inter.noise
27-30 AUGUST 2017
HONG KONG

The Helmholtz resonator with different types of necks

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ABSTRACT

This paper focuses on improving the noise attenuation performance of the Helmholtz resonator (HR) at low frequencies with a limited space. Three different types of necks: an extended neck or a spiral neck takes the place of the traditional straight neck of the HR. The acoustic performance of the HR with these two types of necks is analyzed theoretically and numerically. The spiral neck is transformed to an equivalent straight neck, and the acoustic performance is then obtained by a one-dimensional approach. A length correction factor for the extended neck is developed through a modified one-dimensional approach to take the non-planar effects into account. The theoretical prediction results fit well with the Finite Element Method (FEM) simulation results. The results show that significant improvement of the acoustic performance of the HR can be obtained by introducing these necks. The acoustic characteristics of HRs with these two different neck types have a potential application in noise control, especially at low frequencies within a constrained space.

Keywords: Helmholtz resonator, extended neck, spiral neck, noise control

1. INTRODUCTION

A ventilation ductwork system is an essential components of modern buildings that maintains comfortable indoor environments, for instance, air temperature, air quality and air humidity [1]. However, the unpleasant noise accompanied with the fresh air from the opening of the ventilation ductwork system in a room is a direct source of annoyance that seriously influence people's living and working quality [2-6]. Moreover, the noise may also have negative impacts on residents in other rooms by transmitting from one room to the nearby rooms through the building structures [7,8]. It is therefore important to reduce duct-borne noise, especially the low frequency and broadband noise in the ventilation ductwork system. Helmholtz resonator is widely used as an effective device for low frequency noise in the ducted system due to its characteristics of tunable, affordable and durable [9-12]. Other traditional methods such as porous duct lining, expansion chamber still suffer from serious drawbacks in low frequency [13,14]. Through the development of active control has provided another possible way to tackle the low frequency problem, serious challenges still exist in engineering applications [15-17]. Therefore, a good design for a Helmholtz resonator is important for noise attenuation in ventilation ductwork systems and has attracted the attenuation of many researchers and engineers.

Aiming at a more accurate prediction and a preferable transmission loss performance, a continuous effort has been made and documented in numerous pieces of literature [18-22]. While the HR is known to be an effective silencer at low frequencies, sometimes its application may be limited by space. It is important to shift the resonance frequency when there is a space constraint. This paper focuses on improving the noise attenuation performance of the HR at low frequencies when there is limited space. A spiral neck or an extended neck may by a feasible way to shift the resonance frequency in such situations. The acoustic performance of HRs with these two types of necks is analyzed both theoretically and numerically.

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Cai, C., Mak, C. M., Shi, X., & Wang, X. (2017, December). The Helmholtz resonator with different types of necks. In INTER-NOISE and NOISE-CON Congress and Conference Proceedings (Vol. 255, No. 7, pp. 923-929). Institute of Noise Control Engineering.

2. Analytical approach of the HR with different necks

2.1 Analytical approach of the HR with a spiral neck

The traditional short neck is replaced by a spiral neck to make the neck as long as possible when there is a space constraint. Meanwhile, the curvature of the spiral neck changes the impedance, and it can then be considered equivalent to the traditional straight neck [19, 23]. For these reasons, this kind of HR can improve noise reduction performance at low frequencies within a limit space, as illustrated in Fig.1. The spiral neck could be divided into three parts: two straight tubes of lengths L_I and L_{II} respectively, and the spiral tube (with N turns of total length L_{III}).

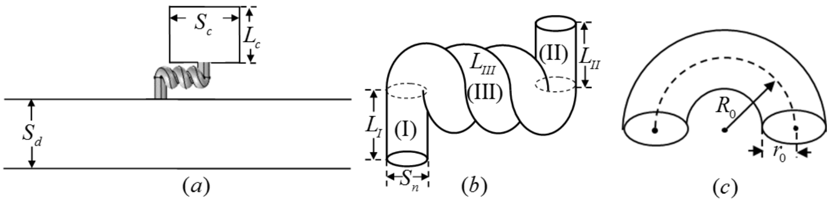

Figure 1 – (a) A Helmholtz resonator with a spiral neck. (b) The spiral neck with three turns. (c) A section of the curved tube.

The particle velocity along the toroidal axis in the spiral tube is determined by the radial dependence of the sound pressure and the curvature dependence of the sound pressure. However, the radial dependence of the sound pressure is quite small due to the low frequency range considered in this paper. This means that the sound pressure remains the same over the cross-section area. Therefore, the particle velocity could be expressed as:

$$v(R_0, \phi) = \frac{-1}{j\omega\rho_0} \frac{1}{R_0} \frac{\partial p}{\partial \phi} \tag{1}$$

where p is the sound pressure, ω is the angular frequency, ρ_0 is the air density, ϕ is the curvature angle, and R_0 is the distance from the point of the curvature center.

The curvature changes the impedance of the spiral tube, and it can then be considered equivalent to a straight tube. For the spiral tube with cross-section area S_n and length L_{III} shown in Fig. 1 (b), the equivalent straight tube with cross-section area S_n' and L_{III}' is expressed as: $S_n' = S_n / \sqrt{F}$ and $L_{III}' = L_{III}\sqrt{F}$ respectively.

The equivalent coefficient F is $0.5(r_0 / R_0)^2 \Big/ (1 - \sqrt{1-(r_0/R_0)^2})$. The equivalent coefficient is practically less than unity, which means that the equivalent straight tube has a larger area and a shorter length. The spiral neck could therefore be considered a combination of three connected straight tubes in a theoretical analysis. The equivalent theoretical model of a HR with a spiral neck is shown in Fig. 2.

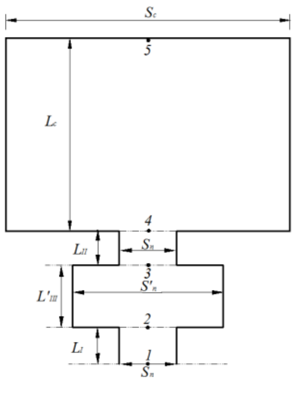

Figure 2 – The equivalent Helmholtz resonator.

The frequency range considered in this paper is well below the cut-off frequency, only planar waves propagate in the neck and cavity. The relation of point 1to point 5 could be obtained through the transfer matrix method as [24]:

$$\begin{bmatrix} P_1 \\ \rho_0 S_n V_1 \end{bmatrix} = \begin{pmatrix} \cos(k_0 L_I) & j(\frac{c_0}{S_n})\sin(k_0 L_I) \\ j(\frac{S_n}{c_0})\sin(k_0 L_I) & \cos(k_0 L_I) \end{pmatrix} \begin{pmatrix} \cos(k_0 L'_{III}) & j(\frac{c_0}{S'_n})\sin(k_0 L'_{III}) \\ j(\frac{S'_n}{c_0})\sin(k_0 L'_{III}) & \cos(k_0 L'_{III}) \end{pmatrix}$$
$$\begin{pmatrix} \cos(k_0 L_{III}) & j(\frac{c_0}{S_n})\sin(k_0 L_{III}) \\ j(\frac{S_n}{c_0})\sin(k_0 L_{III}) & \cos(k_0 L_{III}) \end{pmatrix} \begin{pmatrix} \cos(k_0 L_c) & j(\frac{c_0}{S_c})\sin(k_0 L_c) \\ j(\frac{S_c}{c_0})\sin(k_0 L_c) & \cos(k_0 L_c) \end{pmatrix} \begin{bmatrix} P_5 \\ \rho_0 S_c V_5 \end{bmatrix} \tag{2}$$

The relation of point 1 and point 2 could also be expressed as a simplified equation as:

$$\begin{bmatrix} P_1 \\ \rho_0 S_n V_1 \end{bmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{bmatrix} P_5 \\ \rho_0 S_c V_5 \end{bmatrix} \tag{3}$$

Assuming the walls of the cavity are rigid, the particle velocity at point 5 equals zero (V_5=0). The impedance of HR with a spiral neck could be derived as: $Z_r = P_1 / V_1 S_n = \rho_0 T_{11} / T_{21}$. Once the resonator impedance has been obtained, the transmission of a side-branch HR with a spiral neck can be described as:

$$TL = 20\log_{10}\left|\frac{Z_r}{\rho_0 c_0 / 2S_d + Z_r}\right| \tag{4}$$

2.2 Validation of the predicted transmission loss

The geometries of the HR with a spiral neck are: cavity length l_c=21cm, cavity radius r_c=6.6 cm, fixed neck radius r_n=1 cm, straight tube length L_I= L_{II}=4 cm, neck radius R_0=1.2 cm, and length of spiral tube L_{III}=7.54N cm (each turn is 7.54 cm length). The cross-section area of the main duct is S_d=36 cm^2. The N should be an integer, which indicates the turns of the spiral tube. N equals zero means that the spiral tube is non-existent and the neck only contains two straight tubes, which actually make it a traditional straight neck. Besides, the spiral tube could be considered as equivalent to a straight tube in a theoretical mode, as illustrated in Fig. 2. The predicted transmission loss of a HR with different turn number (N= 0,1,2,3,4) is exhibited in Fig. 3. Added spiral turns will decrease the resonance frequency and narrow the attenuation band, as well. Fig. 4 compares the prediction results with the FEM simulation results, and the prediction results are in good agreement with the FEM simulation results. The resonance frequency of the HR without a spiral neck (N= 0) is 59Hz. However, the resonance frequency decreases to 45Hz, 38Hz, 34Hz, and 30 Hz for N= 1,2,3,4, respectively. This also means that a spiral tube with 30.16cm (N= 4) change results in a 29Hz decrease in the resonance frequency without changing the cavity volume. The effects of a spiral tube on the resonance frequency are obvious, especially at a low frequency range. Moreover, more turns will result in a much lower resonance frequency. The solid lines represent the theoretical prediction and the dotted crosses represent the FEM simulation results in Fig. 4.

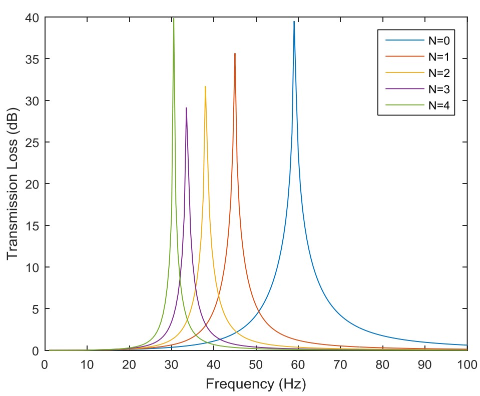

Figure 3 –Transmission loss of the HR with a spiral neck.

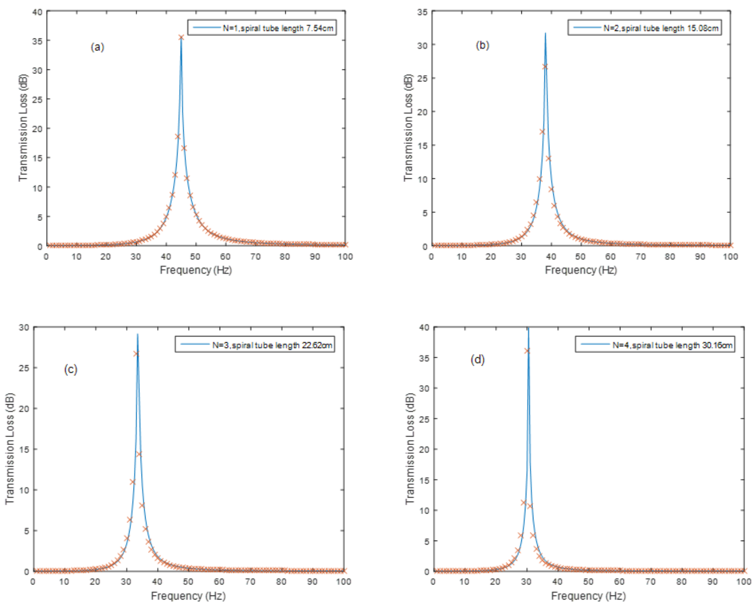

Figure 4 –Comparison of the analytical approach prediction and the FEM simulation for different spiral tube length.

3. Analytical approach of the HR with an extended neck

3.1 Analytical approach of the HR with an extended neck

A two-dimensional approach is introduced to determine the length correction length. Fig. 5 shows the geometries of the circular concentric HR with an extended neck. The two-dimensional sound wave propagation in both the extended neck and the cavity are governed by Helmholtz equation as:

$$\nabla^2 P(r,x) + k^2 P(r,x) = 0 \tag{5}$$

where P is the sound pressure and k is the wave number. The sound pressure and particle velocity could be solved by Eq. (5) as:

$$P_i(r,x_i) = \sum_{n=0}^{+\infty} (A_{i,n} e^{-jk_{i,n}x_i} + B_{i,n} e^{jk_{i,n}x_i}) \psi_{i,n}(r) \tag{6}$$

$$V_i(r,x_i) = \frac{1}{\rho_0 \omega} \sum_{n=0}^{+\infty} k_{i,n} (A_{i,n} e^{-jk_{i,n}x_i} - B_{i,n} e^{jk_{i,n}x_i}) \psi_{i,n}(r) \tag{7}$$

The walls of the neck and the cavity are set to be rigid. At $x_2=0$ or $x_3=l_r$, the rigid wall condition gives $v_2=0$, $v_3=0$. At $x_1=l_e+l_n$ or $x_3=0$, the pressure continuity condition at the neck-cavity interface gives $P_1=P_3$. Similarly, at $x_2=l_e$ or $x_3=0$, gives $P_2=P_3$. The volume velocity continuity condition at $x_1=l_e+l_n$ or $x_3=0$ gives $V_1S_n+ V_2(S_c-S_n)=V_3S_c$. Once the initial oscillation sound pressure and particle velocity have been obtained, then all unknown constants in equation of pressure and particle velocity could be derived by combining all the boundary conditions above.

The frequency range considered in this paper is well below the cut-off frequency of the resonator neck and the cavity. This means that the non-planar wave excited at the abrupt cross-section change (the neck-cavity interface) will decay exponentially. Therefore, it is assumed that only planar waves exist in the HR. The multidimensional effects associated with evanescent high modes at a sudden area change are considered the “length correction factor.” Based on the two-dimensional analytical results, an approximate formula for the length correction factor could be obtained as [18,25]:

$$\delta = 0.6165 r_n - 0.7046 r_n^2 / r_c + 0.2051 e^{-1.7226 l_e/r_c} r_n - 0.3749 e^{-1.3012 l_e/r_c} r_n^2 / r_c \tag{8}$$

The approximate length correction factor fit well with the condition of $r_n/r_c<0.5$. Combining only one-dimensional propagation in the axial x direction in the neck and cavity direction with regard to the effects of the non-planar wave as length correction factor, the transmission loss of such HR could be expressed as:

$$TL = 10\log_{10}\left[1 + \left(\frac{S_n}{2S_d}\frac{\tan k(l_n + l_e + \delta) + (S_c/S_n)\tan k(l_c - \delta)}{1 - (S_c/S_n)\tan k(l_c - \delta)\tan k(l_n + l_e + \delta)}\right)^2\right] \tag{9}$$

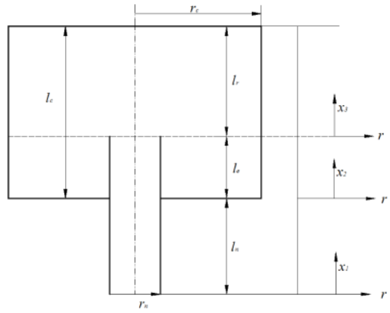

Figure 5 –Helmholtz resonator with extended neck.

3.2 Validation of predicted transmission loss

The geometries of the HR with an extended neck are: cavity length l_c=21cm, cavity radius r_c=6.6 cm, fixed neck radius r_n=1cm, and base neck length l_n=8cm. The cross-section area of the main duct is S_d=36cm^2. The effects of extension length on the transmission loss are studied here.

The transmission loss of a HR with different extension lengths that is analyzed by a modified 1D approach is shown in Fig. 6. It can be seen that with the increase in neck extension length, the resonance frequency decreases with a narrower attenuation band. Fig. 7 compares the predicted results to the FEM simulation results. It is shown that the modified 1D analytical approach predictions fit well with the FEM simulation results. Note that a 15.08cm change in extension length results in a 22 Hz shift in the resonance frequency, while the resonance frequency of a HR without an extended neck is only 59Hz, as shown in Fig. 6. The alteration in resonance frequency is apparent and significant at low frequency range. Furthermore, no change in cavity volume is required for the reduction in resonance frequency. The solid lines represent the theoretical prediction and the dotted crosses represent the FEM simulation results in Fig. 7.

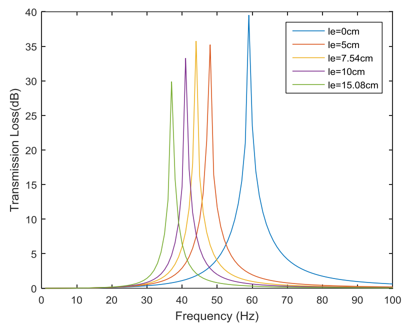

Figure 6 –Transmission loss of the HR with different extension neck lengths.

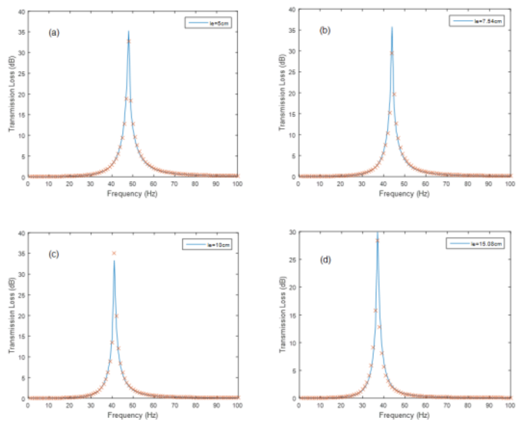

Figure 7 –Comparison of the analytical approach prediction and the FEM simulation for different spiral tube

length.

4. CONCLUSIONS

This paper focuses on improving the noise attenuation performance of the HR at low frequencies within a constrained space. This paper presents theoretical and numerical studies of a HR with an extended neck and a HR with a spiral neck. The modified 1D analytical approach with length correction factor is used in this paper to make an accurate acoustic performance prediction of a HR with an extended neck. The length correction factor is introduced to account for the non-planar wave effects. For the HR with a spiral neck, the curvature of the spiral neck changes the impedance, and the spiral neck can then be considered equivalent to a straight neck with a corrected neck length and cross-section area. The spiral neck is then translated to a traditional straight neck, and the acoustic performance prediction is derived using a 1D analytical approach. The predicted theoretical results fit well with the FEM simulation results. Additionally, the prediction results for the HR with an extended neck also agree nicely with the existing experimental results documented in the literature. With the increasing of the extension length or the spiral neck length, resonance frequency decreases significantly. An identical change in the extension neck length or the spiral neck length will produce the same decrease in resonance frequency. It is clear that a 22Hz decrease in resonance frequency is obtained without changing the cavity volume, a significant difference from the resonance frequency of 59Hz that exists for HRs without these two types of necks. The extension neck length is flexible but limited to the cavity length. Although there is no limit to the spiral neck length, more spiral turns could be added to lengthen the neck. However, the spiral tube length of each turn is fixed. For a certain designed resonance frequency of HR, the utilization of the extended neck or the spiral neck can reduce the cavity volume. The acoustic characteristics of HRs with these two different neck types have a potential application in noise control at low frequencies within a constrained space.

ACKNOWLEDGEMENTS

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 152116/14E).

REFERENCES

1. Ai ZT, Mak CM, Cui DJ, Xue P. Ventilation of air-conditioned residential buildings: A case study in Hong Kong. Energ Buildings. 2016;127:116-127.

2. Mak CM, Wang Z. Recent advances in building acoustics: An overview of prediction methods and their applications. Build Environ 2015;91:118-126.

3. Mak CM, Wu J, Ye C, Yang J. Flow noise from spoilers in ducts. J Acoust Soc Am 2009;125(6):3756-3765.

4. Mak CM. A prediction method for aerodynamic sound produced by multiple elements in air duct. J Sound Vib 2005;287(1-2):395-403.

5. Mak CM, Yang J. A predition method for aerodynamic sound produced by closely spaced elements in air ducts. J Sound Vib 2000;229(3):743-753.

6. Mak CM, Au WM. A turbylence-based prediction technique for flow-generated noise produced by in-duct elements in a ventilation system. Appl Acoust 2009;70:11-20.

7. Ou DY. Low frequency sound insulation analysis and evaluation of stiffened building structures. Build Environ 2015; 94(2):802-809.

8. Ou DY, Mak CM. A review of prediction methods for the transient vibraion and sund radiation of plates. J Low Freq Noise V A 2013;32(4):309-332.

9. Wang X, Mak CM. Acoustic performance of a duct loaded with identical resonators. J Acoust Soc Am

2012;131(4): EL316-EL322.

10. Cai C, Mak CM. Noise control zone for a periodic ducted Helmholtz resonator system. J Acoust Soc Am 2016;140(6): EL471-EL477.

11. Cai C, Mak CM, Wang X. Noise attenuation performance improvement by adding Helmholtz resonators on the periodic ducted Helmholtz resonator system. Appl Acoust 2017;122:8-15.

12. Wu D, Zhang N, Mak CM, Cai C. Noise attenautiona performance of a Helmholtz resonator array consist of several periodic parts. Sensors 2017;17(5):1029.

13. Wang XN, Choy YS, Cheng L. Hybrid noise control in a duct using a light micro-perforated plate. J Acoust Soc Am 2012;132(6): 3378-3387.

14. Wang CQ, Cheng L, Huang LX. Realization of a braodband low-freqeuncy plate silencer using sandwidch plates. J Sound Vib 2008;318:792-808.

15. Sen Mk, Morgan D. Active noise control systems: algorithms and DSP implementations. New York, USA: John Wiley & Sons;1995.

16. Chu YJ. A new regularized subband ANC algorithm with online secondary-path modelling: Perforamnce analysis and application to buildings. Build Environ 2015;94(2):873-882.

17. Chu YJ, Chan SC. A new local polynomial Modelling-based Variable Forgetting Factor RLS Algorithm and its acoustic application. IEEE/ACM Transaction on speech and language processing 2015;23(11): 2059-2069.

18. Cai C, Mak CM, Shi X. An extended neck versus a spiral neck of the Helmholz resonator. Appl Acoust 2017;115:74-80.

19. Shi XF, Mak CM. Helmholtz resonator with a spiral neck. Appl Acoust 2015;99:68-71.

20. Selamet A, Lee IJ. Helmholtz resonator with extended neck. J Acoust Soc Am 2003;113(4):1975-1985.

21. Chanaud RC. Effects of geometry on the resonance frequrncy of Helmholtz resonator. J Sound Vib 1994;178(3):337-348.

22. Tang PK, Sirignano WA. Theory of a generalized Helmholtz resonator. J Sound Vib 1973;26(2):247-262.

23. Nederveen CJ. Influence of a toroidal bend on the wind structure tuning. J Acoust Soc Am 1998;104;1616-26

24. Ji ZL, Sha JZ. Four-pole parameters of a duct with Low Mach number flow. J Acoust Soc Am 1995;98(5):2848-2850.

25. Kang ZX, Ji ZL. Acoustic length correction of duct extension into a cylindrical chamber. J Sound Vib 2008;310(4-5):782-791.