PRELIMINARY ACOUSTIC PERFORMANCE INVESTIGATION OF CONCENTRIC-TUBE PERFORATED MUFFLER DESIGN

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INTRODUCTION

It has been demonstrated through simulation and experimental techniques that perforated tube mufflers have better acoustic attenuation properties than simple expansion chamber mufflers. Such perforated tube elements are widely used in resonators and mufflers to attenuate exhaust system noise.

A systematic aeroacoustical analysis of perforated-elements by Sullivan and Crocker was applied in a mathematical model for the prediction of transmission loss of concentric-tube resonators [1]. The analysis, however, was limited to simple cases with constant impedance of the perforation along the tube, an appropriate mode number (plane waves), and a rigid end boundary condition. In addition, the results were for a zero mean flow in the cavity and hence the acoustic performance of cross-flow element was not be predicted. A later model by Sullivan used a segmentation method, which does not suffer the above limitations [2, 3]. In this method the perforated element is physically treated as a branch and a solid pipe in between for each segment. A separated transfer matrix can be derived in each segment. The negative aspect of this method is the slow convergence of the solution if variation in the impedance of the perforation (nonlinear model) is considered. A decoupling approach was further developed and used to simulate the transmission loss of various perforated designs [4].

The impedance of the perforated mufflers used in the transmission loss evaluation can be found through theoretical derivation, or from experiments on a sample. In this paper two impedance models based on the theoretical and empirical results are compared using a one dimensional segmentation method to explore the differences in predicted transmission loss (TL) of a concentric-tube perforated muffler with zero mean flow. The results are also compared with those from a Ricardo Wave simulation. The present study shows the usefulness of using a simple theoretical model to predict acoustic performance of a perforated muffler during the preliminary design and analysis phase.

THEORY OF SEGMENT MODEL

In the segmentation method developed by Sullivan, the perforated tube shown in Fig.1 (a) is physically divided into numerous segments shown in Fig.1 (b) [2, 3]. The physical simplification includes the effect of perforation in each segment which is considered as a branch with a solid tube connecting the branches of each adjoining segment. The assumed simulation conditions are at room temperature without flow.

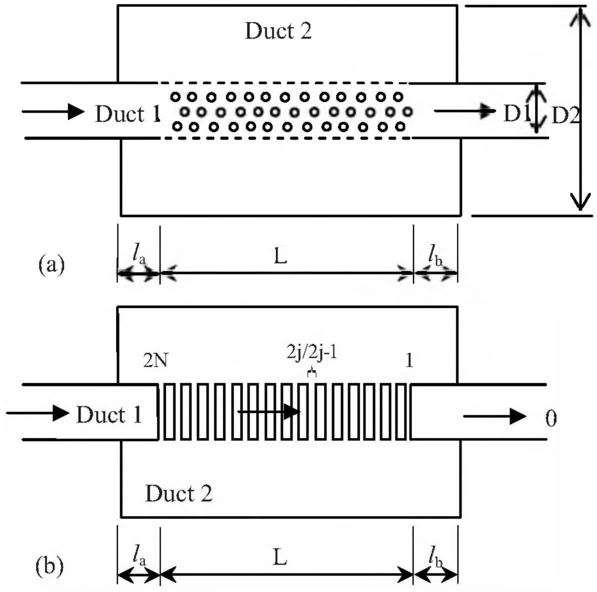

Figure 1. (a) Configuration of concentric-tube perforated muffler (b) Simplification of (a) in segmentation method

The equations for determining the acoustic pressures and mass velocities at the branches are derived from the equations of mass continuity and energy continuity. The equations between each branch assume that the wave travels as plane wave between-branches in ducts 1 and 2. Applying boundary conditions, the transmission loss is simply related to transfer matrix parameters as [See References 1 and 2].

$$TL = 20\log_{10}\left(\frac{1}{2}\left|T'_{1,1} + T'_{1,2} + T'_{2,1} + T'_{2,2}\right|\right) \tag{1}$$

MODELLING AND SIMULATION

The impedance of the perforation can be approximately derived from radial momentum continuity are given by [5]:

$$\zeta = 8\frac{kl^*}{S^2} + j\frac{4kl^*}{3},\quad S < 1 \tag{2}$$

$$\zeta = 2^{1/2}\frac{kl^*}{S} + jkl^*,\quad S > 10 \tag{3}$$

The perforate impedance in the absence of mean flow and low sound pressure level of the source reported by Sullivan is given by [2, 3]:

$$\zeta = 6\times10^{-3} + jk\left(l + 1.5r_0\right) \tag{4}$$

The transmission loss of a concentric-tube perforated resonator is calculated based on the above two impedance models. The dimensions of the resonator are: L=66.7, l_a=l_b=6.4, D_1=49.3, D_2=101.6 (all in mm). The duct 1 of wall thickness 0.81 mm was drilled uniformly with 2.49 mm diameter holes with a porosity of 3.7%. Figure 2 shows the prediction of transmission loss at a temperature of 22°C and experimental data of Sullivan [3]. The agreement between the two models and the empirical results in the first peak region is quite good. The large discrepancy is in the second peak region of high frequencies. The second peaks of both predictions are around 2920 Hz, whereas Sullivan's experimental data shows the peak to be around 2750 Hz.

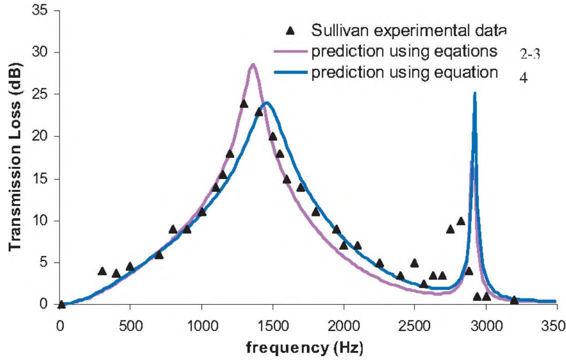

Figure 2. Comparison of transmission loss with two different perforate impedance models

A numerical prediction of a nonlinear perforated impedance model was also performed using Ricardo WAVE, a computer-aided engineering code which analyzes the dynamics of the pressure waves, mass flows, and energy losses in ducts. As a one dimensional simulation tool, WAVE has the capability of simulating the transmission loss of a concentric-tube muffler based on geometric and operating parameters as inputs.

Acoustic nonlinear impedance of orifices has been observed and investigated by many researchers. Once the sound pressure level (SPL) is greater than 130 dB and the velocity amplitude in the orifice is more than 10 m/s, a strong nonlinear resistance has been found. Figure 3 shows the transmission loss of a concentric-tube muffler simulated by Ricardo WAVE. Simulation results indicate acoustic nonlinearity exists wven when the SPL is less than 130 dB. The fundamental difference lies in the two peak regions shown.

The transmission loss calculated by Wave with a 90 dB sound source is compared with Sullivan's experimental data and segment modeling using linear perforate impedance models. The results are shown in Figure 4. It is noted that the three calculated curves are very similar to the measured results except at the second peak.

SUMMARY AND CONCLUSIONS

A one dimensional segment model is compared with Ricardo WAVE, a commercial software modeling package. For a small size (and relatively short) concentric-tube muffler configuration with a 3.7% perforation rate, all simulation results agree very well with the experimental data. For a large size muffler configuration with a 10% perforation rate, large discrepancy in prediction of transmission loss is found between the WAVE and the linear segment model. Further investigation is ongoing.

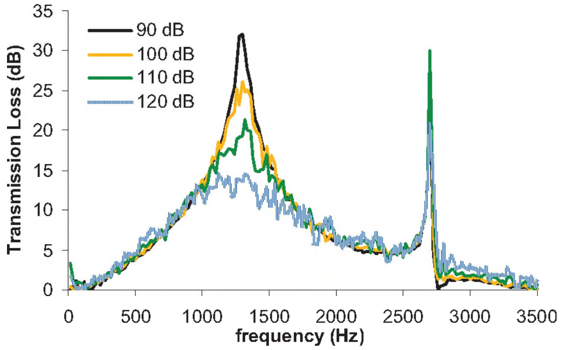

Figure 3. Comparison of transmission loss with varying SPL of sound source using a WAVE simulation

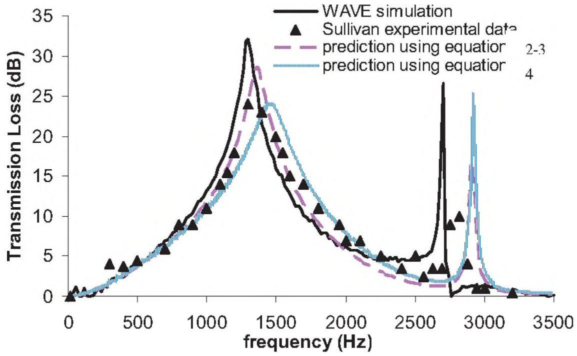

Figure 4. Comparison of muffler performance prediction by WAVE simulation, segment modeling and Sullivan experimental data

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