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4 authors, including:

Daoqing Chang
Chinese Academy of Sciences

Bilong Liu
Chinese Academy of Sciences

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Low-frequency sound absorptive properties of double-layer perforated plate under grazing flow

Daoqing Chang[a,*], Fuan Lu[b], Weinan Jin[b], Bilong Liu[c]

[a] Key Laboratory of Noise and Vibration Research, Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, PR China
[b] Shenyang Blower Works Group Corporation, Development Road, Economic & Technical Development Zone, Shenyang 110869, PR China
[c] School of Mechanical Engineering, Qingdao University of Technology, 777 Jialingjiang Road, Qingdao 266520, PR China

ABSTRACT

The sound absorptive properties of double-layer perforated plate with large back-cavity depth under grazing flow are investigated in this paper. The specific resistance and reactance are measured in a flow duct using the straightforward method presented by Jing. Then the sound absorption coefficient is calculated using the results of measured impedance. The sound absorption coefficient is also predicted by a theoretical model, in which the impedance of the layer of perforated plate under grazing flow is estimated by an empirical model. The predicted results agree well with the measured results. The influences of flow speed and the parameters of double-layer perforated plate on the sound absorptive properties are also investigated. Most notably, an interesting phenomenon is revealed that different from the case without flow, the sound absorption performance of a perforated plate under grazing flow is insensitive to the aperture of perforation and plate thickness.

1. Introduction

Perforated plates or sheets are extensively used to attenuate the noise in aero engines, exhaust mufflers and other mechanical systems with or without flow. The acoustic impedance of an orifice without flow under low sound pressure level can be easily determined using the linear formulas [1–3]. Under sound pressure levels of more than 120 dB, the impedance of orifice will be closely related to the sound pressure level, and nonlinear acoustic models of the orifice can be found in the literature [3–6]. With the presence of flow along the surface of a perforated panel, the acoustic impedance of each orifice will be greatly influenced by the flow speed. However, the acoustic impedance of orifice in such case can hardly be determined by rigorous mathematical modeling, and most of the existing impedance models [7–11] are empirical that have taken the flow effects into account.

Although high sound pressure and flow can greatly increase the acoustic resistance of perforated panel, and also the sound absorption bandwidth to a certain extent, a single perforate panel could hardly meet the requirements in noise control engineering. Many researchers have made great efforts to improve the sound absorption bandwidth by serial or parallel assembling perforated plates. In order to broaden the absorption bandwidth of a single micro-perforated plate (MPP) (which has wideband sound absorption compared with the traditional perforated plate [2,12,13]), Maa [2] proposed a double-deck MPP. Sakagami et al. [14–16] studied the acoustical properties of double-leaf micro-perforated panel absorbers and wideband sound absorber composed of two parallel-arranged MPP absorbers, and the results showed that the impedance discontinuity between the parallel-arranged MPPs could provide extra sound absorption to broaden the sound absorption bandwidth of the MPP. Wang and Huang [17,18] also investigated the coupling effect of parallel-arranged MPPs with different air cavities, and concluded that multi-resonant systems have the potential to improve the bandwidth of sound absorption. Qian et al. [19] designed a wideband MPP sound absorber through a serial and parallel coupling manner. Li and Chang et al. [20,21] discussed how to design a low-frequency perforated-panel sound absorber in a space with limited thickness, focusing on the frequency range of 100–300 Hz and thickness of 100 mm, and the combination of three perforated plates with extended tubes (PPET) and one MPP were also investigated to improve the low-frequency sound absorption.

In the modern turbo fan engine, significant progress has been made in the reduction of jet noise using high bypass-ratio engines, while modifications to the fan geometry have been combined with conventional, perforate-facing-honeycomb acoustic liners installed in the interior walls of aircraft engine nacelles to significantly reduce the tonal component of fan noise. The dominant spectral characteristic of fan noise thus change from the tonal form to broadband. Therefore, although the attenuation of fan tones is still a major goal in the design of

* Corresponding author.
E-mail address: changdq@mail.ioa.ac.cn (D. Chang).

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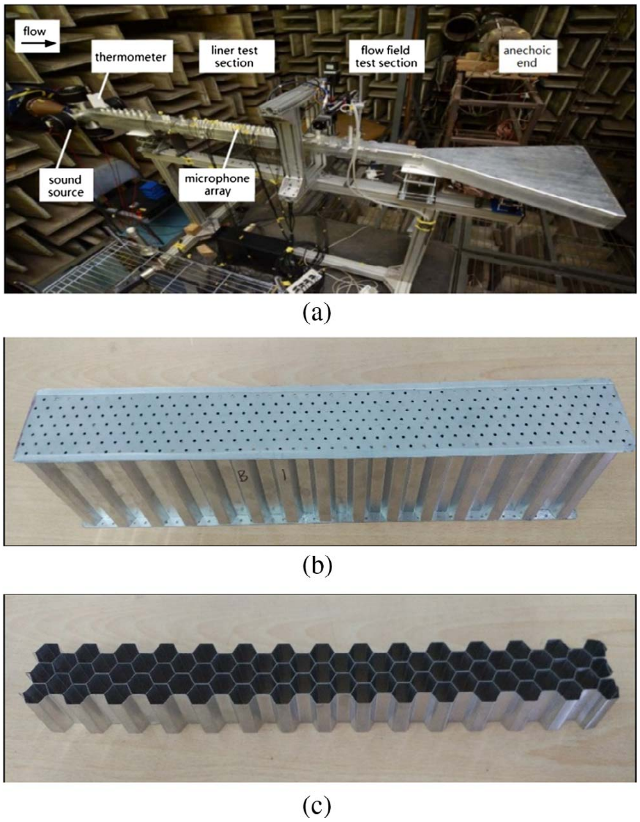

Fig. 1. The experimental setup and samples: (a) measurement setup; (b) the first layer of perforate plate and honeycomb core; (c) the second layer of honeycomb core.

engine acoustic liners, the reduction of broadband fan noise also becomes more important. Drevon [22] introduced how to measure the flow resistance of a perforated septum and the acoustic resistance of a double-layer liner to be applied on the outer wall of the by-pass duct of the nacelle. Jing et al. [23,24] proposed to divide the liner cavity into sub-cavities with judiciously selected lengths or geometry to broaden the effective bandwidth of an acoustic liner through multiple cavity resonances. Syed and Ichihashi [25] also constructed a one-dimensional wave propagation model to compute the impedance of double-layer liners based on the Hexcel honeycomb with embedded porous septa, known as mesh-caps. Jones et al. [26] evaluated three concepts of broadband acoustic liner in an environment without flow and tested them in the NASA normal incidence tube. Sutliff et al. [27] measured the effects of multi-layer acoustic liners and compared the traditional single-layer liners installed in the bypass duct of a scaled model of high-speed fan.

Most of the aforementioned previous studies considered the acoustic properties of double-or multi-layer perforated plates under the condition without flow. However, the presence of flow can greatly increase the resistance of a perforated plate and will make the impedance of double-layer perforated plate become insensitive to certain parameters. This paper investigates the low-frequency sound absorptive properties of double-layer perforated plate with large cavities under grazing flow. Firstly measurement of the acoustic impedance of a double-layer perforated plate in a flow duct is introduced, and the sound absorption coefficient is also calculated based the measured acoustic impedance. Secondly an empirical model is presented to predict the sound absorption coefficient, which is also compared with the measured result. Thirdly a parametric study of double-layer perforated plate is presented before discussion and conclusions are finally made.

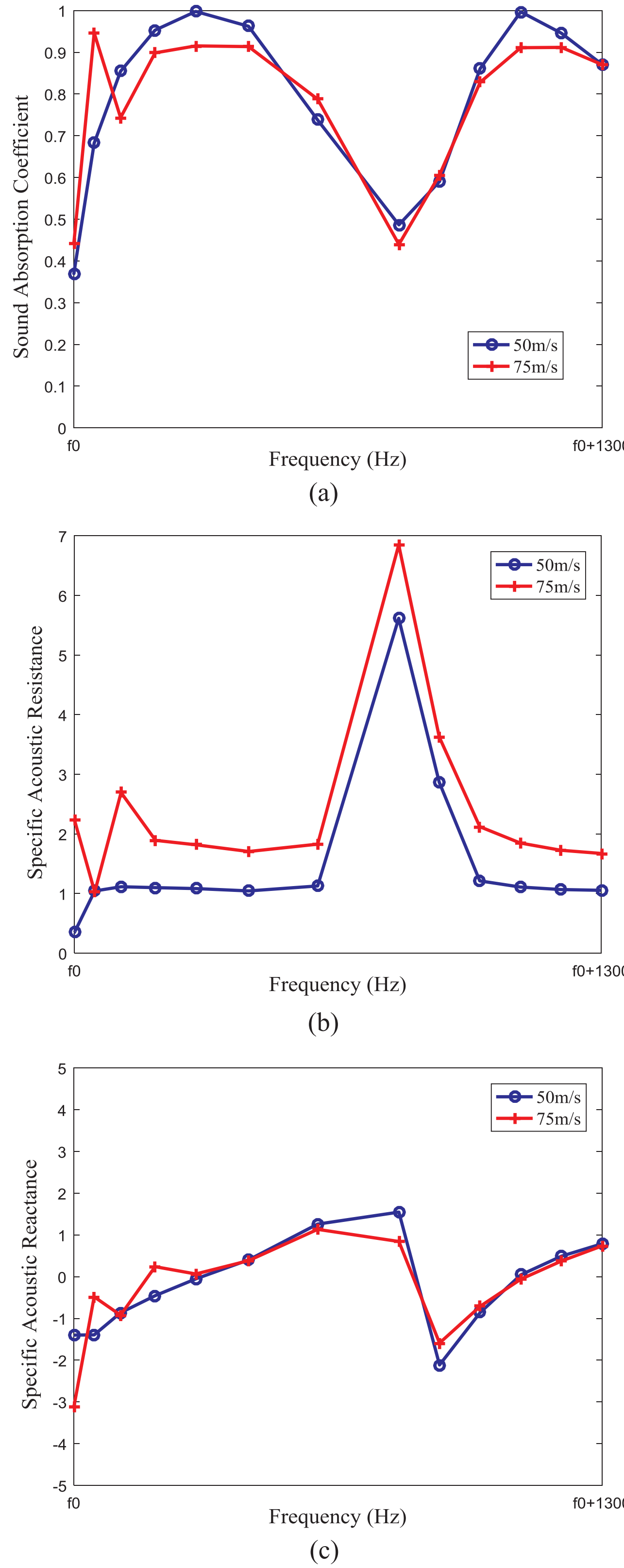

Fig. 2. Comparison of the sound absorptive performance of the double-layer perforated plate under flow at the speed of 50 m/s and 75 m/s.

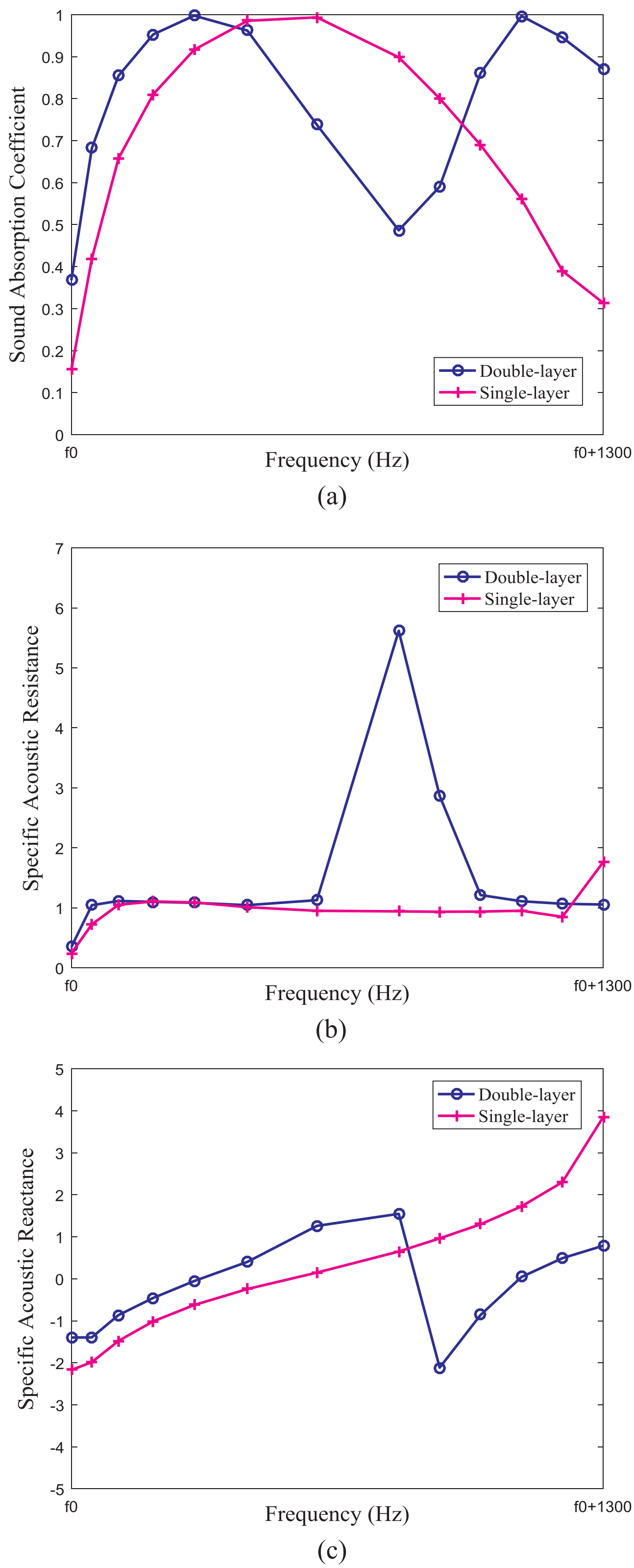

Fig. 3. Comparison of the sound absorptive performance of the double-layer and single-layer perforated plate.

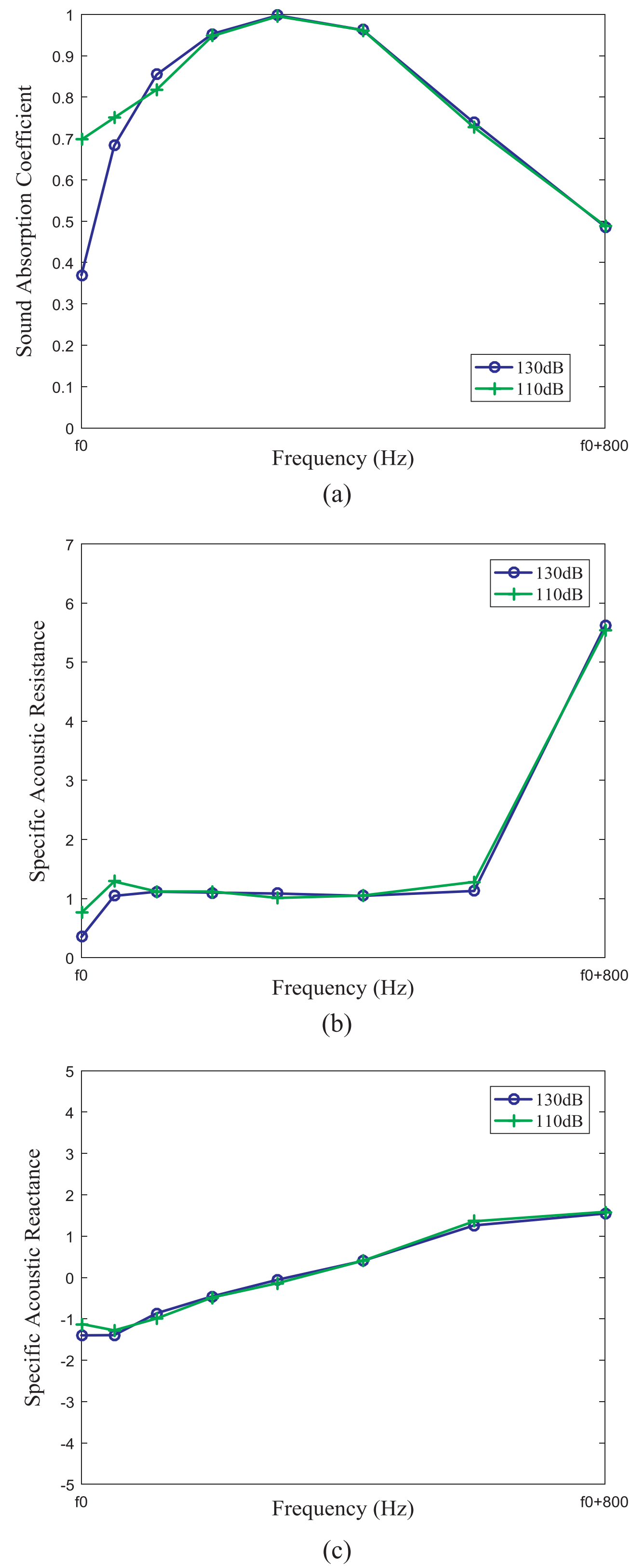

Fig. 4. Influence of sound pressure level on the sound absorptive performance of the double-layer perforated plate under grazing flow.

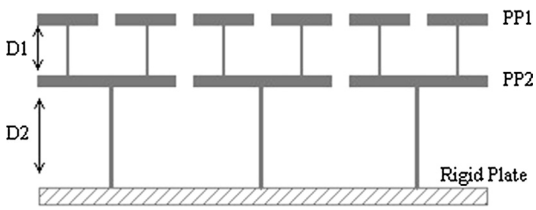

Fig. 5. Double-layer perforated plate.

2. Measurement of acoustic impedance in flow duct

The acoustic impedance of a double-layer perforated plate is measured in a flow duct using the straightforward method first proposed by Jing for wall impedance eduction [28]. The key step in this method is the modal decomposition only based on the wall sound pressure data rather than the whole sound field data in the flow duct, and the single forward and backward wave number is obtained for acoustic impedance eduction. Jing et al. [28] solved this problem with the Prony's method [29].

The measurement is conducted using the flow duct shown in Fig. 1(a) in the Fluid and Acoustic Engineering Laboratory, BUAA. In the experiment the data collected by a 16-microphone array in the wall on the opposite side of a double-layer perforated plate are used to calculate the acoustic impedance of the perforated plate.

The tested sample of double-layer perforated plate has width of 51 mm and length of 400 mm, as shown in Fig. 1(b). It is composed of two perforated plates bonded to two honeycomb cores, as shown in Fig. 1(c). The perforated plate facing the fluid side is defined as PP1 and the other perforated plate is defined as PP2. On the other side of the honeycomb core bonded only to PP2, one thick plate is attached, which can be treated as a rigid boundary. The honeycomb cores can not only stiffen the thin perforated plates but also improve their oblique or field incidence sound absorption performance, particularly at low frequencies [30–32]. Acoustically, they serve the function of making the perforated plates locally reactive.

We investigate the sound absorption coefficient rather than transmission loss of double-layer perforated plate under grazing flow, and it will become easier to observe the effect of parameters on sound absorption performance. However it is not easy to define and calculate the diffuse field incident sound absorption coefficient of a finite sample in a moving medium. In a sense we can assume that a plane acoustic wave is normally incident on an infinite plane with a specific acoustic impedance Z equal to that of the double-layer perforated plate under grazing flow. Then the normal incident sound absorption coefficient formula (1) can be used to evaluate the sound absorption characteristics based on the measured impedance Z.

$$\alpha = \frac{4Real(Z)}{(1+Real(Z))^2+(Imag(Z))^2} \qquad (1)$$

Because of the legal obligations associated with this study, absolute coordinates are not marked for all the test curves. The measured sound absorption coefficients of the double-layer perforated plate under different levels of grazing flow are shown in Fig. 2(a). The blue[1] line marked with circles and the red line marked with "plus" signs represent the test results at the flow speed of 50 m/s and 75 m/s, respectively. The resonance of PP1 induces the first sound absorption peak in the low frequency range. The second sound absorption peak in the high frequency range is induced by the resonance of PP2. The values of both sound absorption peaks at 75 m/s are less than those at 50 m/s. This is mainly because the flow speed greatly increases the specific acoustic resistance to be greater than 1, as shown in Fig. 2(b). The peak of the specific acoustic resistance shown in Fig. 2(b) is induced by the anti-resonance of the double perforated plate. The flow speed has little influence on the specific acoustic reactance, as shown in Fig. 2(c).

The measured sound absorption coefficient of the single-layer perforated plate (the second honeycomb core is removed) under the grazing flow speed of 50 m/s is shown in Fig. 3(a). The double-layer

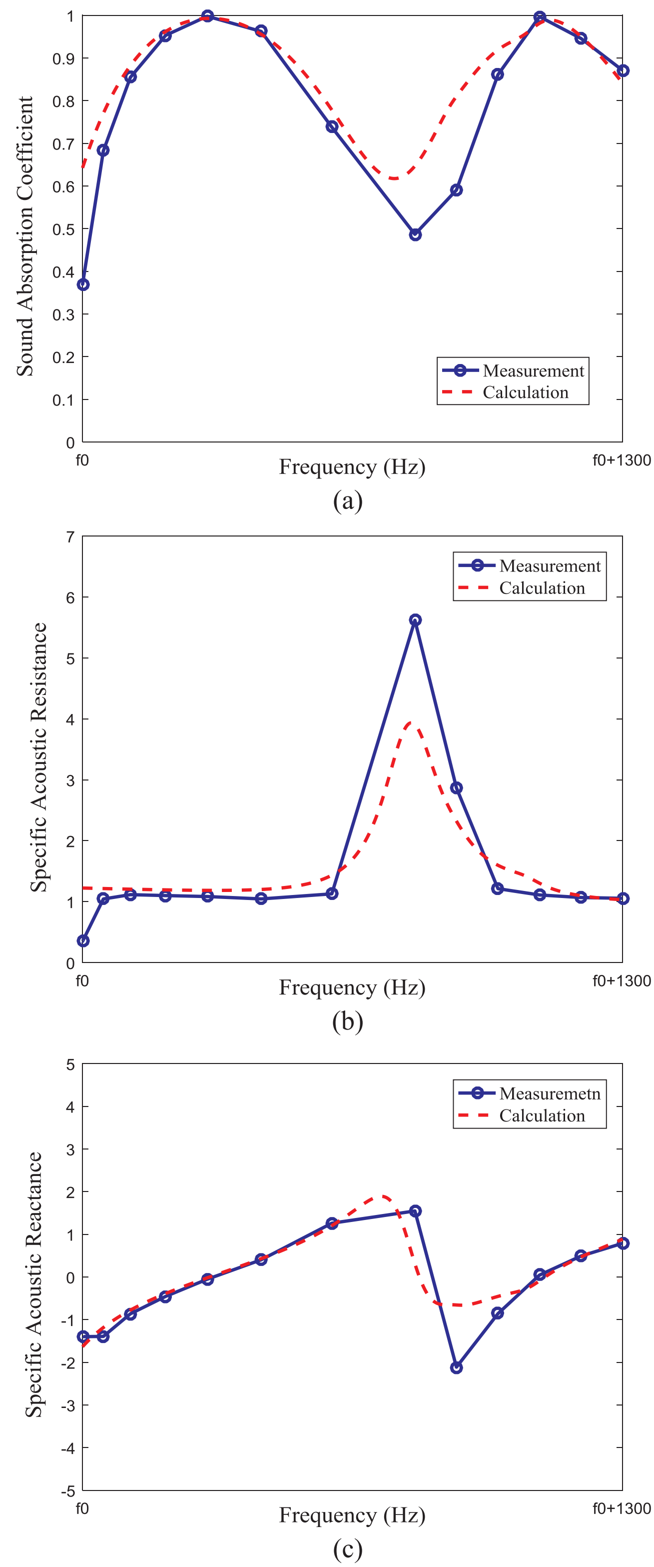

Fig. 6. Comparison of the measured and calculated results for double-layer perforated plate under flow at the speed 50 m/s, and at SPL of 130 dB.

[1] For interpretation of color in Figs. 2 and 4, the reader is referred to the web version of this article.

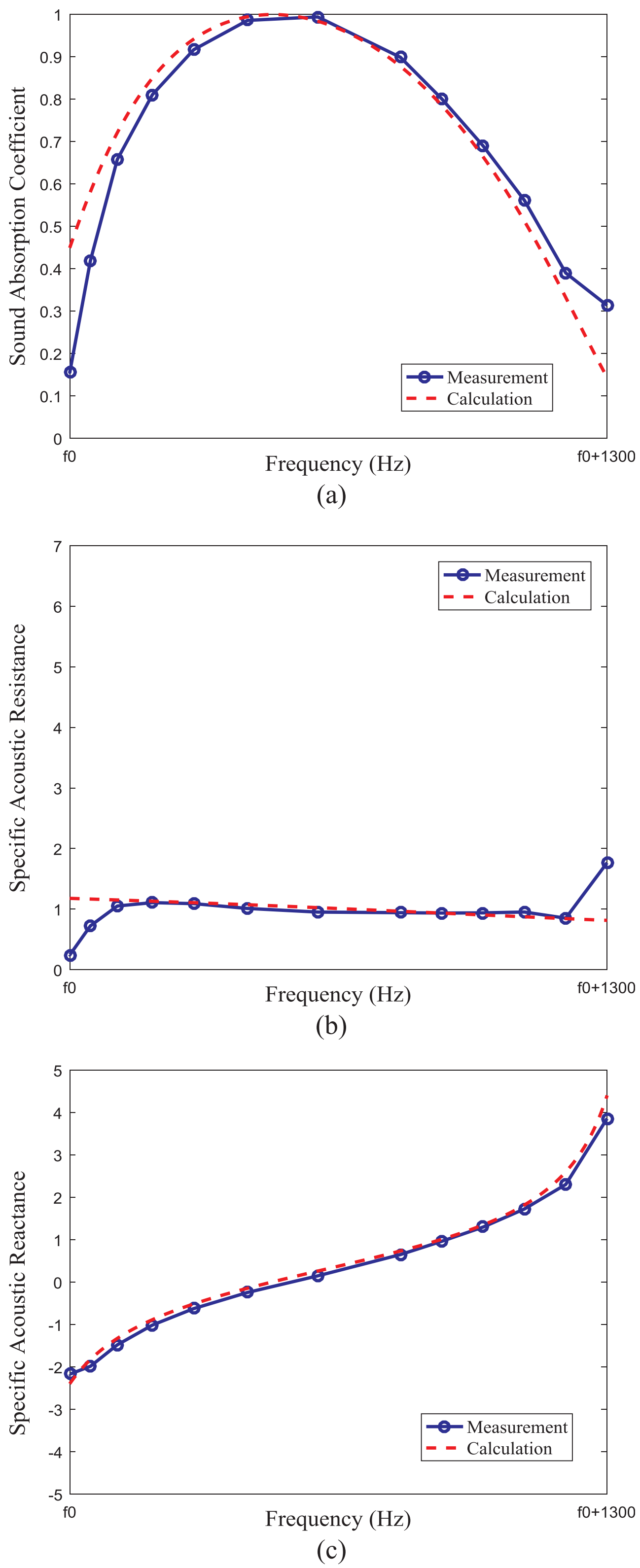

Fig. 7. Comparison of the measured and calculated results for the single-layer perforated plate under flow at the speed of 50 m/s, and at SPL of 130 dB.

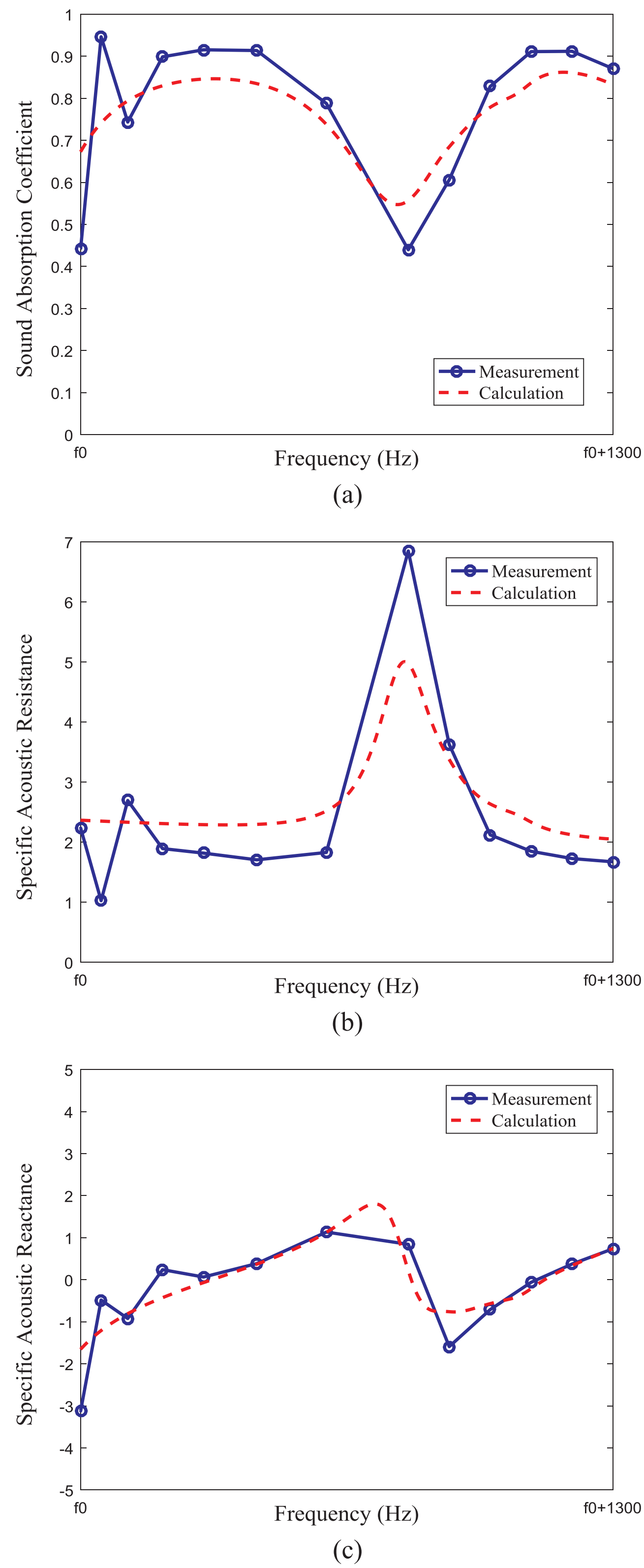

Fig. 8. Comparison of the measured and calculated results for the double-layer perforated plate under flow at the speed of 75 m/s, and at SPL of 130 dB.

perforated plate has better sound absorbing performance in the low and high frequency ranges compared with the single-layer perforated plate. However it has a sound absorption trough in the middle frequency range owing to the anti-resonance. The specific acoustic resistance and reactance of the single-layer perforate plate (PP1) are also shown in Fig. 3(b) and Fig. 3(c), respectively.

The influence of sound pressure level (SPL) on the sound absorption coefficient of the double-layer perforated panel is also measured, as shown in Fig. 4(a)–(c). The blue line marked with circles and the green line marked with “plus” signs represent the test results at sound pressure levels of 130 dB and 110 dB, respectively. Different from the case

Table 1
The reference parameters of the sample.

Samples	PP1					PP2			
	d_1 (mm)	t_1 (mm)	σ_1 (%)	D_1 (mm)	Flow (m/s)	d_2 (mm)	t_2 (mm)	σ_2 (%)	D_2 (mm)
Parameters	1.5	1.0	8	90	50	1.5	1.0	3	40

without flow, the SPL below 130 dB has little influence on the sound absorption coefficient of the perforated plate under grazing flow. A similar conclusion was also mentioned in Ref. [11].

3. Theoretical model

The double-layer perforated plate shown in Fig. 5 is equivalent to two impedances in serial. The nonlinear effect of high sound pressure level is ignored in the following model because the sound pressure level is not higher than 130 dB in the experimental test. The PP1 is subject to the grazing flow, so an impedance model with flow is required, but the linear impedance model of perforated plate can be directly applied to the PP2 unaffected by the flow. The specific acoustic impedance of PP1 can be written as

$$z_{1f} = R_{1f} + jI_{1f} \tag{2}$$

where R_{1f} and I_{1f} are the specific acoustic resistance and reactance of the PP1 under the gazing flow, respectively. Many empirical models can be found in the Refs. [7–11] for different conditions. An empirical impedance model is used in this paper, which was derived by Lee and Ih [11] using the nonlinear regression analysis of various results obtained in the parametric tests. The parameters used in this study right fall in the range of this model. In this empirical model, the specific acoustic resistance is

$$R_{1f} = a_0(1 + a_1|f - f_0|)(1 + a_2M)(1 + a_3d_1)(1 + a_4t_1)/\sigma_1 \tag{3}$$

where

$$a_0 = 3.94 \times 10^{-4}, a_1 = 7.84 \times 10^{-3}, a_2 = 14.9, a_3 = 296, a_4 = -127$$

$$f_0 = \varnothing_1\frac{1 + \varnothing_2M}{1 + \varnothing_3d}$$

$$\varnothing_1 = 412, \varnothing_2 = 104, \varnothing_3 = 274$$

In the model, f, M, d_1, t_1 and σ_1 are the frequency, Mach number of the flow, diameter of the orifices, thickness of the perforated plate, and perforation ratio of the perforated plate, respectively. In the regression analysis of impedance, the ranges of the valid data are as follows: $60 \leqslant f \leqslant 4000$ Hz, $0 \leqslant M \leqslant 0.2$, $2 \leqslant d_1 \leqslant 9$ mm, R_2 $1 \leqslant t_1 \leqslant 5$ mm, and $2.79\% \leqslant \sigma_1 \leqslant 22.3\%$.

The acoustic reactance I_{1f} is written as

$$I_{1f} = \frac{\omega(t_1 + \Delta t_1)}{c_0\sigma_1}\delta_1 \tag{4}$$

where δ_1 is a modification using the Fok's function by Melling [3]. The end correction term Δt_1 is written as

$$\Delta t_1 = \frac{0.85 d_1(1 - 0.7\sqrt{\sigma_1})}{1 + 305M^3} \tag{5}$$

The specific acoustic impedance of PP2 can be written as

$$z_2 = R_2 + jI_2 \tag{6}$$

where and I_2 are the specific acoustic resistance and reactance of PP2, respectively:

$$R_2 = \frac{\sqrt{8\mu\omega}}{c_0\sigma_2}\left(1 + \frac{t_2}{d_2}\right) \tag{7}$$

$$I_2 = \frac{\omega(t_2 + \Delta t_2)}{c_0\sigma_2}\delta_2 \tag{8}$$

where the end correction $\Delta t_2 = 0.85d_2$. The depth of the cavity behind PP2 is D_2. The corresponding specific acoustic resistance can be written as

$$z_{D_2} = \coth\left(\frac{\omega D_2}{c_0}j\right) \tag{9}$$

The surface impedance at the front surface ofPP2 can then be written as

$$z_{2s} = z_2 + z_{D_2} \tag{10}$$

Using the transfer matrix method, the specific acoustic impedance at the front surface of the double-layer perforated plate can be written as

$$z = z_{1f} + \frac{z_{2s}\cos(\omega D_1/c_0) + j\sin(\omega D_1/c_0)}{\cos(\omega D_1/c_0) + jz_{2s}\sin(\omega D_1/c_0)} \tag{11}$$

Once the specific acoustic surface impedance Z of the double-layer perforated plate under grazing flow has been decided, the sound absorption coefficient can be calculated using equation (1).

Fig. 6 compares the measured and calculated sound absorption coefficients of the double-layer perforated plate under the grazing flow at the speed of 50 m/s. The prediction agrees well with the measured results except for the region near the anti-resonant frequency, where the specific acoustic resistance shows a certain deviation. Fig. 7 compares of the measured and calculated sound absorption coefficient of the single-layer perforated plate under the grazing flow at the speed of 50 m/s. The prediction also agrees well with the measured results. Fig. 8 compares the measured and calculated sound absorption coefficient of the double-layer perforated plate under the grazing flow at the speed of 75 m/s. The calculated sound absorption coefficient is lower than the measured results at two resonant frequencies, as shown in Fig. 8(a). This is mainly because in the vicinity of the resonant frequencies, the model gives a higher estimate of the specific acoustic resistance. In the regression analysis of the impedance model [11], the range of valid flow speed data is "$0 \leqslant M \leqslant 0.2$", so the grazing flow at the speed of 75 m/s in this paper exceeds the valid range. In general, the model can give good predictions in the valid rang of parameters.

4. Parametric study of the double-layer perforated plate under grazing flow

It is well known that the sound absorptive performance of perforated plates in the absence of flow is mainly determined by such parameters as the diameter of the orifice, plate thickness, perforation ratio and depth of the back cavity. However, the effects of these parameters on the sound absorptive performance of perforated plates under grazing flow are different. Next, an example of theoretical analysis is used to discuss the impact of these parameters on the sound absorption coefficient of double-layer perforated pate under grazing flow. The reference parameters of the sample in the theoretical analysis are shown in Table 1.

The effect of flow speed on the sound absorptive performance of the double-layer perforated plate is shown in Fig. 9. The following flow speeds are considered: 10 m/s, 30 m/s, 50 m/s and 70 m/s. The grazing flow greatly increases the specific acoustic resistance of the double-layer perorated plate, as shown in Fig. 9(b). As the flow speed increases,

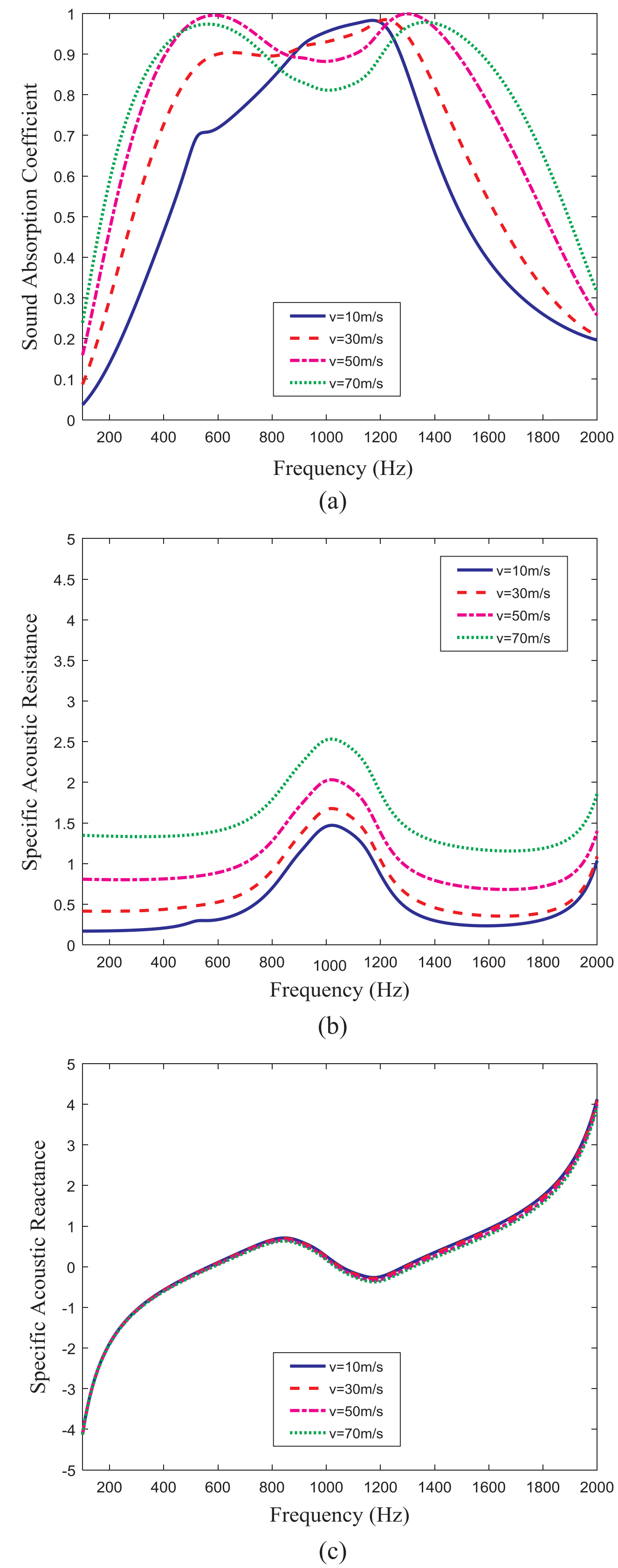

Fig. 9. The influence of flow speed on the sound absorptive performance of the double-layer perforated plate.

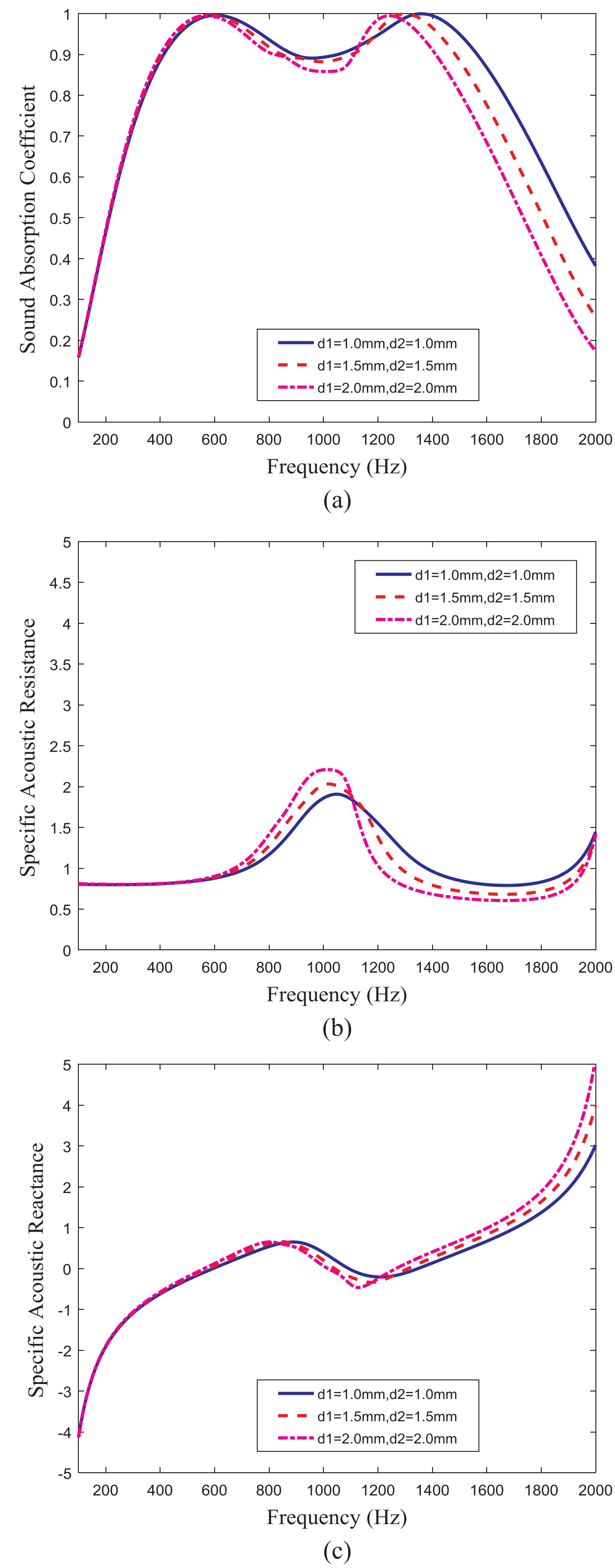

Fig. 10. The influence of perforation aperture on the sound absorptive performance of the double-layer perforated plate.

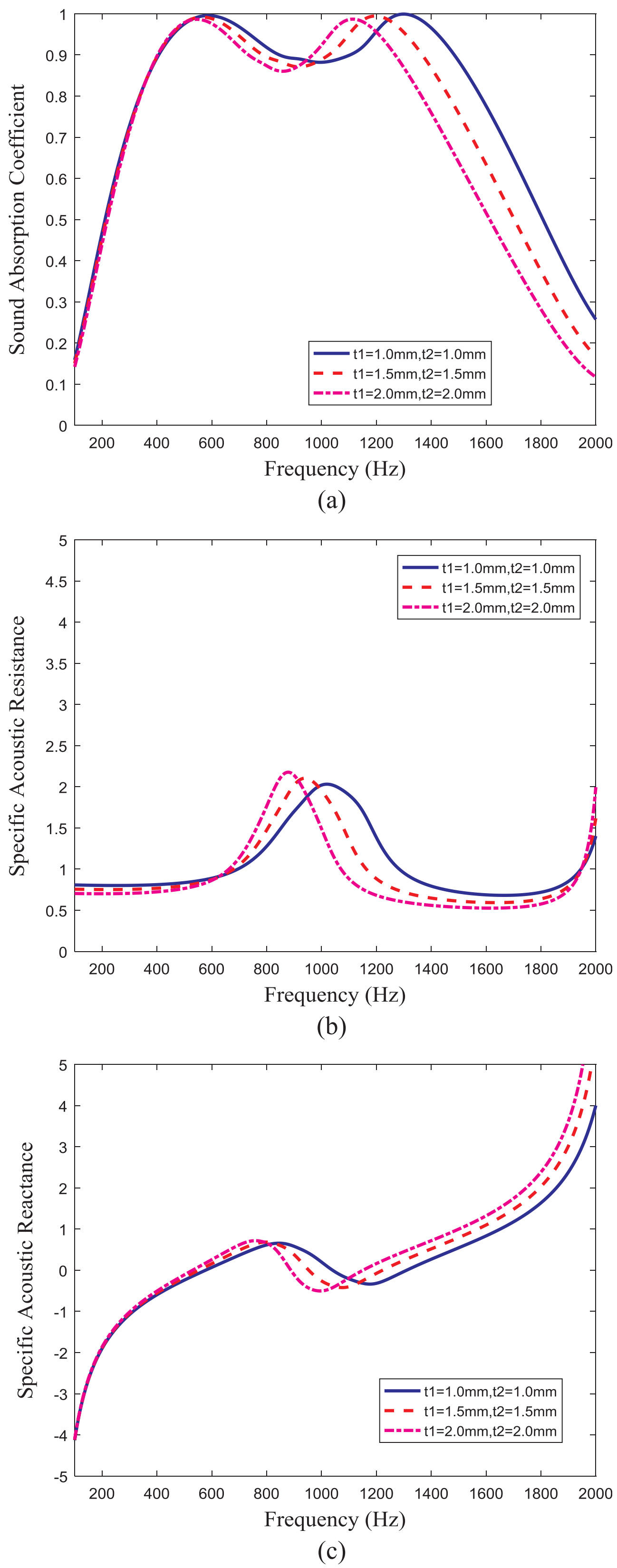

Fig. 11. The influence of plate thickness on the sound absorptive performance of the double-layer perforated plate.

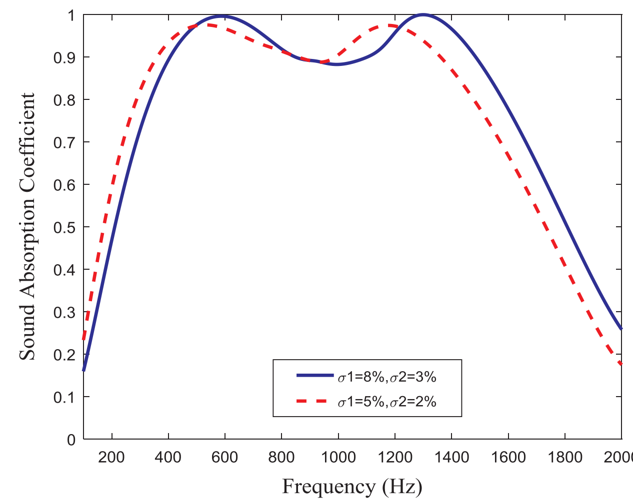

Fig. 12. The influence of perforation ratio on the sound absorptive performance of the double-layer perforated plate.

the specific acoustic resistance approaches to 1, and the sound absorptive performance is greatly improved. When the specific acoustic resistance is greater than 1, the sound absorption coefficient begins to decrease, but the sound absorption bandwidth continues to increase. The effect of flow speed on the specific acoustic reactance is not obvious, as shown in Fig. 9(c).

The influence of orifice diameter on the sound absorptive performance is shown in Fig. 10. It is well known that increasing the orifice diameter can make the absorption peak position of the non-flow perforated plate move to a lower frequency. However, for the perforated plate under grazing flow, the location of sound absorption peak is not sensitive to the aperture. As shown in Fig. 10(a) and (c), increasing the aperture from 1.0 mm to 2.0 mm and keeping the perforation ratio unchanged, the location of the sound absorption peak of PP1 is almost unchanged, while the sound absorption peak of PP2 has moved to a lower frequency. The specific acoustic resistance of PP1 is also unchanged, but the specific acoustic resistance of PP2 is reduced, as shown in Fig. 10(b). Similar results can be obtained for the effect of plate thickness, as shown in Fig. 11. Increasing the thicknesses of both plates can make the absorption peak position of the non-flow perforated plate move to a lower frequency. However, the location of the sound absorption peak of the perforated plate under grazing flow is insensitive to the thickness.

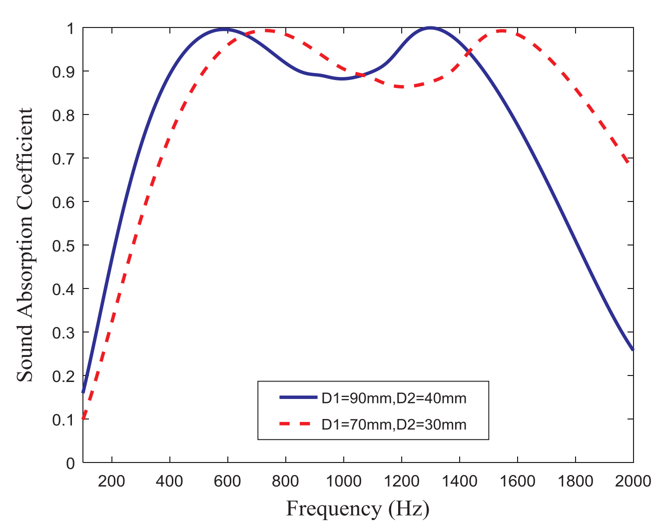

Fig. 13. The influence of cavity depth on the sound absorptive performance of the double-layer perforated plate.

The effect of perforation ratio and cavity depth on the sound absorptive performance of a perforated plate under grazing flow is similar to that of a perforated plate without flow, as shown in Figs. 12and 13.

5. Conclusions

The specific acoustic impedance of double-layer perforated plate with large back-cavity depth under grazing flow is measured in a flow duct. The sound absorption coefficient derived based on the measured impedance is used to characterize the sound absorptive performance of the double-layer perforated plate. An empirical model is also presented to predict the sound absorption coefficient and the prediction agrees well with the measured results. The grazing flow not only greatly influences the sound absorptive performance of the first-layer perforated plate, but also that of the second-layer perforated plate owing to their coupling effect. Additionally, the sound absorption coefficient of the perforated plate under the grazing flow is not sensitive to the perforation aperture and plate thickness, which is different from the case without flow. The flow speed, perforation ratio and cavity depth are the key parameters to determine the sound absorptive performance of a perforated plate under grazing flow.

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