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Technical note

An extended neck versus a spiral neck of the Helmholtz resonator

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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. 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 length correction factor is introduced through a modified one-dimensional approach to account for the non-planar effects that result from the neck being extended into the cavity. The spiral neck is transformed to an equivalent straight neck, and the acoustic performance is then derived by a one-dimensional approach. The theoretical prediction results fit well with the Finite Element Method (FEM) simulation results. Without changing the cavity volume of the HR, the resonance frequency shows a significant drop when the extended neck length or the spiral neck length is increased. 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.

1. Introduction

A ventilation ductwork system is an essential system in buildings that provides conditioned or fresh air to indoor environments so as to ensure good indoor air quality. However, it is common to encounter a duct-borne noise problem in these ventilation systems [1,2]. The unpleasant noise in the ventilation ductwork system can be a disturbance to human activities. It is therefore important to reduce duct-borne noise, especially the low-frequency and broadband noise in the ventilation ductwork system [3]. A dissipative silencer is usually adopted to control noise at mid to high frequencies. However, it is not effective for low-frequency noise control [4]. In recent years, active noise control has become a rapidly developing area of duct-borne noise control. An active noise control system can provide environmental-adaptive noise attenuation, especially at low frequencies. Nevertheless, there are still some problems related to its reliability and high cost [5,6]. For these reasons, the Helmholtz resonator (hereafter, HR) is still widely used as an effective silencer for low-frequency duct-borne noise control due to its characteristics of being tunable, durable, and affordable [7,8]. Therefore, a good design for a Helmholtz resonator is important for noise attenuation in ventilation ductwork systems.

Many researchers and engineers around the world have devoted their attention to improving the attenuation performance of the HR. A lot of achievements have been made and are documented in numerous pieces of literature. Chanaud [9] examined the effects of different orifice shapes and cavity geometries on the resonance frequency of the HR. Tang and Sirignano [10] investigated various neck lengths of the HR, and their results showed that the resonance frequency of the HR was reduced by increasing its neck length. To improve the sound absorption capacity of the HR in a limited space, Selamet and Lee [11] proposed a HR with an extended neck and examined the effects of length, shape, and perforation of neck extension on acoustic performance. Selamet et al. [12] then presented another approach by lining the HR with fibrous material to improve attenuation performance without changing the geometries of the HR. Pillai and Ezhilarasi [13] investigated the acoustic performance of HRs with tapered necks both experimentally and theoretically. Shi and Mak [14] proposed a HR with a spiral neck to improve attenuation performance by using a curvature effect on the spiral neck.

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 extended neck will lower the resonance frequency without an extra cavity volume requirement, and the spiral neck can make the neck as long as possible under a space constraint to reduce the resonance frequency. The acoustic performance of HRs with these two types of

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necks is analyzed both theoretically and numerically. A modified one-dimensional (1D) analytical approach with a length correction factor is used in this paper to accurately predict the acoustic performance of an HR with an extended neck. The length correction factor is introduced due to the apparent multidimensional sound field inside the cavity of an HR with an extended neck [15]. The length correction factor is obtained using a two-dimensional (2D) analytical approach. The wave propagation of an HR with a spiral neck is also analyzed. 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 is predicted using a 1D analytical approach.

2. Analytical approach of the HR with an extended neck

The sound fields inside an HR with an extended neck are clearly multidimensional. A modified 1D analytical model, which includes a length correction to account for the non-planar effects at the neck-cavity interface, is proposed here to improve the accuracy of the acoustic performance prediction. The length correction is derived using a 2D analytical approach.

A 2D analytical approach is introduced to determine the length correction length. Fig. 1 shows the geometries of the circular concentric HR with an extended neck. The 2D sound wave propagations in both the extended neck and the cavity are governed by the Helmholtz equation in cylindrical coordinates as:

$$\nabla^2 P(r,x) + k^2 P(r,x) = 0 \tag{1}$$

where p is the sound pressure and k is the wave number. The sound pressure and particle velocity can be solved by Eq. (1) as [16]:

$$P_i(r,x_i) = \sum_{n=0}^{+\infty} (A_{i,n} e^{-jk_{i,n}x_i} + B_{i,n} e^{jk_{i,n}x_i}) \psi_{i,n}(r) \tag{2}$$

$$V_i(r,x_i) = \frac{1}{\rho_0 \omega} \sum_{n=0}^{+\infty} k_{i,n} (A_{i,n} e^{-jk_{i,n}x_i} - B_{i,n} e^{jk_{i,n}x_i}) \psi_{i,n}(r) \tag{3}$$

$$k_{i,n} = \begin{cases} \sqrt{k_0^2 - (\alpha_{1,n}/a_i)^2}, & k_0 > \alpha_{1,n}/a_i \\ -\sqrt{k_0^2 - (\alpha_{1,n}/a_i)^2}, & k_0 < \alpha_{1,n}/a_i \end{cases} \tag{4}$$

where $i = 1, 2, 3$ represents different coordinate axis x domains, $A_{i,n}$ and $B_{i,n}$ represent the modal amplitudes corresponding to components traveling in positive and negative directions in different domains, respectively, ρ_0 represents the air density, $k_{i,n}$ represents the wave number, k_0 represents the wave number of the zero mode, and $\psi_{i,n}(r)$ represents the eigenfunction. The eigenfunction $\psi_{i,n}(r)$ is given as:

$$\psi_{i,n}(r) = \begin{cases} J_0\left(\alpha_{i,n} \frac{r}{a_i}\right), & i = 1,3 \\ J_0(\alpha_{2,n} \frac{r}{a_2}) - \frac{J_1(\alpha_{2,n})}{Y_1(\alpha_{2,n})} Y_0(\alpha_{2,n} \frac{r}{a_2}), & i = 2 \end{cases} \tag{5}$$

where J_m is the Bessel function of the first kind and order m, Y_m is the Bessel function of the second kind and order m, and $\alpha_{i,n}$ is the root matching the rigid wall condition of $\psi_{i,n}(r) = 0$.

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 neck-cavity interface gives $P_1 = P_3$. Similarly, at $x_2 = l_e$ or $x_3 = 0$, it gives $P_2 = P_3$. The volume velocity continuity condition at $x_1 = l_e + l_n$ or $x_3 = 0$ gives $V_1 S_n + V_2(S_c - S_n) = V_3 S_c$. Set the relation of initial oscillation sound pressure P_0 and particle velocity V_p at $x_1 = 0$ as

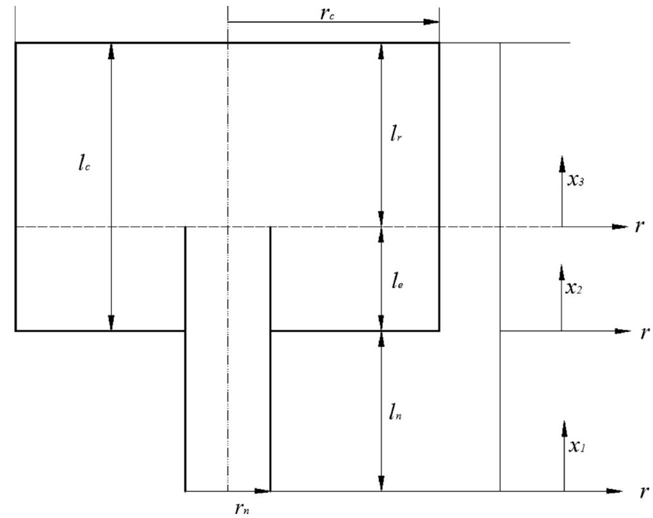

Fig. 1. Helmholtz resonator with extended neck.

$P_0 = \rho_0 c_0 V_p = 1$. c_0 represents the sound speed. Then all unknown $A_{i,n}$ $B_{i,n}$ can be obtained 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." As a consequence, Eqs. (2) and (3) can be simplified as:

$$P_i(r,x_i) = A_{i,0} e^{-jk_0 x_i} + B_{i,0} e^{jk_0 x_i} \tag{6}$$

$$V_i(r,x_i) = \frac{1}{\rho_0 c_0} (A_{i,0} e^{-jk_0 x_i} + B_{i,0} e^{jk_0 x_i}) \tag{7}$$

Then, at the neck-cavity interface ($x_1 = l_e + l_n$ or $x_3 = 0$), the discontinuity effects will be equivalent to the equation [17]:

$$P_1 = P_3 + \delta Z S_n V_1 \tag{8}$$

where S_n is neck area, Z is the characteristic impedance of the plane mode given as $Z = j\rho_0 c_0 / S_n$, and δ represents the length correction factor. Combining Eqs. (6) and (7) with Eq. (8) gives:

$$\delta = \left| \frac{P_1 - P_3}{j\rho_0 c_0 V_1} \right| = \left| \frac{(A_{1,0} + B_{1,0}) - (A_{3,0} + B_{3,0})}{jk(A_{1,0} - B_{1,0})} \right| \tag{9}$$

Based on the 2D analytical results, an approximate formula for the length correction factor could be given as:

$$\delta = 0.6165 r_n - 0.7046 r_n^2 / r_c + 0.2051 e^{-1.7226 l_e / r_c} r_n - 0.3749 e^{-1.3012 l_e / r_c} r_n^2 / r_c \tag{10}$$

The approximate δ formula agrees well with the simulation and experimental results for $r_n/r_v < 0.5$ [11,18]. Combining only 1D propagation in the axial x direction in the neck and cavity with regard to the effects of the non-planar wave as length correction factor δ, the transmission loss of a side branch HR with an extended neck can be expressed as:

$$TL = 10\log_{10}\left[1 + \left(\frac{S_n}{2S_d} \frac{\tan k(l_n + l_e + \delta) + (S_c/S_n)\tan k(l_c - \delta)}{1 - (S_c/S_n)\tan k(l_c - \delta)\tan k(l_n + l_e + \delta)}\right)^2\right] \tag{11}$$