

Acoustic Attenuation Performance Analysis of Three-pass Perforated Tube Muffler with End-resonator

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ABSTRACT

The one-dimensional (1-D) time-domain approach and the three-dimensional finite element method (FEM) are used to predict and analyze the acoustic attenuation performance of three-pass perforated tube mufflers with and without end-resonator. For the given muffler configurations, the transmission loss results obtained from the 1-D time-domain approach agree reasonably well with the FEM predictions within the plane wave region, while the 1-D results derive the FEM predictions at higher frequencies. The FEM is then used to investigate the effects of internal structure on the acoustic attenuation performance of the mufflers, while the 1-D time-domain approach is employed to examine the influence of high temperature gas flow on the acoustic attenuation performance of the mufflers within the plane wave region.

INTRODUCTION

The three-pass perforated tube mufflers are widely used in automotive exhaust systems to reduce the engine exhaust noise produced by engine operation. Dickey *et al* [1] developed the one-dimensional time-domain approach, Munjal [2, 3] and Selamet *et al* [4] presented the one-dimensional frequency-domain approaches to predict the acoustic attenuation performance of the typical three-pass perforated tube mufflers. For a prototype muffler, their predictions of transmission loss agree reasonably well with the experimental results within the plane wave region. The one-dimensional plane wave theories are valid at lower frequencies only, a multi-dimensional approach is needed for accurate predictions of the acoustic attenuation performance of the mufflers at higher frequencies in view of the complex internal sound field. Ji and Selamet [5] developed the three-dimensional boundary element method to predict the acoustic attenuation performance of the three-pass perforated tube mufflers, and the numerical predictions agree well with experiments for a prototype muffler in the frequency range of interest.

In order to improve the low frequency noise attenuation, the typical three-pass perforated tube muffler may combine an end-resonator to form the three-pass

perforated tube muffler with end-resonator as shown in Figure 1, which is also widely used in the modern vehicles to reduce the engine exhaust noise. However, no computational or experimental guidance has been provided to determine the acoustic attenuation characteristics of three-pass perforated tube muffler with end-resonator.

The objective of the present study is then (1) to employ the one-dimensional time-domain approach based on the axial plane wave propagation assumption and the three-dimensional finite element method to predict the acoustic attenuation performance of the three-pass perforated tube mufflers with and without end-resonator, as well as to determine the effective frequency range of the one-dimensional time-domain approach, (2) to investigate the effects of internal structure and geometrical parameters on the acoustic attenuation performance of the mufflers, and (3) to examine the influence of high temperature gas flow on the acoustic attenuation performance of the mufflers.

ONE-DIMENSIONAL TIME-DOMAIN APPROACH

The commercial software GT-Power is used to predict transmission loss of the three-pass perforated tube mufflers with and without end-resonator. GT-Power is based on the one-dimensional non-linear fluid dynamic model and using the time-domain approach to simulate the acoustic problems in engine exhaust systems. The special graphical pre-processing program GT-Muffler of the software may be used to create the muffler model. This program has a two-dimensional drawing area, and users may edit the shell and end-baffles. In the model library of this program, there are a number of muffler components, such as straight pipe, bending pipe, co-axial pipe, annular pipe, three-pass perforated pipes, baffles, perforation and sound-absorbing materials, etc. Users may lay out the components in the drawing area to build a muffler model. In this program, the two-dimensional drawing may be converted into the three-dimensional geometry, and its internal structure and relative position may be checked by changing model vision. Finally, a data file *.dat is generated and introduced into the program GT-ISE, which may finish automatically the discretization of the model. In this

program, a module about the transmission loss measurement is defined, which does not need the engine model and uses the "EndFlowSpeaker" to generate the white noise as the noise source. The two-

microphone random-excitation technique proposed by Seybert and Ross [6] is used to calculate the transmission loss of muffler in the present paper. The calculated results are stored in the program GT-POST.

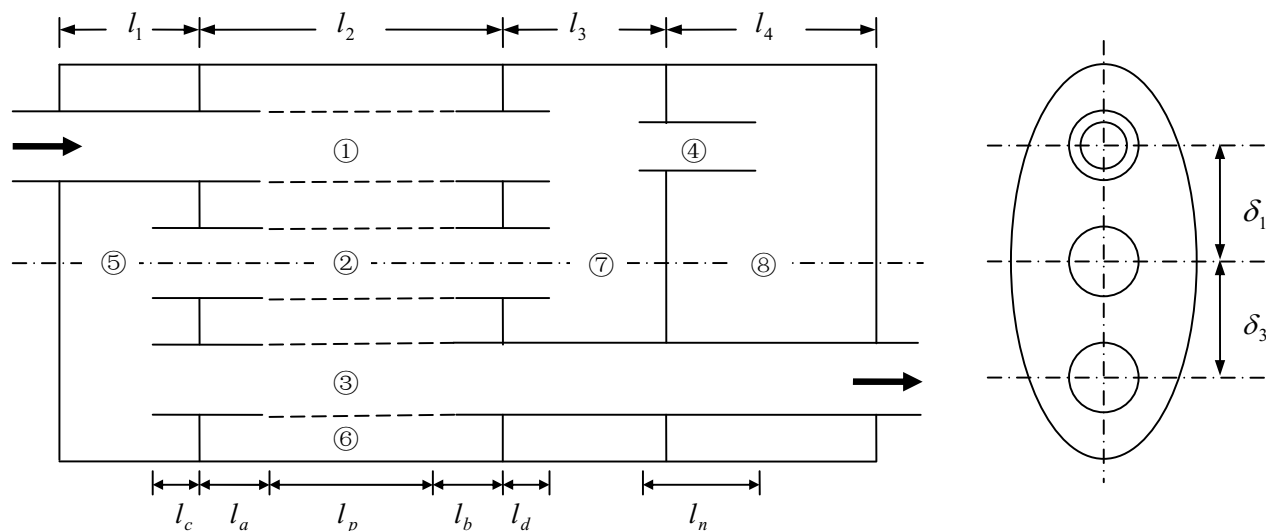


Figure 1. Three-pass perforated tube muffler with end-resonator.

FINITE ELEMENT APPROACH

The three-dimensional wave propagation in the muffler is governed by [7]

$$\nabla^2 p + k^2 p = 0 \quad (1)$$

where p is sound pressure and k is wavenumber.

The finite element method and the commercial software Sysnoise is used to calculate transmission loss of the mufflers to account the effect of three-dimensional waves inside the muffler. The detailed treatment of the FEM numerical solution procedure for muffler acoustic analysis may be found in literature [7].

In order to predict the acoustic attenuation performance of perforated tube mufflers, it is necessary to determine the specific acoustic impedance of perforations. In the present study, the following empirical expression for the perforate specific acoustic impedance presented by Sullivan and Crocker [8]

$$\zeta_p = [0.006 + jk(t + 0.75d_h)] / \phi \quad (2)$$

is used. Here t is the wall thickness of perforated tube, d_h the perforate diameter, and ϕ the porosity of perforation. Expression (2) was obtained for a small (16 cm²) sample of perforated plate. The test sample consisted of a 0.081 cm thick plate with 0.249 cm diameter holes drilled on a 0.965x0.965 mm center-to-center pattern, resulting in a percentage open area of 4.2%. It may be expected that the calculated acoustic impedance of perforate from expression (2) may be different from the real impedance if the geometric parameters of perforate are different from the sample

plate. Therefore, the relation of acoustic variables of inner and outer wall of the perforated tube may be expressed as [9]

$$\begin{bmatrix} v_{s1} \\ v_{s2} \end{bmatrix} = A \begin{bmatrix} 1 & -1 \\ -K & K \end{bmatrix} \begin{bmatrix} p_{s1} \\ p_{s2} \end{bmatrix} + \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (3)$$

where v_{si} and p_{si} ($i=1, 2$) are the normal particle velocity and sound pressure at the inner ($i=1$) and outer wall ($i=2$) of the perforated tube, respectively, $A=1/\rho c \zeta_p$, $K=d/(d+2t)$, d is the inner diameter of the perforated tube. The factor K takes into account the thickness of perforated tube. a_1 and a_2 are complex sound source coefficients ($=0$ in this case).

If the plane wave conditions are satisfied at the inlet and outlet, transmission loss of the muffler can be determined by [7]

$$TL = 20 \lg \left| \frac{p_i}{p_t} \right| \quad (4)$$

where p_i and p_t are the incident sound pressure at the inlet and the transmitted sound pressure at the outlet, respectively. An alternative expression for the transmission loss calculation may be written as

$$TL = 20 \lg \left| \frac{p_1 + \rho c v_1}{2 p_2} \right| \quad (5)$$

where p_1 and v_1 are the sound pressure and particle velocity at inlet, respectively, p_2 is the sound pressure

at outlet, ρ is the density of air, c is the speed of sound. If v_1 is given, the sound pressures at inlet and outlet may be obtained by FEM, and then the transmission loss of muffler can be determined by equation (5).

RESULTS AND DISCUSSION

For all configurations, the present study considers the elliptical muffler with $d=100\text{ mm}$ and $D=260\text{ mm}$ for the inner short and long diameters of the cross-section, $d_1=d_3=48.8\text{ mm}$ for the inner diameters of inlet and outlet tubes with offsets $\delta_1=\delta_3=73.0\text{ mm}$ from the centerline of muffler, $d_2=42.5\text{ mm}$ for the inner diameter of center tube, which is coaxial with the muffler body, $l_p=129\text{ mm}$ for the length of common perforated section with porosity 4.5%, $d_h=3.0\text{ mm}$ for the hole diameter, and $t=1.0\text{ mm}$ for the wall thickness of three perforated tubes, $d_4=38.1\text{ mm}$ for the inner diameter of the neck tube of end-resonator, and the neck tube is coaxial with the inlet tube.

The default values are given as: $l_1=54\text{ mm}$, $l_2=229\text{ mm}$, $l_3=51\text{ mm}$, $l_4=183\text{ mm}$ for the lengths of four chambers, $l_a=l_b=50\text{ mm}$ for the lengths of the solid sections of perforated tubes in the communication chamber, $l_c=l_d=10\text{ mm}$ for the tube extensions into the left end-chamber and transition chamber, and $l_n=150\text{ mm}$ for the length of the neck of end-resonator, and speed of sound $c_0=344\text{ m/s}$.

Figure 2 compares the transmission loss results of the three-pass perforated tube muffler with end-resonator from the 1-D time-domain approach and FEM. It may be

seen that, the 1-D solutions agree well with the FEM predictions at lower frequencies below 300 Hz. As frequency is increased, the 1-D solution starts to deviate from the FEM prediction. For this specific muffler configuration, the first higher order mode gets cut-on at around 1140 Hz. The difference between 1-D solution and FEM prediction below the cut-on frequency of the first higher order mode may be attributed to the fact that the sound propagation in the left end-chamber and the transition chamber seems to be the diametrical instead of the axial plane wave. This behavior is illustrated in Figure 3. Beyond the cut-on frequency of the first higher order mode, the multi-dimensional wave will propagate and affect the acoustic attenuation characteristics of the muffler. Thus, a multi-dimensional approach is needed for the accurate prediction of acoustic attenuation performance at higher frequencies. The transmission loss of this specific muffler reveals a superposition of dome behavior due to the expansion in communication chamber ⑥ and resonance peaks of resonators at lower frequencies due primarily to the right end-resonator ⑧, the left end-chamber ⑤ and the transition chamber ⑦. The first primary resonance of the muffler is controlled by the end-resonator, while the second and third resonances are contributed by the left end-chamber and the transition chamber. It may be judged from the fact that the resonance frequency of a lumped Helmholtz resonator is inversely proportional to square root of the volume and length of the neck.

The FEM is then employed to investigate the effect of geometrical parameters and internal structure on the acoustic attenuation performance of the muffler.

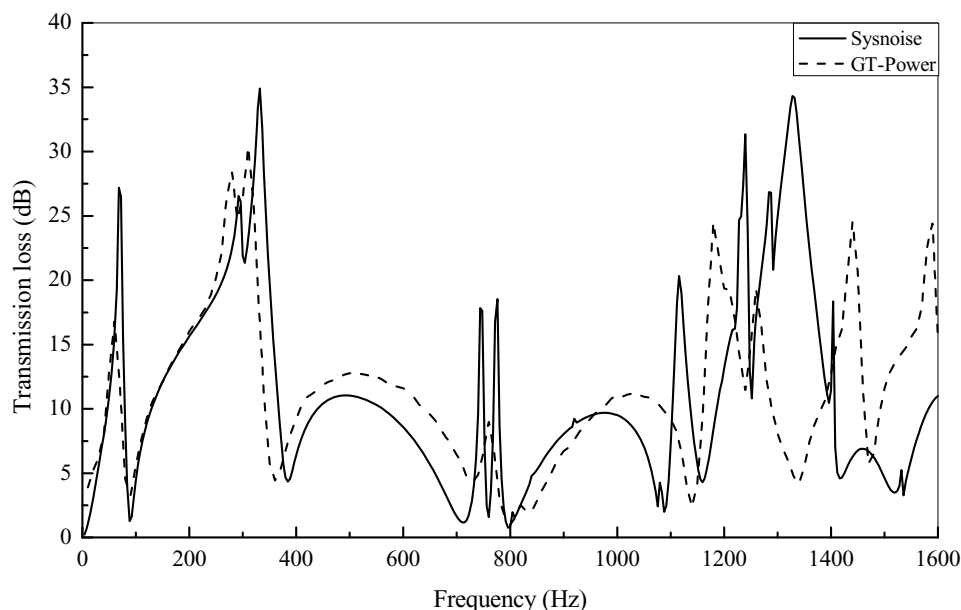


Figure 2. Transmission loss predictions of three-pass perforated tube muffler with end-resonator, solid line: FEM predictions, dashed line: 1-D time-domain results.