

Adding Bypass Ducts to Enhance Muffler Performance without Increasing Size

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ABSTRACT

It was demonstrated that a bypass duct similar to a Herschel-Quincke tube could be used to increase the transmission loss of mufflers at selected frequencies. In many cases, the duct can be short and thought of as a leak. It was shown that the optimal length and cross-sectional area could be determined by using a simple optimization technique known as the Vincent Circle. Most importantly, it was demonstrated that the attenuation at low frequencies could be improved by as much as 15 dB. To prove the concept, a muffler was designed and optimized using transfer matrix theory. Then, the optimized muffler was constructed and the transmission loss measured using the two-load method. The measured results compared well with prediction from transfer matrix theory. Boundary element simulation was then used to further study the attenuation mechanism.

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INTRODUCTION

In industry, it has been observed that adding short bypass ducts or intentional leaks into a muffler or silencer can sometimes be beneficial to the performance. Specifically, it had been observed that the maximum attenuation for an expansion chamber muffler could be improved in excess of 15 dB by simply adding a hole or a short duct. The goal of the reported work was to demonstrate this by analysis and measurement.

A short bypass duct can be thought of as a variation of the Herschel-Quincke tube. The classical Herschel-Quincke tube is the combination of two parallel pipes, which have arbitrary lengths and equal cross-sectional areas. The idea is to produce a wave of opposite phase by carefully selecting the length of the parallel branch. In that case, the sound wave from the branch will cancel the other at the junction. Along with the easy to understand cancellation induced by the different branch length, Stewart [1] found that the mechanism was more complex and that sound reflection also played a role.

The classical Herschel-Quincke tube has narrow band attenuation due to the following restrictions: (1) The equality of the cross-sectional area of the parallel branches and (2) the equality of the sum of the cross-sectional areas of the two branches with that of the inlet or outlet duct. Selamat et al. [2] made an important contribution by generalizing the equations to include variations of the duct cross-sectional areas. Later,

Selamet and Easwaran [3] generalized the classical two-duct Herschel-Quincke tube to an n-duct configuration.

In this paper, a silencer is designed and modeled using the transfer matrix method. Then, an impedance modification between two positions on the inlet and outlet is introduced by adding a bypass duct similar to the Herschel-Quincke tube. It is shown that the length and cross-sectional area of the bypass duct can be optimized using a complex transformation called the Moebius transformation if the bypass duct is short. Accordingly, the complex plane can be used to find at optimal solution that provides the highest transmission loss. It is shown by experiments and boundary element simulation that this method of optimization can efficiently enhance the performance of mufflers at the target frequency without increasing the muffler dimensions.

DESIGN

Concept

The design concept investigated is a Herschel-Quincke tube that wraps around an expansion chamber as illustrated in [Figure 1](#). Though the design shown is impractical, the configuration can be reimagined with the inlet and outlet pipes on the same side with a bypass duct connecting the two pipes (also in [Figure 1](#)). Additionally the inlet and outlet pipes can be curved or angled towards one other so that the bypass duct is short. Of course, the bypass duct could be

positioned inside the muffler shell. An arrangement similar to the concept shown was examined in this work.

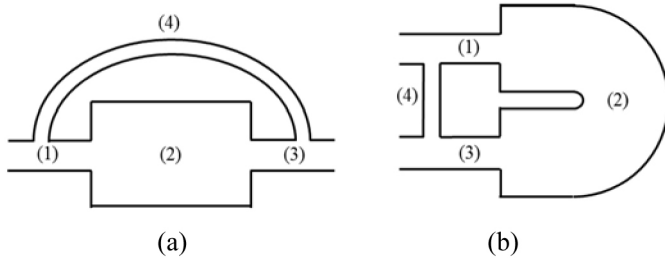


Figure 1. (a) Herschel-Quincke tube wraps around expansion chamber. (b) Curved expansion chamber: inlet and outlet on the same side.

Transfer Matrix Solution

The arrangement or arrangements similar to that shown in Figure 1 can be analyzed in the following manner. The duct cross-sectional dimensions are assumed to be small compared to an acoustic wavelength so that plane waves propagate in the silencer. In that case, the familiar transfer matrix theory developed by Munjal [4] can be used. The transfer matrix relates the sound pressure and particle velocity at the inlet (p_1 and v_1) to the outlet (p_2 and v_2) via

$$\begin{Bmatrix} p_1 \\ s_1 v_1 \end{Bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{Bmatrix} p_2 \\ s_2 v_2 \end{Bmatrix} \quad (1)$$

where s_1 and s_2 are cross-sectional areas at inlet and outlet, respectively. In the equation above A_i , B_i , C_i , D_i are the four-pole parameters for element i . Assuming the transfer matrix for the main stream is T_1 and the transfer matrix for the bypass element is T_2 , the combined transfer matrix is T_T where

$$A_T = \frac{A_1 B_2 + A_2 B_1}{B_1 + B_2} \quad (2a)$$

$$B_T = \frac{B_1 B_2}{B_1 + B_2} \quad (2b)$$

$$C_T = C_1 + C_2 + \frac{(D_1 - D_2)(A_2 - A_1)}{B_1 + B_2} \quad (2c)$$

$$D_T = \frac{D_1 B_2 + D_2 B_1}{B_1 + B_2} \quad (2d)$$

The transmission loss of the muffler can then be calculated using four-pole parameters as

$$TL = 20 \log \left| \frac{1}{2} \left(A_T + \frac{S}{\rho_0 c} B_T + \frac{\rho_0 c}{S} C_T + D_T \right) \right| \quad (3)$$

if it is assumed that both the inlet and outlet ducts have the same cross-sectional area S . The density of the fluid and speed of sound are ρ_0 and c respectively.

SELECTION OF BYPASS DUCT DIMENSIONS

The Moebius Transformation

In noise and vibration analysis, the complex plane is commonly used in modal identification, path contribution analysis, and stability analysis. Though infrequently used, the complex plane can also be advantageous for plotting the response due to specific design changes. For instance, Vincent [5] and Done and Hughes [6] discovered that the response will trace a circle in the complex plane if a spring, of which the stiffness is varied from minus to plus infinity, is introduced in a mechanical system. This principle has been called the Vincent circle. Tehrani et al. [7] contributed by noting that a complex transformation called the Moebius transformation can be used to relate the response to any impedance modification between two points at a constant frequency. Herrin et al. [8] expanded the usage of the Vincent circle from mechanical to acoustical impedance modifications. Additionally, Herrin et al. [8] showed that it was applicable to both series (source, termination, and transfer) and parallel (side branch) impedances.

The Moebius transformation can be expressed as

$$Z = \frac{\alpha z + \beta}{\gamma z + \delta} \quad (4)$$

where α , β , γ , and δ are complex constants such that $\alpha\delta - \beta\gamma \neq 0$. A straight line or circular modification of z will result in a straight line or circle for Z when plotted in the complex plane. The Moebius transformation can be decomposed into the following sequences of simple transformations [9].

$$z \mapsto z + \frac{\delta}{\gamma} \quad (5a)$$

$$z \mapsto \left(\frac{1}{z} \right) \quad (5b)$$

$$z \mapsto -\frac{\alpha\delta - \beta\gamma}{\gamma^2} z \quad (5c)$$

$$z \mapsto z + \frac{\alpha}{\gamma} \quad (5d)$$

The transformations in Equations (5a) and (5d) are translations. Equation (5b) is a complex inversion, which maps any straight lines that don't pass through the origin into circles, and maps straight lines that pass through the origin