Acoustic performance of a plate with varying perforations

Xiaonan WANG; Weichen ZHANG; Lechun YING

Shanghai Academy of Environmental Sciences, Shanghai, China

ABSTRACT

A theoretical study of a plate with varying perforations is presented in this paper. The Bloch wave theory and the transfer matrix method are used to investigate the acoustic performance of the plate. It is found that different from the original attenuation characteristic of the plate with periodic perforations that brought about by structural periodicity, the varying perforations provides a unique structure performance. All of the results predicted by the theory fit well with a numerical simulation using a finite element method. As a result, the proposed structure may have a potential application in duct noise control under careful parameter design.

Keywords: The Bloch wave theory, perforation, transmission loss

I-INCE Classification of Subjects Number(s): 51.4

1. INTRODUCTION

Perforated plate is widely used in noise control engineering. For example, sound radiation can be reduced by constructing the vibrating plate from perforates. Studies have been conducted to determine the sound radiation from a vibrating perforated plate [1-3]. Active control method is also conducted by using perforated panel[4]. Furthermore, perforated plate is used for sound dissipation. The transmission loss in the duct inserted by perforated plate is modeled theoretically and measured for validation [5]. In other occasions, perforated plate is backed by the cavity which is filled with porous absorbing materials [6-7]. The impedance of the plate with perforation is studied by considering grazing gas flow. It shows that porous backing layer has a large effect on the impedance of plates with circular perforations and little or no effect on louvred perforates.

However, the above studies have not consider a perforated plate with varying hole diameter. In the present study, a plate with several columns of holes is studied. The effect of varying hole diameter is analyzed theoretically and numerically. It shows that by setting different hold diameter in one plate, the noise reduction bandwidth is widened comparing with a perforated plate with constant diameter setting.

2. THEORETICAL ANALYSIS

As shown in Fig.1, a segment of duct wall is replaced by a perforated plate. The plate has several columns of holes, and for the different column, the hole diameter is set to be different. In this configuration, the hole diameter of each column can be set different. When sound wave incidence, reflection occurs due to impedance discontinuity in-between each column of holes. The vibration of the plate is excluded in the present study. l_0 is the plate thickness, while w_n is the hole diameter of the n-th column, for example, w_2 is the hole diameter for the 2rd column, noted in Fig.1. The distance between each column is denoted as D, which is set to be constant.

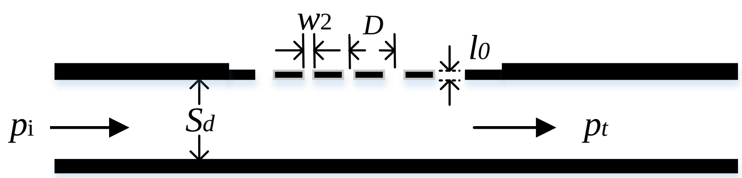


Figure 1-The configuration of the perforated plate inserted into the duct wall

When incident sound wave comes, part of the sound energy is reflected upstream at each column of holes and part of the sound is transmitted downstream. For one single hole, the impedance of the hole can be expressed as

$$Z_{0,n} = j\omega M_{0,\mathrm{n}} \tag{1}$$

Where $M_{0,n}$ is the air mass within the hole of n-th column, which can be described as $M_{0,n} = \frac{4\rho_0 l_n}{\pi d_n}$, In which ρ_0 is the air density.

Assuming the frequency range considered is well below the cut-on frequency of the duct. In the duct segment of the nth cell for $(n-1)D \le x \le nD$, the sound travels in positive-x and negative-x direction, and the sound pressure can be expressed as $p_n^+(x) = C_n^+ e^{-jk[x-(n-1)D]}$, and $p_n^-(x) = C_n^- e^{jk[x-(n-1)D]}$, where "+" and "-" represent the travelling sound direction of positive-x and negative-x respectively. C_n^+ and C_n^- are complex constants and k is the wave number. Referring to the continuity of sound pressure and volume velocity at the point $x=nD$[8,9],

$$\begin{bmatrix} C_{n+1}^+ \\ C_{n+1}^- \end{bmatrix} = \begin{bmatrix} (1-\xi)e^{-jkD} & -\xi e^{jkD} \\ \xi e^{-jkD} & (1+\xi)e^{jkD} \end{bmatrix} \begin{bmatrix} C_n^+ \\ C_n^- \end{bmatrix} = T \begin{bmatrix} C_n^+ \\ C_n^- \end{bmatrix} \tag{2}$$

Where the 2×2 matrix T is the transfer matrix, $\xi = Z_d / 2Z_0$, as $Z_d = \rho_0 c_0 / S_d$. According to the Bloch wave theory, Eq.(2) can be expressed as

$$[C_{n+1}^+ \quad C_{n+1}^-] = e^{-jqD} \begin{bmatrix} C_n^+ & C_n^- \end{bmatrix}^T \tag{3}$$

In which the superscript T is the transposition and q is the Bloch wave number. By combining Eq.(2) and Eq.(3), the eigenvalue $\lambda = e^{-jqD}$ and the corresponding eigenvector $v = [v^+ \quad v^-]$ for the transfer matrix T can be solved. Combing Eqs. (2) and (3) gives

$$\cos(qD) = \cos(kD) + j\xi \sin(kD) \tag{4}$$

The eigenvalue λ can describe the propagation property of a characteristic wave type, which is known as the Bloch wave. The Bloch wave is defined by its corresponding eigenvalues $[v^+ \quad v^-]^T$, which indicates the linear combination of positive and negative going planar waves. The Bloch wave number q is a complex. There are ranges of frequencies in which q can be described as $q = q_r - jq_i$, which indicates the sound energy is attenuated when travelling through each column of holes, and these frequency ranges are called stop-bands. In other frequencies, $q = q_r$, which indicates that there is only a phase delay when sound waves travel through each column, and these frequency ranges are called pass-bands.

3. RESULTS AND DISCUSSION

3.1 Comparison between theoretical and numerical results

Finite element method is used to validate the theoretical analysis. The configuration is set as D=0.6m, l_0 =0.01m, diameter of the holes of five columns are set as w_0 =0.02m. As shown in Fig.2, the numerical result is generally coincident with the result calculated theoretically, as pass-band and stop-band occur in the same frequency range. In the study transmission loss shown in the figure is the total TL divided by 5, which emphasis the TL ability of each column of holes. Below 200Hz, the transmission loss is relatively high, especially below 100Hz，TL is above 15 dB. With the frequency increasing, the TL reduces rapidly till 200Hz and what follows is a stopband within the range of 200~300Hz. And pass-band appears within about 300~400 Hz. These characteristics are both shown by theoretical analysis and numerical prediction. However, there are some difference between the two results, as there are ripples in the stop-band of the theoretical results. This is mainly because the end correction is not considered in the present study, also the interactions between the holes in the other opening, e.g. the opposite opening towards the duct are not considered, either.

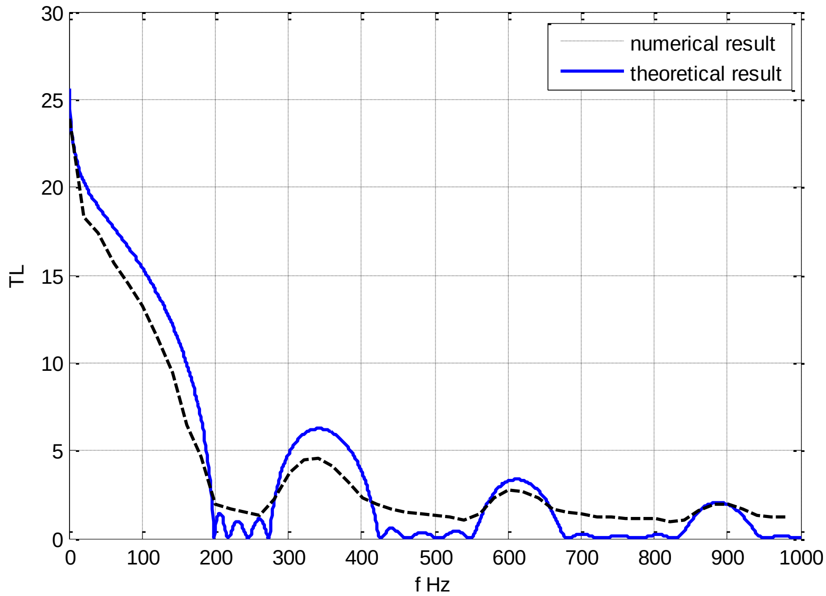


Figure 2-Comparison between theoretical and numerical analysis

3.2 Performance of the perforated plate

Multiple columns are considered in this study, so five columns are used. The performance is compared with the plate with single column holes, as shown in Fig.3. The dotted line represent the TL of the single column holes, while other lines represent the average TL obtained by one column for the multiple column configuration. For the configuration with single column, transmission loss reduces within the frequency. If the distance between each column is D=0.5, stop-band and pass-band appear. Within 50~220 Hz, the TL performance is improved, which means one column of holes contributes more to TL when interaction happens between columns. If D is reduced to 0.3, the first stop-band is further widened, while if D=0.1, the first stop-band is within the frequency range of 0~650Hz. It indicates that when the distances between columns are smaller, the interaction is more obvious, and moreover, the interaction is beneficial for the TL improvement.

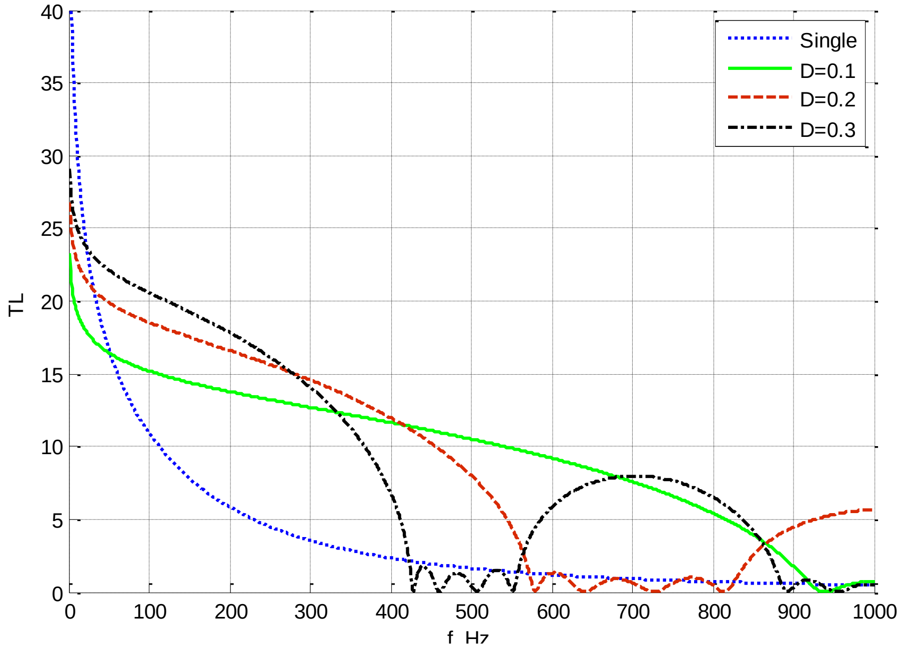


Figure 3-Transmission loss of perforated plate with different configuration

When the diameters of holes are artificially set to vary, shown in the solid line of Fig.4, The hole diameter of each column is set as 0.002, 0.004, 0.006, 0.008 and 0.01, shown in the solid line. It can be seen that, with 5 columns of holes of same diameter, the TL is already improved within 100~550Hz, compared with the plate with single column of holes. When the hole diameter varies, seen in the solid line, the TL performance is improved generally within the frequency range. About 2.5 dB improvement in TL is obtained when the hole size is artificially tailored. The difference in hole size for each column enhances the interaction between each column of holes, which is beneficial for reducing the sound transmission, hence less sound is transmitted downstream.

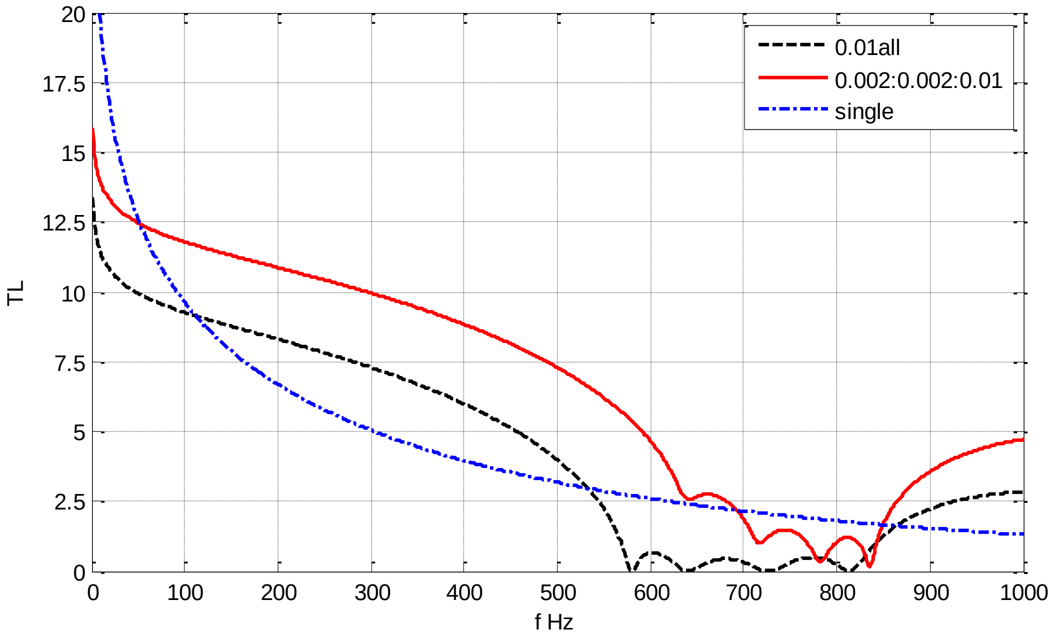
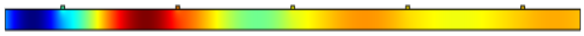


Figure 4-Performance of the plate with varying hole diameter

3.3 Sound distribution in the duct

For the perforated plate with varying holes, the pass-band and the stop-band appears one after one within the frequency range. The sound distributions are shown in Fig.5. At f=350 Hz, by referring to Fig.1, which is in the stop-band, the sound pressure downstream is reduced significantly; while at *f*=500 Hz, which is within the passband, thus there is no obvious sound pressure reduction, seen from Fig.5(b). The observations are coincident with the result shown in Fig.1.



(a) *f*=350 Hz

(b) *f*=500Hz

Figure 5-Sound distributions in the duct for the perforated plate with varying hole diameter

4. CONCLUSION

In the present study, perforated plate with varying hole diameters is investigated. By adopting Bloch wave theory, the sound transmitted and reflected in-between each two columns of holes are studies. It is shown that by tuning hole diameter, which is to artificially set the hole diameter differently within one plate is beneficial for increase the transmission loss in the duct.

This study is a primary study, as in practice, the plate should be backed by a cavity preventing sound leakage. Further studies are undertaken to give a thorough study on the perforated plate with varying hole diameters and its potential in reduction sound transmission within the duct.

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REFERENCES

[1] F.J. Fahy, D.J. Thompson, The effect of perforation on the radiation efficiency of vibrating plates, Proceedings of the Institute of Acoustics 26 (2004).

[2] A.Putra, and D.J. Thomson, Sound radiation from perforated plates. Journal of Sound and Vibration329 (20), 4227-4250.

[3] A.Putra, and D.J. Thomson, Radiation efficiency of unbaffled and perforated plates near a rigid reflecting surface. Journal of Sound and Vibration330 (22), 5443-5459.

[4]J.Pan, C.H.Hansen, D.A. Bies. Use of a perforated panel for the active control of sound radiated from vibrating structures, I: Low-frequency analysis. Journal of Sound and Vibration 156(2), 349-359(1992).

[5]T.E.Vigran. Normal incidence sound transmission loss in impedance tube-Measurement and prediction methods using perforated plates. Applied Acoustics 73(4), 454-459(2012).

[6] H.Aygun, K. Attenborough. The insertion loss of perforated porous plates in a duct without and with mean air flow. Applied Acoustics 69(6), 506-513(2008).

[7] R. Kirby, A. Cummings. The impedance of perforated plates subjected to grazing gas flow and backed by porous media. Journal of Sound and Vibration 217(4),619-636(1998).

[8] C. Kittel, Introduction to Solid State Physics, 6th ed. (John Wiley and Sons, Inc., New York, 1986),

Chap. 8, pp. 181–216.
[9] X. Wang and C. M. Mak, Acoustic performance of a duct loaded with identical resonators. J. Acoust. Soc. Am. 131 (4), EL316-EL322.