 are the key property parameters. But in addition to these parameters, our proposed method focuses on acquiring a linear MPP absorber at high sound pressure environments, and a significant parameter to describe a linear MPP absorber is critical SPL P_0 [5], which means that when the SPLs are less than the critical value, no (or very little) nonlinear effects occur. So in this study, the resonance frequency f_0, the maximum absorption coefficient a_0 and the critical SPL P_0 are used to describe the acoustic characteristics of an MPP absorber. When it comes to the real noise environment, there always exists the most undesirable frequency f_r and the maximum SPL P_m. At the same time, for the most undesirable frequency, its absorption is always expected to achieve a desired value based on the practical demands. Therefore the actual requirements can be described by these three parameters – the most undesirable frequency f_r, the desired absorption coefficient a_r at frequency fr and the maximum SPL P_m.

It is well known that as a resonant absorber, an MPP absorber usually attenuates the noise at the resonance frequency with the greatest efficiency. According to this, the resonance frequency f_0 of the designed MPP absorber should correspond to f_r in order to get efficient reduction of noise at the most undesirable frequency. For the resonance absorption coefficient a_0, it should not be less than a desired value of a_r. Meanwhile, the critical SPL P_0, which is used as a key criterion to measure the success of the design in the next subsection, must be set greater than or equal to the maximum SPL P_m in order to ensure that a linear MPP absorber can be attained in a given noise environment.

2.2. Design steps

The basic idea to design a linear MPP absorber according to the requirements falls into two major steps: firstly, a set of structure parameters of an MPP absorber that satisfy the required acoustic characteristics in terms of the required resonance frequency f_0 and absorption coefficient a_0 are calculated by using the accurate linear impedance model. This is a reverse calculation process. And then the design results are checked by the critical SPL P_0 which is evaluated by Hersh's nonlinear impedance model [10]. If the critical SPL is greater than the maximum environmental SPL, the design is finished; if not, try again. This obviously involves a forward prediction and checking process. It should be noted that as a semi-empirical model, although quantitative agreement between the experiments and the theoretical predictions is lacking in Hersh's model, it can qualitatively reflect the changing trend of the normalized specific acoustic impedance with increasing SPL and is, therefore, sufficient for evaluating and defining the critical SPL [6].

Before diving into the specific design steps, the rules controlling the influence of the parameters on the critical SPL are briefly introduced firstly, which can help us better determine the structure parameters. That is because when the demand is certain, there are far more than one set of structure parameters that can satisfy the demand. Research indicates that the critical SPL is greatly affected by the structure parameters, and can be enhanced by a small orifice diameter d and a large aspect ratio of the orifice (i.e., the ratio of the panel thickness to the diameter $[t/d]$) [6]. Based on this, in order to avoid the blindness and casualness in design process, it's better to predetermine some key parameters, such as d and t/d. Although the perforation ratio σ also has some effects on the critical SPL [5], it is used only as the controlled variable due to the inter restricted relationship among d, t/d and σ. The specific steps are described below in more detail:

(1) The frequency spectrum and sound pressure levels under noise environment are analyzed to find out the most undesirable frequency f_r and the maximum SPL P_m. For maximum absorption at the frequency f_r, a desired value for a_r is usually set to 1.
(2) According to the rules controlling the influence of the parameters on the critical SPL, predetermine a set of $\{d, t/d\}$ depending on the measured maximum SPL P_m. For a large P_m, set d relatively low and t/d relatively high; on the contrary, set a relatively large d and a relatively small t/d. In general, d is set less than 0.1 mm and t/d is set more than 3. Note that although a decreasing d or an increasing t/d can improve the critical SPL greatly, it also brings an increased manufacturing cost. Thus the orifice diameter d and the aspect ratio t/d should be carefully selected.
(3) Based on the selected parameters $\{d, t/d\}$, the perforation ratio can be calculated as following [11]:

$$\sigma = \frac{1.47\times10^{-3}t}{d^2}\left(\sqrt{1+\frac{k^2}{32}}+\frac{\sqrt{2}k}{8}\frac{d}{t}\right) \tag{1}$$

With $k = d\sqrt{f_0/10}$ which is the perforate constant. At this point, the parameter combination $\{d, t/d, \sigma\}$ is obtained. As we know that at the resource frequency, the specific acoustic reactance is equal to zero, therefore the cavity depth D can be calculated from the following equation [11]:

$$D = \operatorname{arccot}(\omega m)\times c_0/\omega \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency, m is the acoustic mass and c_0 is the speed of sound. So far, the parameter combination $\{d, t/d, \sigma, D\}$ as an output result is obtained and an MPP absorber is determined.

(4) With the parameter combination obtained in the previous step and the resonance frequency f_0 ($f_0 = f_r$), plot the changing curve of the nonlinear impedance Z as a function of the incident sound pressure