IOP Conf. Series: Materials Science and Engineering **884** (2020) 012098 doi:10.1088/1757-899X/884/1/012098

Complex geometry automotive muffler sound transmission loss measurement by experimental method and 1D simulation correlation

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Abstract. A muffler is a device to attenuate noise from the exhaust. The muffler performance determined by the acoustic performance is called sound transmission loss (STL). This paper aims to measure the STL experimentally and correlated with the 1D simulation result. STL was measured using the impedance tube. Four-pole method (microphone) and two-load method were applied to measure the STL. The STL was also determined through the 1D simulation tools software. Three types of mufflers STL were measured; small expansion chamber, big expansion chamber and complex muffler. The respective error between simulation and experiment were 0.17%, 7.89%, and 11.40%. Hence, the STL experiment result was well correlated with the 1D simulation model.

1. Introduction

This paper briefly discusses the method of measurement for Sound Transmission Loss (SLT) using an impedance tube. The result was correlated with the 1D acoustic simulation. This paper focuses on the frequency below 1000 Hz. The sound transmission loss is defined by the ratio of sound power levels between inlet and outlet [1]. The STL is dependent on the internal geometry of the muffler, and it is often used to evaluate acoustic performance [2]. The STL was measured using the impedance tube with four-pole method and two-load technique. Two loads were applied at the end of the tube which is a hard end and the anechoic end. Two loads method give accurate measurement within the interested frequency range [3]. Another method to measure STL is using three-pole method (three microphones). However, the three-pole method is difficult to measure the incident wave [4]. To get rid of the complexity involved in the three-pole method, the four-pole method is widely used to measure STL [5]. Sound pressure signals from four pre-defined points are used to evaluate the transfer matrix coefficients. The four-pole method can be implemented either with the two-load or the two-source condition. The four-pole measurement method extracts the sound pressure ‘p’ and particle velocity ‘u’

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upstream and downstream of the acoustic filter to estimate the STL. Numerical errors can be eliminated by adopting the four-pole technique.

The 1D simulation was conducted using Ricardo Wave Build and Ricardo Wave Build 3D. The 1D simulation model limited to the low-frequency region and the complexity of the geometry [6]. In the 1D simulation, the wave was assumed according to plane wave theory. However, at high frequencies, the plane wave theory failed because the wave was no longer in plane [7]. The 1D simulation model was accepted for low frequency. However, at a higher frequency, discrepancies occur due to the three-dimensional effects, which are neglected in the present 1-D approach [8,9]. The 3D simulation takes a longer time compared to the 1D simulation [10]. Yasuda et al. also reported that a 1D simplified model could save 90% of execution time with acceptable accuracy [11]. This paper will briefly discuss the correlation between the experimental result and the 1D simulation result of a simple expansion chamber muffler and complex muffler.

2. Methodology

The experiment was carried out using an impedance tube at Malaysia Japan International Institute of Technology Universiti Teknologi Malaysia, Kuala Lumpur (MJIIT UTM, KL). The experiment was conducted based on the standard ASTM E2611-09 [12]. Four microphones were used to measure acoustic pressure, two microphones at upstream and another two at downstream. Two load methods were used, hard end and the anechoic end. **Table 1** shows the impedance tube specifications.

Table 1. Impedance tube specifications.

Tube diameter (mm)	34.80
Microphone spacing (mm)	29.21
Microphone type	B&K 1/2 inch
Signal analyzer and generator	LMS Scadas

Prior to the experiment, phase calibration was performed. Microphone 3 was set as reference microphone and then microphone 3 was exchanged between microphone 1, 2 and 4 to complete the phase calibration. A test piece was inserted, and a white noise signal was generated by the signal analyzer. Four microphones captured the acoustic pressure developed in the tube and the complex acoustic transfer function was computed using Equation 1 [12].

$$H_{n,ref} = \frac{G_{n,ref}}{G_{ref,ref}} \tag{1}$$

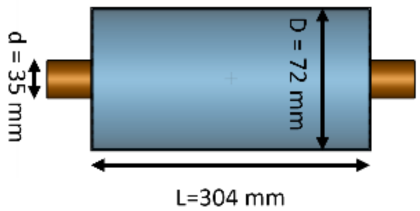
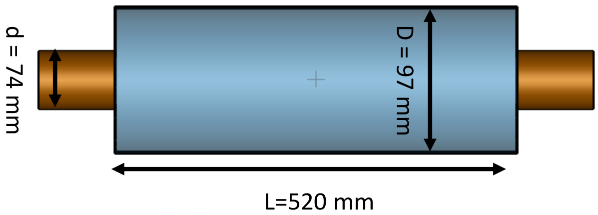
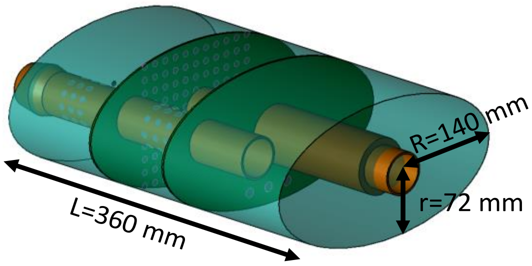
The STL was measured with two different loads, which are the hard end and anechoic end. Then, the transfer matrix yield from Equation 2 and the STL were computed using Equation 3 [12].

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{p_{0_a} u_{d_b} - p_{0_b} u_{d_a}}{p_{d_a} u_{d_b} - p_{d_b} u_{d_a}} & \dfrac{p_{0_b} p_{d_a} - p_{0_a} p_{d_b}}{p_{d_a} u_{d_b} - p_{d_b} u_{d_a}} \\ \dfrac{u_{0_a} u_{d_b} - u_{0_b} u_{d_a}}{p_{d_a} u_{d_b} - p_{d_b} u_{d_a}} & \dfrac{p_{d_a} u_{0_b} - p_{d_b} u_{0_a}}{p_{d_a} u_{d_b} - p_{d_b} u_{d_a}} \end{bmatrix} \tag{2}$$

$$STL = 20 \log_{10} \left[\frac{T_{11} + (T_{12}/\rho c) + \rho c T_{21} + T_{22}}{2e^{ikd}} \right] \tag{3}$$

Three specimens were tested on the impedance tube to measure STL experimentally and correlated with 1D simulation works. Table 2 shows the tested muffler characteristics and geometry. The muffler 3D model was developed using Ricardo Wave 3D Build.

Table 2. Muffler characteristics and parameter.

Specimen name	Specimen 3D model and dimension
Small expansion chamber	
Big expansion chamber	
Complex muffler	

The experiment started with a small expansion chamber. Next was the big expansion chamber, and the last specimen was the complex muffler. Since the impedance tube was a commercial product, a cone was fabricated as a connector for the big expansion chamber and complex muffler. The cone dimensions design was governed by Equation 4 [13].

$$\alpha = 2\ \tan^{-1}\left(\frac{R_2}{L}\right) \tag{4}$$

The small and big expansion chamber was designed from a theoretical Equation 5. This was purposefully designed to validate the experimental setup and 1D simulation model were correct and working perfectly.

$$TL = 10\ \log_{10}\left[1 + \left(m - \frac{1}{m}\right)^2 (\sin k\, L)^2\right] \tag{5}$$

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Figure 1 shows the big expansion chamber setup. The expansion chamber was made from acrylic, and the cone was made from mild steel and was fabricated by the bending process. The rectangular box shows the signal analyzer and signal generator. Figure 2 shows the complex muffler setup on impedance tube. The oval box indicates the position of the microphone. Figure 3 shows the internal geometry of the complex muffler. The internal geometry consists of perforated pipe, perforated baffle, perforated resonator and three holes on the baffle plate.

Figure 1. Expansion chamber setup.

Figure 2. Complex muffler setup.

Figure 3. Complex muffler internal geometry.

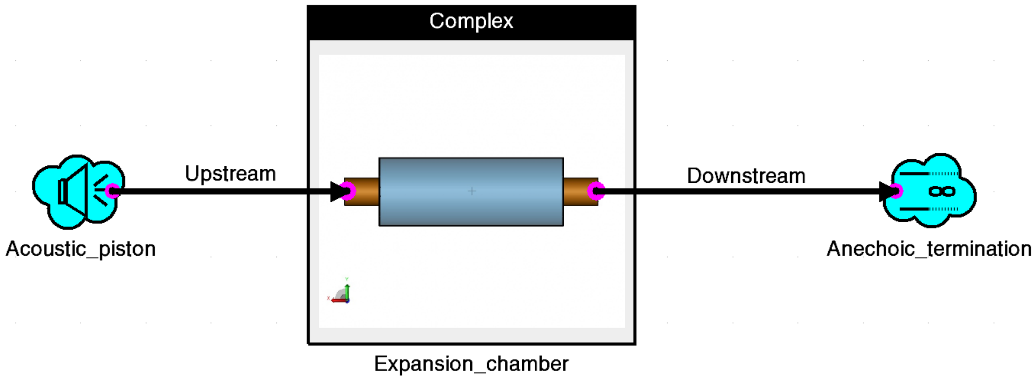

Figure 4. Big expansion chamber 1D simulation setup.

The experimental data was validated with the 1D simulation model. Ricardo Wave Build was used as simulation tools. The 3D model was developed using Ricardo Wave 3D Build. Figure 4 shows the 1D simulation model. An acoustic piston was put at the upstream tube and acts as a noise generator. The noise released was sine step wave, from 10 Hz to 1000 Hz with increment 1 Hz. The STL calculation was computed by the software. The Ricardo Wave Build calculation using a transfer function method [14]. All mufflers 3D model were developed in the Ricardo Wave Build 3D as shown in Table 2.

3. Results

Figure 5 shows the small expansion chamber results. The theoretical result was obtained from Equation 5. All three results show a good trend. There is a fluctuation below 200 Hz. This is due to noise loses toward the surrounding because the specimen is poor acoustic absorption material (acrylic). The poor material acoustic insulation gave little effect on the experimental result on low frequency [15]. The noise loses towards the surroundings were very significant towards the STL result. With the small expansion chamber, the STL result shows a good correlation. The average STL small expansion chamber for theory is 13.62 dB, while that of the experiment and simulation are 14.25 dB and 14.20 dB, respectively. The error between simulation and experiment is 0.17%. The test continues to the big expansion chamber result.

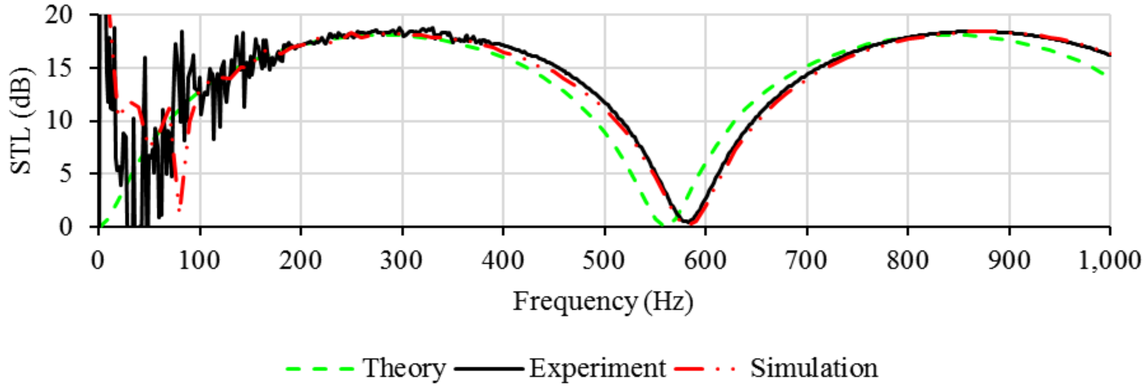

Figure 5. Small expansion chamber STL result.

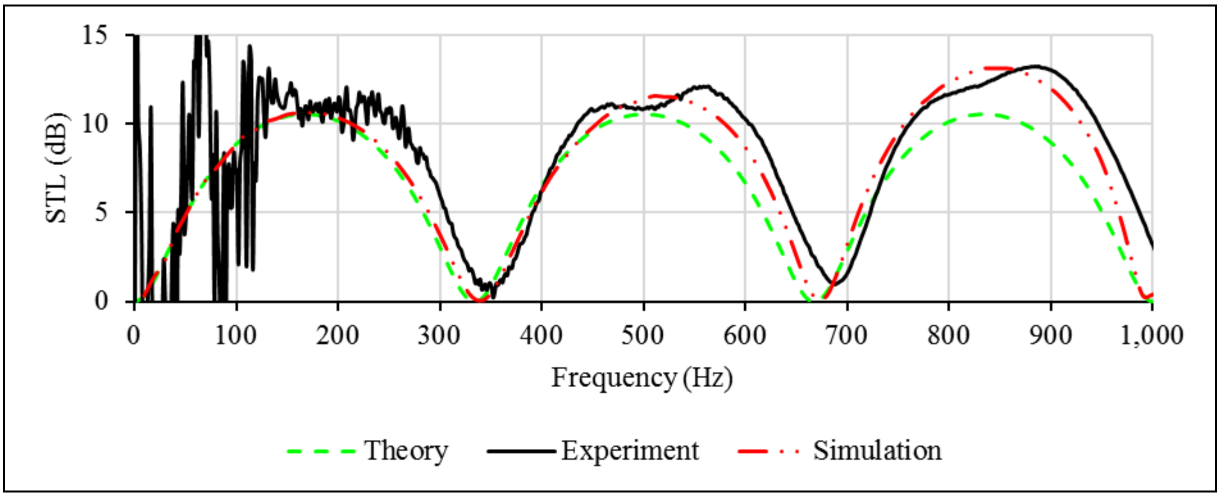

Figure 6. Big expansion chamber STL result.

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Figure 6 shows the big expansion chamber result. All three results show good trend, but at the frequency of 500 Hz, all trends start to deviates because of the 1D effect and 3D effect. The experimental result on low frequency (below 300 Hz) shows a huge amplitude fluctuation. This occurs due to the presence of the cone and the less dense material (acrylic). The cone causes a minimal effect toward the STL result. At the peak of 500 Hz and 800 Hz, there are a bit dented because of the joining effect between cone, big expansion chamber and impedance tube. The air gap between the joining yielded an extra noise, thus affecting the STL result. The experimental result also shows a significant higher amplitude STL. This is due to the noise loses to the surrounding across the expansion chamber. The average STL big expansion chamber for theory is 6.79 dB, while that of the experiment is 8.41 dB and simulation is 7.74 dB. The error between simulation and experiment is 7.89%.

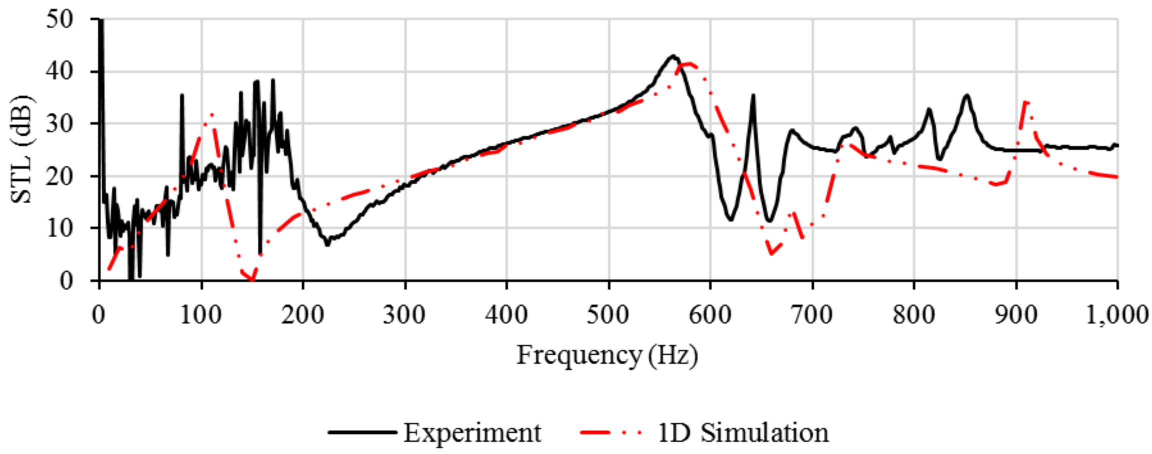

Figure 7. Complex muffler STL result.

Figure 7 shows the complex muffler STL result. The result shows a deviation between experiment and simulation. The result starts to deviate at a very low frequency, below 100 Hz. The simulation runs on 1D simulation; hence, the deviation will be huge because of the 1D simulation limitation. The exact volume and geometry cannot be captured during simulation because the volume and geometry were converted into the massless ducts and Y-junction. Furthermore, the wave is no longer in plane as the geometry is too complex. In the simulation tools, the meshing was also limited to 2000 ducts. The shell material also thin layer of stainless-steel plate and contribute towards the STL to the surrounding during experiment. The average STL for experiment and simulation are 23.93 dB and 21.21 dB, respectively. The error is 11.41%.

4. Conclusion

In conclusion, the experimental STL result and simulation STL result were correlated. For a simple geometry like the expansion chamber, the STL curve shows good agreement between experiment and simulations with an error at 0.17% for small expansion chamber and 7.89% for big expansion chamber. However, when the STL expansion chamber result was compared with the theoretical result, a discrepancy occurs due to the assumption of plane wave theory on the theoretical equation. For complex geometry, the discrepancy starts at a very low frequency. The muffler geometry was too complex and caused the wave no longer in plane. However, the error is only 11.40% which is still acceptable for a complex muffler. Although the discrepancy occurs, 1D simulation is still a good tool to validate preliminary results before proceeding to the 3D simulation and future works. The percentage of error between experiment and simulation also increased as the geometry complexity increased. The next step of this research work will go through the parametric studies of the complex muffler using 1D simulation tools.

Acknowledgment
The authors would like to acknowledge the Universiti Teknologi Malaysia (UTM) for financial support under the research university grant Q.J130000.2524.17H17.

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