Applied Acoustics 111 (2016) 135–142

Contents lists available at ScienceDirect

Applied Acoustics

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

Acoustic properties of micro-perforated panel absorber having arbitrary cross-sectional perforations

J.F. Ning, S.W. Ren, G.P. Zhao *

State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 31 March 2016
Accepted 15 April 2016
Available online 25 April 2016

Keywords:
MPP
Perforated shape
Acoustic impedance
FEM

ABSTRACT

Micro-perforated panel absorber is used in many noise control applications as a next-generation absorbing material. Perforation shapes of micro-perforated panel studied are usually circular in the past. However, in practice, the perforations are often non-circular or irregular shape due to manufacturing techniques. Sound absorption coefficient and absorption bandwidth of the micro-perforated panel absorber may be further improved, when the perforations in shape are changed. In view of the existing exact solutions of sound propagation in tubes, the simple formulas of specific acoustic impedances of the tubes for triangle and square cross-sectional perforations are derived. Mass reactance end correction of the micro-perforated panel is obtained based on the sound radiation of a shaped piston. The specific acoustic impedance ratio of the micro-perforated panel absorber is calculated and analyzed, which can predict its sound absorption bandwidth. Finally, for closed perforations, the influences of the perforations in shape (including triangle, circle, square and irregular circle) on sound absorption of the MPP absorber are discussed in collaboration with FE simulations.

1. Introduction

Micro-perforated panel (MPP) absorber without additional fibrous or porous material has been widely used in harsh and corrosive environment [1–3]. The perforations of the MPP having diameter of sub-millimeter, which provide enough acoustic resistance and low acoustic mass reactance, are necessary for wide-band sound absorber [4]. The MPP absorber is normally manufactured from plastic or metal, and the perforations of the MPP are usually circular. A new MPP having perforations of triangle cross-sectional shape and the burr is developed [5], in which sound absorption coefficient is improved and absorption bandwidth is widened experimentally. Due to reasons of the manufacturing techniques, the perforations are sometimes processed into non-circular or irregular cross section by using a laser or drill machines [6]. However, Maa's theoretical model [4] was developed for circular cross-sectional perforation having uniform diameter. So far, the effect of the perforations in shape on the sound absorption of the MPP absorber is analyzed scarcely.

The MPP may be considered a lattice of short narrow tubes, whose specific acoustic impedance can be derived from particle velocity through the tubes. The existing exact solution of the particle velocity is about sound propagation in a tube of circular or rectangular cross section [7]. Other exact expressions have been found for a tube of narrow slit cross section based on a limiting case of rectangular tube and a tube of triangle cross section [8]. A large amount of literatures [4,9,10] are also devoted to the application of these solutions to the design of sound absorption structures. The MPP absorber is firstly proposed by Maa [4,9] based upon an approximate model for the specific acoustic impedance of the short narrow tube, instead of the exact model [7].

In order to add the specific acoustic impedance of the short narrow tubes, end corrections including additional resistance and additional mass reactance [11,12] are necessary. The sound radiation impedances of a circular and an elliptical piston are used as additional mass reactance of circular and narrow slit cross sections, respectively. Ingard [11] pointed out that the additional mass reactance for an arbitrary cross section is sometimes written a formula related to the cross-sectional area according to circular piston. Mechel [13] introduced an approximate expression of radiation impedance of rectangular piston, which is better to suit for smaller ratio b/a (a and b represents width and length). Lindemann [14] described an exact model, in which the sound radiation impedance of a baffled piston of arbitrary shape is Laplace transform of an impulse response directly related to the geometrical shape of the piston.

* Corresponding author.
E-mail address: zhaogp@mail.xjtu.edu.cn (G.P. Zhao).

http://dx.doi.org/10.1016/j.apacoust.2016.04.012
0003-682X/

Effective geometric parameters of the MPP absorber with irregular cross-sectional perforations are determined using nonlinear least square data fitting from the measured sound absorption [6]. It is shown that if effective geometric parameters are brought in Maa's equations [4], the predicted results are very well comparing with the measured sound absorption. A cheap MPP with irregular cross-sectional perforations is manufactured by an infiltration technique, which consists of mixing a polymeric resin with common salt grain. The sound absorption performance of the cheap MPP can be predicted well by both modified Maa model and modified fluid equivalent model [15]. Since a thin panel has no sufficient strength in engineering applications, a thick MPP by using a tapered perforation or a variable cross section is developed as an interior finish of room walls [16,17]. The point-matching method is used to solve sound propagation through polygonal ducts such as in hexagonal and Voronoi honeycombs [18]. For a given porosity, the effect of cell shape on sound absorption of porous material is small. For the sake of altering vibra-acoustic coupling pattern, a MPP absorber backed by an irregular shaped cavity is studied to broaden the sound absorption bandwidth, and the theoretical predictions are in good agreement with the measured results in the normal incidence [19].

Besides, the acoustic behavior of the multiple MPP absorbers with different cavity depths can be simulated by using COMSOL Multiphysics which is a commercial finite element software package for solving partial differential equations, and the numerical predictions are in good agreement with the experimental results [20]. Craggs and Hilderbrandt [21] employed finite element method to study the velocity profiles and boundary shear forces, when acoustic wave propagates in narrow tubes of hexagonal and other cross sections.

In this paper, acoustic properties of the MPP having arbitrary cross-sectional perforations are studied. Firstly, approximate expressions of the specific acoustic impedance for triangle and square cross sections are obtained, and the end corrections are developed. Then, based on the calculated specific acoustic impedances, the ratios of the real and imagery part of specific acoustic impedances for the four tubes (triangle, circle, square and slit) are given, which could predict the sound absorption bandwidth of the MPP absorber. Finally, for closed perforations, the influences of the perforations in shape (including triangle, circle, square and irregular circle) on sound absorption characteristics of MPP absorber are discussed in collaboration with FE simulation results.

2. Theoretical model

A MPP may be considered a lattice of short tubes, separated by distance much larger than their diameters, but smaller than the wavelength of impinging sound wave [4]. A typical structural configuration of MPP absorber consists of a large number of small uniform tubes, as shown in Fig. 1(a). Considering a uniform tube, the cross-sectional shape of the tube is arbitrary but constant along the length of the tube, e.g. circle, slit, triangle or square cross sections in Fig. 1(b).

2.1. Specific acoustic impedances

The sound propagation in a short tube is primarily controlled by the viscous effect, and the equation of aerial motion is required [4,12,22]. The equation of aerial motion in the short tube is

$$\frac{\partial \upsilon^2}{\partial x^2} + \frac{\partial \upsilon^2}{\partial y^2} - \frac{i\omega\rho_0}{\eta}\upsilon = \frac{1}{\eta}\frac{\Delta p}{t} \tag{1}$$

where ρ_0 and η are the density and viscosity of air, $\omega = 2\pi f$ is the angular frequency, Δp is the sound pressure difference between the two ends of the tube, and t is the length of the tube. The particle velocity υ of the solution is obtained analytically and is equal to zero at the tube walls, which is a function of x and y coordinates. The average velocity through the cross section area A is calculated

$$\bar{\upsilon} = \frac{1}{A}\int_A \upsilon(x,y)dxdy. \tag{2}$$

The ratio Z of the sound pressure difference to the average velocity gives the specific acoustic impedance of the short tube

$$Z = \frac{\Delta p}{\bar{\upsilon}} \tag{3}$$

An approximate formula of the specific acoustic impedance of the MPP having circular or slit cross section, for all values of perforate constant k_c and k_s, is introduced by Maa [4,9]

$$Z_{circular} = \frac{32\eta t}{d^2}\sqrt{1+\frac{k_c^2}{32}} + i\omega\rho_0 t\left(1+\left(3^2+\frac{k_c^2}{2}\right)^{-1/2}\right) \tag{4}$$

$$Z_{slit} = \frac{12\eta t}{d^2}\sqrt{1+\frac{k_s^2}{18}} + i\omega\rho_0 t\left(1+(5^2+2k_s^2)^{-1/2}\right) \tag{5}$$

where perforation constants $k_c = r\sqrt{\omega\rho_0/\eta}$ for the circle and $k_s = b\sqrt{\omega\rho_0/\eta}$ for the narrow slit cross sections. Here, d is perforation diameter, e.g. $d = 2r$ for a circular tube of radius r and $d = 2b$ for a narrow slit of half-width b.

Next, corresponding approximate formulas of the specific acoustic impedances of the MPP having equilateral triangle and square cross-sectional perforations are derived as follows. Firstly, according to Eqs. (1)–(3), the exact expression of the specific acoustic impedance of the short tube of an equilateral triangle cross section is [8],

$$Z_{triangle} = i\omega\rho_0\varepsilon^2/(\varepsilon^2 - 3\varepsilon\coth\varepsilon + 3) \tag{6}$$

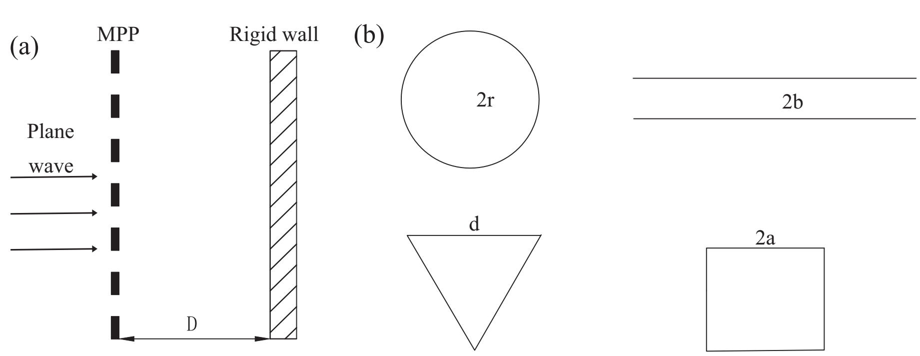

Fig. 1. (a) Model of a MPP absorber (b) with different cross-sectional perforations.