Acoustical Characteristics of One Novel Reactive Muffler with the Vortex-Shaped Expansion Chamber

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Abstract. In order to enhance the acoustical performance and reduce the installation volume of muffler, one novel perforated reactive muffler is proposed, in which vortex-shaped expansion chamber is applied. The finite element method was used to predict the transmission loss of the muffler and identify its acoustical characteristics. The results shows that replacing the smooth expansion chamber with the vortex-shaped one could improve the acoustical performance of muffler at 1800~2400Hz. It’s further found the depth and intersection angle of vortex structure are the main factors influencing acoustical performance.

Introduction
Transmission loss (TL) is an important evaluation index for muffler design. Currently, there are three main methods to calculate TL: transfer matrix method (TMM), finite element method (FEM) and boundary element method (BEM). Among them, the FEM is suitable for analyzing complex geometric and takes up less computational memory. So it is widely used to predict TL of muffler with the complex structure.

Qian investigated the noise reduction performances of thick perforated plates used in valve, FEM was adopted to predict TL of thick perforated plates in different geometric parameters[1]. Verma used FEM to study the noise attenuation characteristics and developed a design guideline for the three chamber U-bend hybrid muffler in order to prove its performance[2]. Chiu adopted FEM in combined with the polynomial neural network model, simplified the optimization process of a rectangular plenum internally equipped with two crossed Baffles[3]. The above cases proved that FEM is an effective tool to investigate the noise reduction structure which has not been thoroughly studied.

The vortex-shaped tube is one novel tube home-made by our laboratory, some cavity and protrusion are formed on the wall surface of the tube[4]. The abrupt change of cross-section inside the vortex-shaped tube could reflect a portion of the incident sound waves back toward the source, which is in line with the working principle of reactive muffler. So the vortex-shaped tube could be utilized as a part of reactive muffler. In the paper, one perforated reactive muffler with vortex-shaped expansion muffler was proposed at the first time, The acoustical performance of the proposed muffler was studied by using FEM.

Model and Method
Geometric Model
The configuration of the muffler with the smooth expansion muffler M1 and with vortex-shaped expansion chamber M2 are depicted in Fig.1. The length of expansion chamber is 288mm and the diameter is 180mm. The perforated duct is characterized by porosity $\phi=10\%$, diameter $d$ is 60mm, thickness $t_p$ is 1mm and the diameter of the small hole $d_h$ is 3mm. The depth of the vortex structure $h$ is 18mm, and the width $w$ is 89mm, respectively. The area ratio $m (D^2/d^2)$ of the muffler is 9. The sections diagram of M2 is showed in Fig.2, in which, the intersection angles of adjacent vortexes $\theta=60^\circ$. 
Governing Equations and Boundary Conditions

In the present work, air is chosen as the medium which is assumed to be the perfect gas. The density of air is set to be 1.225 $kg/m^3$, and the sonic velocity is 340 $m/s$. The corresponding wave propagation is expressed as:

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla \cdot (\nabla p) = 0$$

(1)

where $P$ is the sound pressure, Pa, and $c$ is the sonic velocity, m/s.

Based on the assumption, the incident sound wave is a plane wave, a unit velocity is applied at the entrance. The inner wall surfaces are assumed to be rigid, that is, the normal velocity of the surfaces is 0. The full sound absorption condition is applied at the exit.

There are several empirical formulas to calculate the acoustic impedance of the perforated plate. The simpler one, proposed by Sullivan and Crocker[5], is given by:

$$Z_p = \rho c \left[ 0.006 + \left( \delta p - 0.75 \delta h \right) \phi \right]$$

(2)

where $k$ is wave number, $m^{-1}$. Based on Eq.2, the thickness correction coefficients $a$ of the perforated plate is calculated[6]. The corresponding revised formula is given as following.
The model is meshed with tetrahedral grids, and the maximum element size is set equal to the minimal wavelength divided by 6. A grid-independent test has been done for the different grid numbers ranging from 1.35~1.73*10^4, the grid system around 1.43*10^4 was chosen for all calculation.

Transmission Loss

Generally, TL is used to characterize the acoustical performance of a muffler, as it is representative of the muffler itself and unaffected by the termination impedance and sound source. TL is defined as the ratio between the incident and transmitted acoustic energy. When the diameters of inlet and outlet pipe are the same, TL can be evaluated by:

\[ TL = 20 \log_{10} \frac{p_i}{p_t} \]  

where \( p_i \) and \( p_t \) are the incident and transmitted pressures, respectively.

Results and Discussion

Validation of the Numerical Method

To validate the FEM adopted in present work, the calculated TL of one perforated reactive muffler is compared with the corresponding experiment data[7] on the same geometric and boundary conditions in Fig.3, which indicates both results agree very well.

Acoustical Performance of Muffler M1 and M2

Fig. 4 gives the acoustical performance of the muffler M1 and M2 in the frequency range of 0~2500Hz. The TL of the muffler is periodically distributed. The former three periods of M1 and M2 are nearly the same, since the period is only determined by the length of expansion chamber \( L \). In the fourth period, the TL peak of M1 and M2 drop down around 1950Hz and 2100Hz, respectively. It is because the sound wave which is higher than a certain frequency passes through the center of the expansion chamber in a narrow beam. The certain frequency is named as the upper cut-off frequency, denoted by \( f_u \). The empirical formula to calculate \( f_u \) is given by:

\[ f_u = 1.22 \frac{c}{D_e} \]  

\( Z_p = \rho C \left[ 0.006 + i_0 k (t_p + 0.75 \alpha d_h) \right] / \phi \]  

\( \alpha = 0.8216 - 1.2626 \sqrt{\phi} + 0.4007 \phi - 0.0610 \phi^3 \)
here $D_c$ is the equivalent diameter of the expansion chamber. Because the cross-sectional area of vortex-shaped expansion chamber is smaller than smooth expansion chamber, the equivalent diameter of muffler M2 is smaller. Consequently, the upper cut-off frequency of M2 is higher.

The value of TL is determined by the area ratio $m$. With the increase in $m$, the value of TL increases. As the vortex-shaped structure results in the smaller cross-sectional area of expansion chamber, TL of muffler M2 in the first and third periods is lower than M1. However, in the range of 1850~2100Hz, the acoustic attenuation performance of Muffler M2 is obviously more excellent than M1 because M2 is capable of muffling sound waves in a wider frequency band.

![Figure 4. TL of the muffler M1 and M2.](image)

**Effect of Geometric Parameters on TL**

The above results have been proven that the vortex structure can enhance the acoustic attenuation by changing the cross-section area of the reactive muffler. So it’s essential to further investigate the effect of the geometric parameters of the vortex structure on the acoustic attenuation. The chosen parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>$d$ [mm]</th>
<th>$L$ [mm]</th>
<th>$h$ [mm]</th>
<th>$w$ [mm]</th>
<th>$\theta$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>288</td>
<td>9 13.5 18 22.5 27</td>
<td>68 76 83 89 96</td>
<td>36 45 60 90</td>
</tr>
</tbody>
</table>

Fig. 5 depicts the variation of TL for the different intersection angles. In the later three periods, the value of TL decline with increasing $\theta$, but it’s just opposite to the first period. The reduction of cross-sectional area may result in the decrease of TL at the lower frequency. At $\theta=90^\circ$, The fourth period includes a arch domain and a peak, at the same time, the value of TL decrease abruptly at the demarcation point. It’s because the sound wave pass through the periphery of the vortex structure in four narrow beams. As a result, changing $\theta$ could have an influence on the value of TL and the wave propagation in specific frequency bands.

The effect of depth on acoustic attenuation performance is similar to the intersection angle. The difference is that the value of upper cut-off frequency is strongly influenced by the depth. When $h$ changes from 22.5mm to 27mm, the values of upper cut-off frequency and TL increase obviously. In the calculated range of $h$, a deeper cavity leads to a better sound attenuation performance.

Fig.7 shows that width of the vortex structure has little effect on TL. The reason is that the different width only changes the cross-sectional area in the axial direction, the cross-sectional area in the radial direction remains nearly constant. Additionally, in the real fabricating process of vortex structure, a large vortex may cause the unpredictable deformation on the tube surface. Therefore, the width of the vortex structure should not be too large.
Summary
The FEM is adopted to predict the acoustical performance of the perforated reactive muffler with a vortex-shaped expansion chamber. Compared to the smooth expansion chamber, the vortex structure on the expansion chamber can enhance the values of TL and the upper cut-off frequency effectively in the higher frequency bands. Therefore, changing the geometrical structure of the vortex is able to improve further the acoustical performance. A smaller intersection angle or a
Deeper vortex leads to a more excellent acoustic performance. However, the vortex width has almost no influence on TL.

References


