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INVESTIGATION OF A MUFFLER WITH MODIFIED HELMHOLTZ RESONATOR VOLUME UNDER MULTI-LOAD OPERATING MODES

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ABSTRACT

Helmholtz resonators are widely applied in exhaust aftertreatment systems to improve acoustic attenuation, but their performance depends on resonator volume and engine operating conditions. This study examines the effect of enlarging the resonator volume from 30.67 L to 57.83 L on the acoustic behavior of a prototype muffler. The objective was to evaluate transmission loss at multiple load points and provide a basis for future optimization. Acoustic measurements were performed under five operating modes, defined by engine speed and torque, with a microphone placed at the outlet. Results were benchmarked against a reference muffler. The modified design achieved notable improvements in insertion loss for four out of five modes, with relative gains up to 46%. Only at the lowest load condition (Mode 1) was a decrease observed. Back pressure remained within acceptable limits, indicating no major penalty in flow performance. Findings confirm that resonator volume has a strong influence on acoustic characteristics across operating conditions. While the prototype achieved substantial improvements, variations between modes emphasize the need for designs optimized for all load points. This work provides experimental evidence on the relationship between resonator volume and acoustic performance, serving as a foundation for future research in multi-load-point optimization.

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1. INTRODUCTION

Reducing noise from the exhaust of heavy-duty diesel engines is still a challenging part of the acoustic design. On top of that, modern emission regulations have made the aftertreatment systems more complex, thus, they physically take up more space in the engine bay where traditional silencers used to be placed. This, in turn, makes it difficult to lower noise levels enough while still maintaining back pressure at acceptable levels. On top of that, there is a large variation of engine modes that make airflow, temperature, and source spectrum change significantly. Due to these differences, conventional muffler designs may sometimes be very efficient and at other times hardly provide any noise reduction.

To solve these problems, Helmholtz resonators (HRs) are usually employed as the reactive components in mufflers that help in the reduction of narrow-band noise associated with engine firing frequencies. A lot of analytical and numerical research has been done on HR behavior. Munjal [1] was the first to provide the theoretical framework for the study of acoustics in ducts and the reactive silencers. He recognized the fundamental concepts for the propagation as well as the reflection of the waves. Bies and Hansen [2] subsequently emphasized the necessity of trading off noise reduction and pressure drop by pointing out that the issue of optimizing multiple objectives in the design of a silencer is of great importance. Selamet and Ji [3] demonstrated by means of their experiments that the noise loss characteristics of single-chamber mufflers depend on the shape of the cavity and neck. Selamet, Denia, and Besa [4] later expanded this work to dual-chamber mufflers, showing the influence of chamber coupling on acoustic performance.

The classical Helmholtz relation $f_H = \frac{c}{2\pi}\sqrt{\frac{A}{VL_{eff}}}$ links the resonator frequency to the neck area A, cavity volume V, and effective neck length L_{eff}. By increasing the cavity volume, the resonant frequency is shifted to lower frequencies, which can be more in line with the diesel engine dominant noise frequency. As conveyed in the paper of Bricault et al. [5], resonators properly tuned can virtually boost the transmission loss largely without any geometrical complexity. However, it should be noted that most of these simulations/studies are done under a single set of steady-state conditions, usually at a fixed flow and temperature. Acoustic impedance and source characteristics change with load in real life, so the single-point optimization performed is not sufficient for real-engine environments, as it is referred to by ISO 5136 [6].

Resonator volume tuning is by far one of the most positive and minor-intrusive design alteration effects

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among all the possible approaches. Resonator volume change allows frequency regulation without a major restructural change although it can also indirectly influence the flow distribution and backpressure. The main limitation of currently researched works is the absence of detailed multi-load experiment scenarios, which can relate changes in HR volume to noise performance and flow resistance under realistic exhaust conditions.

This research is positioned to fill that void by experimentally evaluating the effects of muffler volume enlargement from 30.67 L to 57.83 L. The tests were conducted under five engine operating conditions that are representative of a wide range of exhaust flow and temperature. Knowing how resonator volume affects transmission loss and back pressure behavior is the point of this work, which will create a firm basis for multi-load-point optimization in forthcoming muffler design work.

2. EXPOSITION

The fundamental goal of this work is, by experiments, to gauge the influence on the sound of an exhaust system of a heavy diesel engine by the increase of the resonator volume, particularly in the case of a muffler with a Helmholtz resonator (HR) chamber. The research intends to find out the way the change of the HR volume from 30.67 L to 57.83 L affects transmission loss (TL) and insertion loss (IL) under various engine operating modes representing different speeds and load conditions.

This research is essential as it presents an experimental multi-load-point evaluation of resonator tuning within a production-scale exhaust system, which is a gap that is not sufficiently covered by existing literature. The novelty of this work is in tuning the Helmholtz parameters (volume and frequency response) coupled with engine acoustic performance, along with flow resistance, at the same time.

The results are meant for researchers and engineers engaged in noise, vibration, and harshness (NVH) development of commercial vehicle exhaust systems, as well as for academic studies on flow-acoustic coupling. On the other hand, the findings may be used for designing optimal silencers when the issues of limited space and acoustic targets must be considered simultaneously. Moreover, the results also provide baseline data for future computational-acoustic correlation studies and multi-objective optimization frameworks.

The main thesis put forward in this research is that the volume of the resonator has an overwhelming impact on the acoustic transmission characteristics of the exhaust system under different loading conditions. Changing the volume of the resonator naturally lowers its frequency, which in turn may align better with the dominant low-frequency energy of diesel engine exhaust pulsations.

This hypothesis is supported by theoretical background and the empirical relation of the Helmholtz resonance frequency:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{A}{VL_{eff}}} \tag{1}$$

where A is the neck cross-sectional area, V is the resonator cavity volume, and L_{eff} is the effective neck length.

A larger V therefore reduces f_H, enhancing attenuation at lower frequency bands - a critical range for heavy-duty engine acoustics.

A. Experimental Setup

Two muffler configurations were tested: a Reference Muffler with a 30.67 L resonator and a Prototype Muffler with a 57.83 L resonator. Both designs are geometrically equivalent except for the resonator chamber volume. Testing was performed on a heavy-duty diesel engine under controlled laboratory conditions.

B. Measurement Procedure

Acoustic pressure levels were recorded using a high-sensitivity microphone placed at the exhaust outlet, at a fixed distance along the central axis. Data acquisition was conducted using a calibrated analyzer across the 20–5000 Hz range. Five engine operating modes were defined by combinations of engine speed (rpm) and load (torque) to represent practical duty cycle conditions.

Table 1 *Engines modes defined as speed and load*

Mode	*Engine Speed (rpm)*	*Load (Nm)*
1	*1000*	*25%*
2	*1500*	*50%*
3	*1500*	*100%*
4	*2000*	*Rated Power*
5	*1500*	*Max Torque*

C. Acoustic Parameters

C.1. Insertion Loss (IL):

$$IL_i = L_{p,ref,i} - L_{p,test,i} \tag{2}$$

where $L_{p,ref,i}$ and $L_{p,test,i}$ are sound pressure levels with and without the muffler.

C.2. Tranmission Loss (TL):

$$TL = 10Log_{10}\left(\frac{W_{in}}{W_{out}}\right) \tag{3}$$

C.3. Overall Sound Pressure Level (OASPL):

$$L_{p,tot} = 10Log_{10}\left(\sum_i 10^{L_{p,i}/10}\right) \tag{4}$$

C.4. Back pressure:

$$\Delta p = p_{upstream} - p_{downstream}$$

All parameters were computed using SI units. Ambient temperature and relative humidity were recorded to ensure repeatability. Frequency-domain data were post-processed to obtain IL spectra for each mode. Mode-wise comparisons between Reference and Prototype mufflers were plotted, and performance trends were identified.

D. Tested Results:

Table 2 *Insertion Loss and Backpressure Results for the Referenced Muffler*

Results	*Mode 1*	*Mode 2*	*Mode 3*	*Mode 4*	*Mode 5*
IL (db)	*6.48*	*17.2*	*13.54*	*15.17*	*15.87*
IL (db(A)	*23.8*	*19.66*	*16.1*	*14.44*	*13.79*
BP (kPA)	*1.36*	*5.65*	*11.28*	*15.47*	*11.8*

Table 3 *Insertion Loss and Backpressure Results for the Increased Helmholtz Resonator Chamber Muffler*

Results	***Mode 1***	***Mode 2***	***Mode 3***	***Mode 4***	***Mode 5***
IL (db)	*3.1*	*18.32*	*24.8*	*21.8*	*21.1*
IL (db(A)	*22.3*	*25.4*	*26.3*	*24.5*	*25.9*
BP (kPA)	*1.58*	*7.07*	*14.5*	*20.07*	*14.9*

Table 4 *Comparison between Referenced and New Muffler*

Results	***Mode 1***	***Mode 2***	***Mode 3***	***Mode 4***	***Mode 5***
IL (%)	*-6.7*	*22.6*	*38.78*	*41.06*	*46.76*

3. CONCLUSION

This research, through an experiment, examined the effect of raising the volume of the Helmholtz resonator (HR) from 30.67 L to 57.83 L on the sound quality of the prototype muffler under various engine load conditions, five times. The evidence from the experiments showed that the volume of the resonator is the main factor that determines the frequency and the extent of the sound attenuation in the exhaust system.

At four of the five modes, the bigger resonator brought about major enhancements in insertion loss, thus verifying the argument that a lower resonance frequency would better correspond to the dominant low-frequency components of the exhaust noise spectrum. The only instance in which the performance was lessened was at the lowest load condition (Mode 1), where the lower gas temperature and changed flow characteristics led to the excitation spectrum moving away from the newly tuned frequency. Even with the bigger chamber, the increase in backpressure was still within the acceptable design limits; thus, it is confirmed that volume increment can be done without significant flow losses.

These results provide an answer to the fundamental research question, indicating that tuning based on volume is capable of broadband attenuation enhancement in real situations. The research, however, points out a limitation as well: the frequency change due to volume variations may not correspond to engine operating points.

As a matter of fact, the results offer great help to NVH engineers in charge of silencer development for heavy-duty diesel vehicles. They make it clear that the assessment of the resonator tuning effect needs to be done not only at nominal conditions but also at different load points. The findings presented will be used as a steppingstone for the next study, which will be focused on the effects of load-point changes on acoustic optimization - such as sound computational modeling, neck geometry parametric studies, and hybrid HR configurations for achieving more uniform performance in the whole operating map.

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