MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

The effect of convection of fluid on the acoustic performance of perforated mufflers

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ABSTRACT

Many practical mufflers with complex geometry have large variations in the flow filed. In addition, the flow-reversing pipes and perforated elements in the muffler further complicate the flow patterns. Therefore, the effect of convection of fluid needs be considered in acoustic computations of mufflers. The present study employs the computational fluid dynamics (CFD) software FLUENT to capture the inner flow field, and then the fluid velocity data are imported to the acoustic finite element (FE) model to determine the acoustic attenuation performance of mufflers. The numerical results are compared with previously published experimental measurements demonstrating the applicability of present method. Furthermore, the effect of convection of flow on acoustic attenuation performance of the mufflers is analyzed in detail. It is concluded that the convection of fluid may affect remarkably the transmission loss of perforated mufflers.

Keywords: Perforated muffler, convective effect FEM
I-INCE Classification of Subject Number: 34.1

1. INTRODUCTION

Perforated mufflers are widely used in the intake and exhaust silencing systems and acoustic attenuation performance is mufflers' main evaluation index [1]. As a part of the intake and exhaust silencing systems, the acoustic attenuation performance of perforated mufflers is inevitably influenced by fluid flow [2-3]. In the tubes of the muffler, the flow of the fluid increases the speed of downstream acoustic wave while decreasing the speed of upstream acoustic wave [4]. The interaction between acoustic perturbation and fluid flow near the orifice generates the shedding vortex, which has an effect on the acoustic impedance of the orifice [5-6]. The above two aspects are the main reasons for the effect of fluid flow on the acoustic attenuation performance of the perforated muffler.

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In order to consider the effect of convection of fluid, there are mainly three methods to be used to predict the acoustic performance of mufflers. The first method is computational fluid dynamic (CFD) approach [2-3] which solves the mass, momentum and energy equations to simulate the transmission process of acoustic wave and it could consider the viscosity of the fluid and the effect of complex turbulence. However, CFD approach has large computational amount and it costs long time. The second method is to employ linear Navier-strokes equations in frequency domain [7] to compute the transmission loss of the muffler. In the methodology, the Navier-Stokes equations are linearized about an arbitrary mean flow. Thus, the methodology is general and any realistic time-independent mean flow filed can, in principle, be handled. Comparing to the CFD approach, the computational amount of this method is indeed reduced a lot, but it needs to occupy more computer memory. Therefore, above two methods are not suitable for engineering calculation. Another alternative method is hybrid method in which the velocity distribution of inner muffler is captured by the CFD software and then the fluid velocity data is imported into the acoustic finite element model to consider the effect of the fluid flow on the propagation of the acoustic wave. In order to consider the effect of fluid flow on acoustic impedance of perforated plate, acoustic impedance empirical model is used to define the transfer admittance on both sides of the perforated plate. This hybrid method requires less grids and less computational amount. It costs short time and could be completely applied to engineering calculations.

This paper is organized as follows. Firstly, the calculation method of the internal flow field of perforated muffler and the definition of relevant boundary conditions are introduced. Then the governing equation of acoustic finite element is briefly described and the acoustic impedance empirical model in the presence of bias or grazing flow is presented. Finally, the transmission loss of cross flow perforated-tube muffler and straight perforated-tube muffler is predicted by the hybrid method and the effect of convectional of fluid on acoustic attenuation performance is analyzed in detail.

2. THEORY

In this work, steady-state flow in the mufflers was considered, neglecting the inner periodic pulses. The inner flow filed of muffler was computed by CFD software and the velocity data of muffler was imported into the acoustic finite element model. Then the acoustic response was calculated to obtain the transmission loss of the perforated muffler with the flow.

2.1 Summary of the Calculation of CFD

The steady-state flow in muffler can be predicted by CFD analysis. In this analysis, the CFD software, FLUENT [8] was used. The pressure-based implicit solver is used to solve the discretization equations. Second order upwind discretization scheme is applied for the pressure, density, momentum, turbulent kinetic energy, specific dissipation rate, and energy. SIMPLE (Semi-Implicit Method for Pressure-Linked Equations-Consistent) pressure-velocity coupling algorithm is used in steady flow simulation. Realizable k-ε turbulent model is employed to predict the flow filed of the muffler. The medium is air as an ideal gas and its physical parameters are dependent on the temperature.

To evaluate the velocity distribution of muffler, it is important to use an appropriate boundary condition. The mass-flow-inlet boundary condition is applied at the entrance of the muffler. The pressure-outlet boundary condition, which is specified as one standard atmospheric pressure, is implemented at the outlet of muffler. The remaining walls are set to static, adiabatic and no-slip boundary conditions. When the steady solver running is complete, the inner velocity data of muffler could be obtained.

The information of the grid is descripted briefly here. Discrete grids of perforated orifice need to be established in CFD model. The maximum mesh size of 6 mm is used for the muffler and the maximum mesh size of 0.5 mm is used for the orifice. The number of grids in CFD model is much larger than that of acoustic FE model. Grids in the perforated orifice do not need to be established in FE model, which greatly reduces the number of grids.

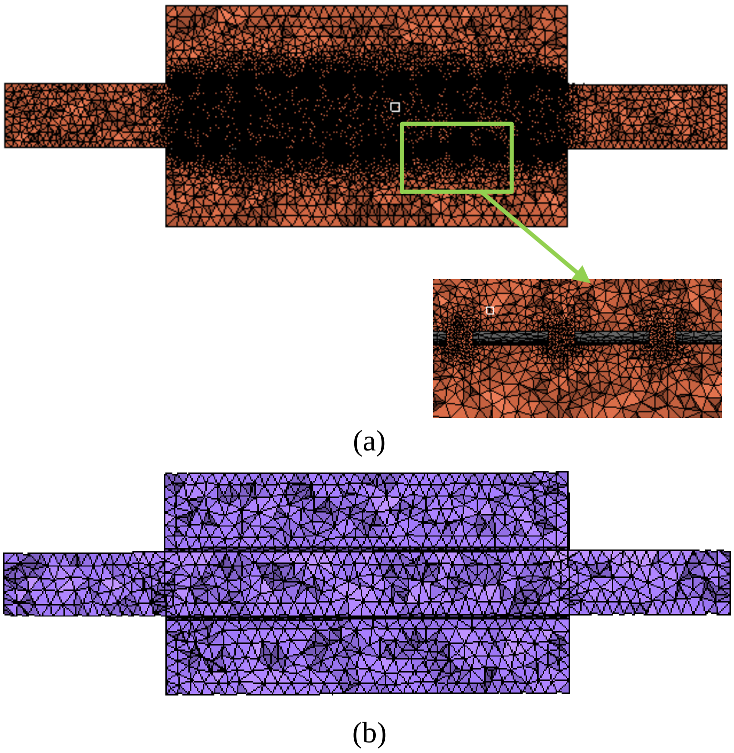


Figure 1 Grids (a) CFD model (b) FEM model

2.2 Acoustic FE Formulation

The linear wave equation in a mean flow medium can be derived as [9]

$$\nabla^2 P-\frac{1}{c_0^2}\frac{\partial^2 P}{\partial t^2}-\frac{2}{c_0^2}\rho_0\frac{\partial}{\partial t}\left(V_0\cdot\nabla P\right)-\frac{1}{c_0^2}\left(V_0\cdot\nabla\right)\left(V_0\cdot\nabla P\right)=0 \qquad (1)$$

where P, V_0, and c_0 are the pressure, flow velocity and speed of velocity, respectively. This equation can be written in term of the Mach number $M=V_0/c_0$ as

$$\nabla^2 P-\frac{1}{c_0^2}\frac{\partial^2 P}{\partial t^2}-\frac{2}{c_0}\rho_0\frac{\partial}{\partial t}\left(M\cdot\nabla P\right)-\left(M\cdot\nabla\right)\left(M\cdot\nabla P\right)=0 \qquad (2)$$

Assuming that in the steady state harmonic pressure can be written as $P = p\mathrm{e}^{\mathrm{j}\omega t}$, the last equation can be expressed as

$$\nabla^2 p+k^2 p-2jkM\cdot\nabla p-\left(M\cdot\nabla\right)\left(M\cdot\nabla p\right)=0 \qquad (3)$$

Equation (3) is the convectional acoustic wave equation.

In order to predict the transmission loss of the muffler, one boundary condition should be specified at each position on the muffler. An incident wave (normally a plane wave) is defined at the inlet of the muffler and the sound power of incident wave is constant. An anechoic termination is applied on the outlet of the muffler. It is worth to note that the anechoic termination is defined by the “Automatically Matched Layer (AML)” [10] instead of the simple characteristic impedance boundary condition. The AML is a special implementation of the “Perfectly Matched Layer” boundary condition for non-reflective boundaries.

2.3 Model of Acoustic Impedance

In the presence of bias flow, the non-dimensional acoustic impedance of orifice is expressed as [6]

$$Re = \rho U_o d_h / \mu \tag{4}$$

$$S_t = \omega t / U_o \tag{5}$$

$$\begin{cases} r_o = a * S_t^{\,4} + b * S_t^{\,3} + c \\ a = \dfrac{116.6 \times Re^{-0.7617}}{(\varphi + 0.1946) \times (t / d_h + 0.1658)} \\ b = \dfrac{4.776 \times 10^{-5} \times (Re - 1.544 \times 10^4)}{(\varphi + 0.2263) \times (t / d_h + 0.2559)} \\ c = -3.096 \times \varphi + 2.406 \end{cases} \tag{6}$$

$$\begin{cases} x_o = d \times S_t + e \\ \begin{cases} \begin{cases} d = 7.672 \times 10^{-3} / (t / d_h)^{2.817} + 0.6704 \\ e = 0 \end{cases} & S_t \le S_t^{'} \\ \begin{cases} d = -2.869 / \varphi^{0.244} \times \left(1 / (t / d_h) - 7.402\right) \times \left(Re^{0.1} - 2.08\right) \\ e = \left(7.672 \times 10^{-3} / (t / d_h)^{2.817} + 0.6704\right) \times S_t^{'} - d \times S_t^{'} \end{cases} & S_t > S_t^{'} \end{cases} \\ S_t^{'} = 4.940 \times (t / d_h + 8.997 \times 10^{-2}) \times (Re^{0.1} - 1.854) \end{cases} \tag{7}$$

where U_o is the mean bias flow velocity through the orifice, *Re* is Reynolds number of flow through the orifice, S_t is the Strouhal number based on the thickness of orifice, d_h is the orifice diameter, and t is the thickness of orifice. The acoustic impedance of the perforated plates in the presence of bias flow is expressed as

$$\begin{cases} r_p = r_o \cdot M_o / \varphi \\ x_p = x_o \cdot M_o / \varphi \end{cases} \tag{8}$$

In the presence of grazing flow, the non-dimensional acoustic impedance of orifice is expressed as

$$Re = \rho U_{mean} d_h / \mu \tag{9}$$

$$U_c / U_{mean} = 0.048 Re^{0.2} \tag{10}$$

$$r_{hF} = \begin{cases} -0.9446 Sr + 1.668 & Sr \le 1.77 \\ 0 & 1.77 < Sr \le 3.61 \\ 1.511 Sr - 5.461 & 3.61 < Sr \le 4.09 \\ -0.6096 Sr + 3.204 & 4.09 < Sr \le 5.26 \\ 0 & Sr > 5.26 \end{cases} \tag{11}$$

$$x_{hF} = \begin{cases} 0.2964 Sr^2 - 1.243 Sr & Sr \le 1.86 \\ 0.3998 Sr^2 - 0.8031 Sr - 1.127 & 1.86 < Sr \le 3.58 \\ -1.562 Sr + 6.597 & 3.58 < Sr \le 4.23 \\ 0 & Sr > 4.23 \end{cases} \tag{12}$$

where U_c is the convectional velocity of the vorticity in the aperture, *Re* is Reynolds number of flow grazing over the orifice. The acoustic impedance of the orifice in the absence of flow is expressed as

$$\begin{cases} r_{hG} = \dfrac{\sqrt{8\rho\mu\omega}(1+t/d_h)}{\rho c} \\ x_{hG} = k\left(t+\alpha d_h\right) \\ \alpha = 0.85(1-1.4092\phi^{0.5}+0.33818\phi^{1.5}+0.06793\phi^{2.5} \\ \qquad -0.02287\phi^{3}+0.03015\phi^{3.5}-0.01541\phi^{4}) \end{cases} \tag{13}$$

The acoustic impedance of the perforated plates in the presence of the grazing flow is expressed as

$$\begin{cases} r_p = (r_{hG} + r_{hF}\cdot M_c)/\varphi \\ x_p = (x_{hG} + x_{hF}\cdot M_c)/\varphi \end{cases} \tag{14}$$

3. RESULTS AND DISCUSSION

3.1 Validation

The geometry of cross-flow perforated tube muffler is shown in Fig. 2. Dimensions of cross-flow perforated tube muffler in reference [11] are as follows: D = 101.6 mm, L_1 = L_2 = 128.6 mm, d = 49.3 mm, thickness of perforated tube is t = 0.81 mm, orifice diameter is d_h = 2.49 mm, porosity of perforation φ = 3.9%, and thickness of flow plug is 0.81 mm. Air temperature T is 347K.

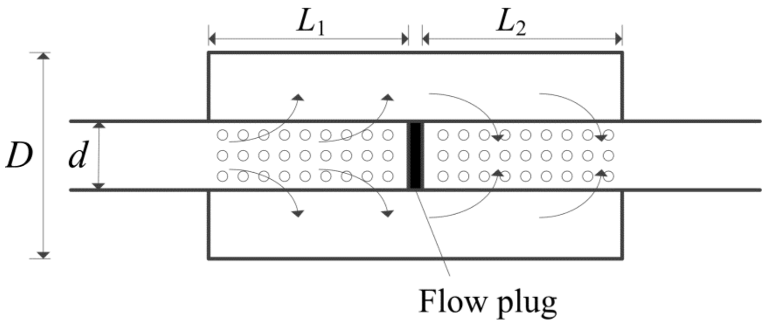
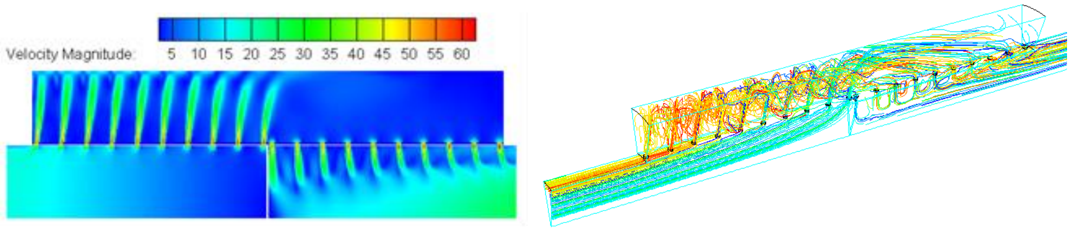


Fig. 2 The geometry of cross-flow perforated tube muffler



(a) (b)

Fig. 3 CFD results of cross flow perforated-tube muffler. (a) velocity (b) velocity streamlines

Fig. 3 shows the velocity and velocity streamline of the cross flow perforated tube. It could be seen that the bias flow velocity is great larger than the grazing flow. Therefore, the effect of grazing flow on the acoustic impedance was neglected. Acoustic impedance of the perforated tube could be obtained from Equations (4)-(8). Fig. 4 shows the transmission loss of cross flow perforated tube muffler with inlet velocity of 17 ms^{-1}. The transmission loss predicted by the hybrid method matches closely with the measurement data in most frequencies. The deviation between the prediction and measurement may be resulted from the non-uniform flow distribution through orifices and the assumption of pure bias flow (neglecting of the effect of grazing flow on acoustic impedance). The acoustic impedance of perforated plate in the presence of the combined grazing-bias flow is worthy to be explored in the future.

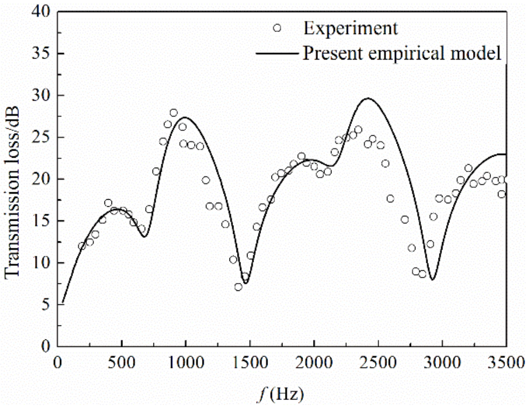


Fig. 4 Transmission loss of cross flow perforated-tube muffler

The geometry of straight perforated-tube muffler is shown in Fig. 5. Dimensions of straight perforated-tube muffler in reference [12] are as follows: D =110 mm, l =200 mm, d =32 mm, thickness of perforated tube is t =2 mm, orifice diameter is d_h =4 mm, porosity of perforation φ =4.7%. Air temperature T is 293K.

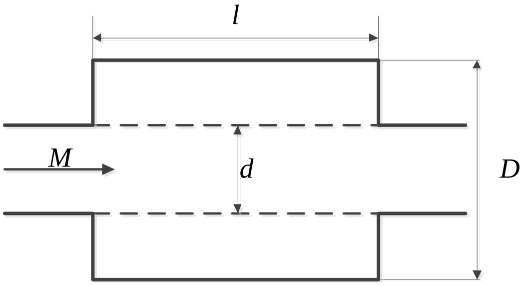
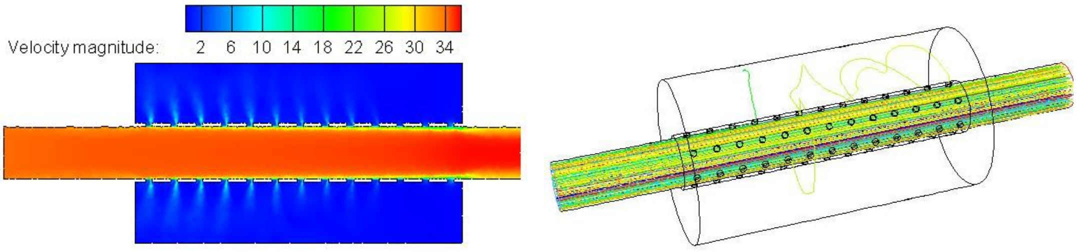


Fig. 5 The geometry of straight perforated-tube muffler



(a) (b)

Fig. 6 CFD results of straight perforated-tube muffler. (a) Velocity (b) Velocity streamlines.

Contours of velocity magnitude and streamlines are shown in Fig. 6. It could be seen that the grazing flow dominates near the orifice and there is little of flow through the orifice. Therefore, the effect of grazing flow on acoustic impedance was neglected. The acoustic impedance of perforated tube could be obtained from equations (9)-(14). Transmission loss of straight perforated-tube muffler with inlet Mach number M=0.1 is shown in Fig. 7. It could be seen that predictions of transmission loss are in agreement with measurement values in most frequencies. However, there are some deviations at 1250Hz < f < 1500Hz and

2200Hz < f < 2750Hz. The reason for deviations at 1250Hz < f < 1500Hz is that the coupling between the instabilities of the shear layer and the resonance of the muffler chamber generated the broadband noise [13]. Therefore the measurement values are less than predictions at 1250Hz < f < 1500Hz. The deviations at 2200Hz < f < 2750Hz are resulted from the perforated orifices' negative resistance which was not considered in the Equation (11).

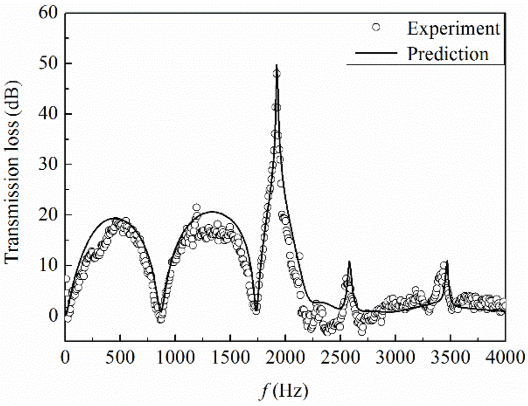
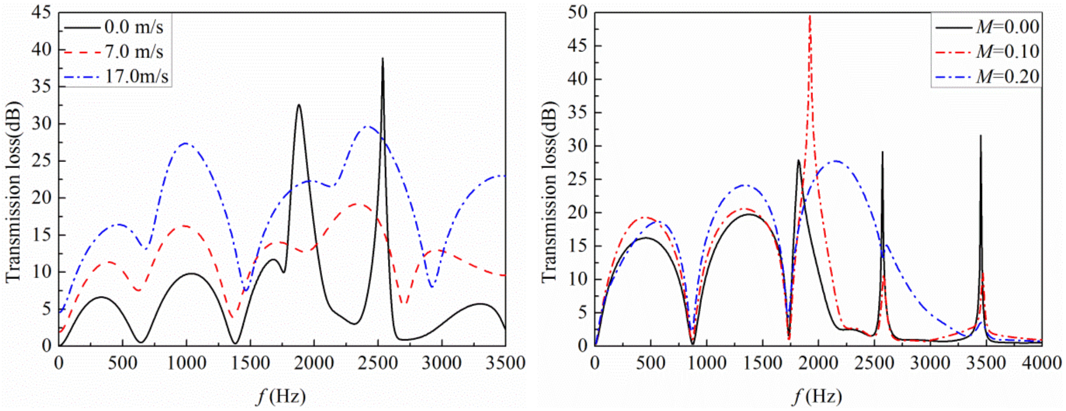


Fig. 7 Transmission loss of straight perforated-tube muffler

3.2 The Effect of Convection of Fluid on Transmission Loss of Perforated Muffler

Predictions of transmission loss agree well with the measurement values in Fig. 4 and Fig. 7, which illustrates that the hybrid method cold be applied to compute the acoustic attenuation performance of muffler with flow. The effect of fluid flow on the transmission loss of the perforated mufflers is shown in Fig. 8. It could be seen from Fig.8 (a) that the transmission loss with flow is greater than that in absence of flow in most frequencies. In general, the transmission loss of cross flow perforated-tube muffler is increased as the flow velocity increases. As for the straight perforated-tube muffler, the transmission loss changes a little when the inlet Mach number M < 0.1. The acoustic attenuation performance at higher frequencies is increased when the inlet Mach number M is up to 0.2.



(a) (b)

Fig. 8 The effect of convection of fluid on the transmission loss (a) cross flow perforated-tube muffler (b) straight perforated-tube muffler

4. CONCLUSIONS

This paper employs the hybrid method to compute the transmission loss of cross flow perforated-tube muffler and straight perforated-tube muffler with flow. Predictions are in agreement with measurement values, which verifies the accuracy of the hybrid method. The fluid flow has a strong effect on the transmission loss of cross flow perforated-tube muffler in most frequencies. The transmission loss is increased as the flow velocity increases. However, the transmission loss of straight perforated-tube muffler changes a little with the increase of the flow velocity at lower frequencies while the transmission loss is increased at higher frequencies.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of research grant 11674076 from the National Natural Science Foundation of China.

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