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Prediction of Sound Transmission Loss of Simple Expansion Chamber with the Application of FEA Tool

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Abstract: *A muffler reduces the noise from an exhaust system. A reactive muffler achieves noise reduction by reflecting sound waves back towards the source. Transmission loss is commonly used to quantify its effectiveness, comparing the transmitted sound pressure level to the incident sound pressure level. Mufflers are typically arranged along the exhaust pipe as part of the exhaust system of an internal combustion engine to reduce noise. Simple expansion chambers with extended inlet and outlet pipes are commonly used in mufflers. Important data can be obtained for various expansion chambers by analysing these configurations. The results show the transmission loss characteristics of simple expansion chambers based on Finite Element Analysis (FEA) results.*

Keywords: Sound Transmission Loss, Wave 1-D, FEA, Muffler

I. INTRODUCTION

Several parameters describe the acoustic performance of a muffler and its associated piping, including noise reduction (NR), insertion loss (IL), and transmission loss (TL)[1]. NR is the sound pressure level difference across the muffler. While NR is easy to measure, it is not particularly helpful for muffler design. IL is the sound pressure level difference at a specific point, usually outside the system, with and without the muffler present[2]. Although IL is very useful to industry, it is difficult to calculate because it depends on the muffler geometry, source impedance, and radiation impedance. TL is the difference in sound power level between the incident wave entering and the transmitted wave exiting the muffler when the termination is anechoic; TL is a property of the muffler alone. While TL can be calculated from models, it is challenging to measure[3]. This paper focuses on measuring the muffler TL.

Mufflers are primarily used to reduce noise associated with internal combustion engine exhausts, high-pressure gas or steam vents, compressors, and fans[4]. These examples illustrate that a muffler allows the passage of fluid while restricting the free passage of sound

Muffling devices might also be used where direct access to the interior of a noise-containing enclosure is required, but no steady flow of gas is necessary[5]. For example, an acoustically treated entryway between a noisy and a quiet area in a building or factory could be considered a muffling device. A muffler may function in any one or a combination of three ways: suppressing the generation of noise, attenuating noise already generated, or carrying or redirecting noise away from sensitive areas.

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II. CLASSIFICATION OF MUFFLER

Acoustic mufflers can be categorized into reactive mufflers, absorptive mufflers, and combination mufflers, which incorporate elements of both type.

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A. Absorptive Muffler

Absorptive mufflers contain fibrous or porous sound-absorbing materials, such as glass wool. They attenuate noise by converting the sound energy propagating through the passages into heat[6]. This conversion is caused by friction between the oscillating gas particles and the fibrous or porous material.

B. Reactive Muffler

A reactive muffler consists of various pipe segments interconnected with a number of larger chambers[7]. Its noise reduction mechanism relies on the area discontinuities, which create impedance mismatches for sound waves traveling along the pipe

The reflective effect of the muffler chambers and piping essentially prevents some sound wave elements from being transmitted past the muffler. Reactive mufflers are more effective at attenuating lower frequencies than higher frequencies and are widely used to reduce the exhaust noise of internal combustion engines. A typical reactive engine muffler comprises two proportionally sized chambers connected by a pair of interconnecting tubes.

C. Hybrid Muffler

A hybrid muffler combines the principles of reactive and absorptive mufflers to achieve efficient noise attenuation across a broader frequency range. Reactive components, such as chambers and baffles, create impedance mismatches that reflect low-frequency sound waves, effectively reducing low-frequency noise[8]. Absorptive components, like fibrous or porous materials, convert high-frequency sound energy into heat through friction, diminishing high-frequency noise[9].

By integrating both reactive and absorptive elements, hybrid mufflers capitalize on the strengths of each type, making them versatile and highly effective in various applications. They are particularly beneficial in environments where noise reduction is crucial across a wide frequency spectrum, such as in automotive exhaust systems, industrial machinery, and HVAC systems[10]. The combination of these technologies ensures that hybrid mufflers provide superior performance in terms of overall sound attenuation, durability, and adaptability to different noise sources and operating conditions[11].

III. MATHEMATICAL MODELING OF MUFFLER TRANSMISSION LOSS

Transmission loss (TL) refers to the reduction in acoustic intensity as a plane wave of acoustic pressure propagates outward from a source. Figure 1 illustrates the muffler layout[12]. TL in a reactive muffler does not directly correlate with the actual noise reduction experienced upon installation. However, comparing TL across various expansion chamber sizes can provide insights into their noise reduction performance[13]. The simple expansion chamber serves as a practical model for studying TL principles.

$$TL = 10\log_{10}\left[\frac{p_i}{p_t}\right]^2 = 10\log 10\left[\frac{A_i}{A_t}\right]^2 \quad dB \ldots\ldots\ldots..(1)$$

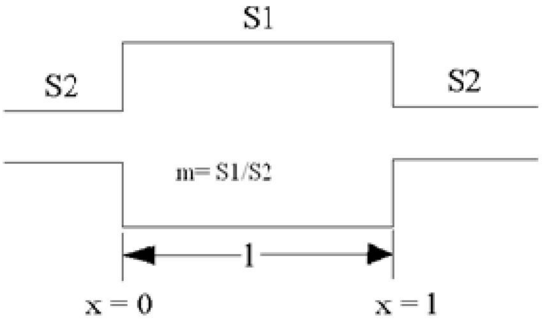

Figure 1: Layout out of muffler expansion chamber

The total sound pressure in the inlet pipe, comprising the incident pressure p_I and the p_R reflected pressure from the expansion chamber entrance, can be expressed using the harmonic pressure solution[14].

$$P_{inlet} = A_I\, e^{j(\omega t - kx)} + A_R e^{j(\omega t + kx + \beta 1)} \text{………(ii)}$$

The total sound pressure in the expansion chamber can be expressed in terms of the right-traveling wave and the reflected left-traveling wave as

$$P_{exp} = A_A\, e^{j(\omega t - kx + \beta 2)} + A_B e^{j(\omega t + kx + \beta 3)} \text{………..(iii)}$$

The total sound pressure in the exit pipe can be expressed as

$$p_T = A_T e^{j(\omega t - kx + \beta 4)} \text{…………..(iv)}$$

The continuity of acoustic pressure and volume velocity at the junction of the inlet pipe and the expansion chamber, located at the coordinate system origin x = 0 , can be described as follows:

$$A_I + A_R e^{j\beta}{}_1 = A_A e^{\,j\beta}{}_2 + A_B e^{j\beta}{}_3 \text{………(v)}$$

$$S_1\,(A_I - A_R e^{j\beta}{}_1\,) = S_2\,(A_A e^{\,j\beta}{}_2 - A_B e^{j\beta}{}_3\,) \text{……..(vi)}$$

At the junction of the expansion chamber and exit pipe, at x = L , the continuity of acoustic pressure and volume velocity can be expressed as[15]:

$$A_T\, e^{-jkL + j\beta}{}_4 = A_A e^{-jkL + j\beta}{}_2 + A_B e^{jkL + j\beta}{}_3 \text{…………(vii)}$$

$$S_1 A_T e^{-jkL + j\beta}{}_4 = S_2\,(A_A e^{-jkL + j\beta}{}_2 - A_B e^{jkL + j\beta}{}_3) \text{………(viii)}$$

By using Equations (v) to (viii), the transmitted sound pressure amplitude can be expressed in terms of the incident sound pressure amplitude as[16]

$$A_T = \frac{2 A_T e^{jkL} e^{-j\beta 4}}{2\cos kl + j\left[\dfrac{s_1}{s_2} + \dfrac{s_2}{s_1}\right]\sin kl} \text{………. (ix)}$$

Substituting the value of A_T from equation IX to equation I then[17],

$$TL = 10\log_{10}\left[\frac{p_i}{p_t}\right]^2 = 10\log 10\left[1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2 kl\right] dB \text{………(x)}$$

Equation (X) is derived using 1-D wave analysis rather than lumped analysis, thus accounting for the effect of axial modes. However, it is not valid if cross modes exist in the chamber.

IV. ANSLYSIS OF TL FOR SIMPLE EXPANSION CHAMBER MUFFLER

A simple expansion chamber depicted in Figure 2 has a pipe radius of 0.6875 inches, with the chamber radius extending 8 inches, and the pipes each measuring 4 inches in length[18].

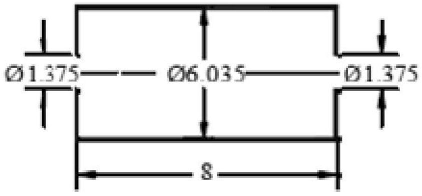

Figure 2: Muffler with dimensions

The analysis in this section is presented as attenuation curves in decibels plotted against frequency in cycles per second. These curves are calculated using the theory of 1-D plane wave analysis. Each attenuation curve is accompanied by a schematic layout of the respective muffler design[19].

Decomposition Method

As depicted in Figure 3, in a one-dimensional sound traveling through a duct, a standing wave forms upon encountering an impedance change at the muffler inlet[20]. The sound pressure can be decomposed into its incident and reflected spectra, SAA and SBB, respectively. One approach to decompose the wave is through the two-microphone method, utilizing decomposition theory to separate these components[21]

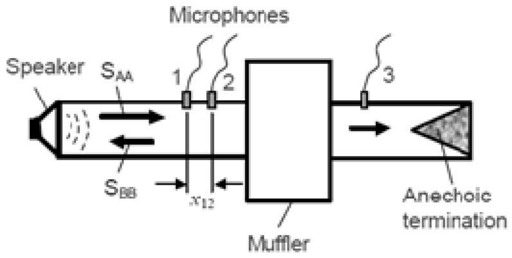

Figure 3: Decomposition Method

The transmission loss (TL) of the expansion chamber depicted in Figure 2 was measured using the decomposition method. The measurement utilized an anechoic termination with an absorption coefficient of approximately 0.95 across the 100-3000 Hz frequency range[22]. These TL results were compared to numerical results obtained from Boundary Element Method (BEM) simulations (also depicted in Figure 3). It is evident that the measured results exhibit deviations from the BEM results across the entire frequency spectrum. This discrepancy is likely attributed to the termination not being sufficiently anechoic.

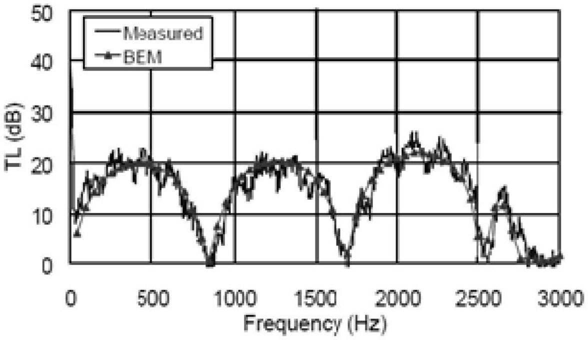

Figure 4: Decomposition method vs BEM

A. Finite Element Method

The muffler, with dimensions where the pipe radius is 0.6875 inches, the chamber radius is 8 inches long, and the pipes are 4 inches long, has been modeled in ANSYS Workbench for transmission loss (TL) evaluation[23].

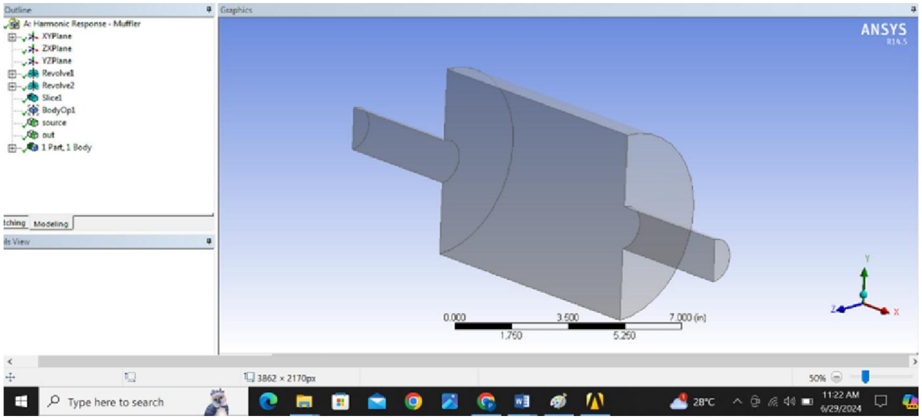

Figure 5: Muffler modelling in ANSYS

Typically, for the quadratic tetrahedral element Fluid221, a minimum of 10 elements per wavelength is recommended for accuracy. The simulation covers frequencies up to 3 kHz, corresponding to a speed of sound of 343 m/s. A mesh size of 8 mm is utilized, providing approximately 14 elements per wavelength

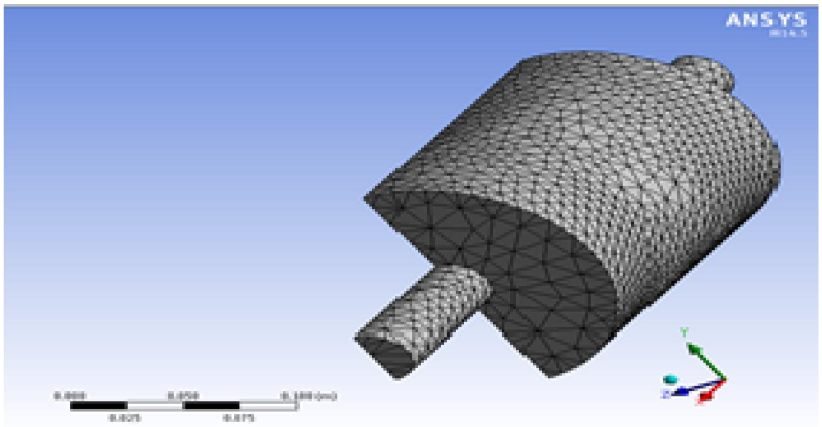

Figure 6: Meshing of muffler in ANSYS

V. RESULTS AND DISCUSSION

This work discusses three methods for measuring muffler transmission loss: measurement, Boundary Element Method (BEM), and Finite Element Analysis (FEA). Specifically, it focuses on the application of FEA using the ANSYS tool to measure transmission loss in mufflers.

FEA offers a robust approach due to its ability to handle complex geometries efficiently, which can be expensive and challenging to analyze practically. By simulating the behavior of acoustic waves within the muffler, FEA provides insights into transmission loss across a range of frequencies. The method involves discretizing the muffler geometry into finite elements and solving acoustic wave equations to predict sound attenuation accurately.

Comparisons between FEA results and practical measurements demonstrate the effectiveness of this approach in predicting muffler performance. The paper emphasizes the advantages of FEA, such as its flexibility in modeling various muffler designs and its ability to simulate different operating conditions. Overall, FEA is highlighted as a valuable tool for achieving reliable and cost-effective assessments of muffler transmission loss, supporting advancements in noise reduction technology for automotive and industrial applications.

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