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SIMULATION OF AUTOMOTIVE EXHAUST MUFFLER FOR TAIL PIPE NOISE REDUCTION

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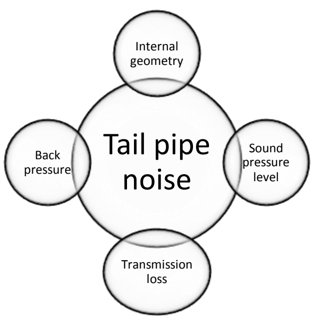
Graphical abstract



Abstract

Automotive muffler is a component used to reduce the noise of high pressure exhaust gases that are produced from the internal combustion engine. The main objective of this study is to analyse the effect of the muffler parameter to the sound pressure level (SPL) at the tail pipe noise using GT-Power simulation software. The muffler runs with a Proton Iriz engine model at engine speed from 1000 RPM to 6000 RPM at full load condition. The parameter of each muffler model was compared to determine the most suitable model to reduce the noise at tail pipe with lower backpressure difference. The results obtained were compared with those from previous research as a mean of benchmarking. The muffler model should not produce a backpressure difference of more than 5% from the benchmark systems. It is found that the most suitable model in reducing the tail pipe noises is Model B, which manage to reduce the noise by 3.07% (average) of the sound pressure level with backpressure difference of 0.35% only by only reducing the perforates number and shorten the perforates length.

Keywords: Perforates parameter, sound pressure level, transmission loss, muffler, backpressure difference

1.0 INTRODUCTION

In automotive industry, muffler is a device designed to reduce the loud noise produced by an internal combustion engine from the exhaust directly into the atmosphere. This is caused when the high-pressure exhaust gases passing through in the cylinder to a normal atmospheric pressure. Thus, muffler is deliberately designed to eliminate or tone down the noise by leading the gases through it [1].

Typically, a muffler consists of a tubular metal jacket containing perforated pipes and chambers finely designed to achieve a desired sound by cancelling the sound waves out partially. These tubes and chambers are arranged perfectly to make the sound wave from the exhaust gases reflected to the engine or by bouncing among the chambers, reducing greatly the amount of noise that is radiated into the environment [2].

There are a lot of muffler designs, but they are commonly classified as absorptive or reactive, depending on whether the acoustic energy is dissipated into heat or is reflected by area discontinuities. However, no practical muffler is completely reactive or absorptive. Every muffler comprises some elements with impedance mismatch and some with acoustic absorption [3, 4]. But in this study, only the reactive mufflers are used because it is related to the study of the noise reduction mechanism of the automotive exhaust muffler system [1, 5-7]. Usually, all types of muffler for 4-stroke engine is from reflective mufflers. There are many types of design in reflective mufflers such as conical connectors, expansion chambers, diffusing type and double expansion chamber or sometimes they are combinations of them.

The muffler parameter lead to the muffler performances. The muffler volume will affect the transmission loss. As the area ratio increases the transmission loss also increases [8-10]. However, by changing the muffler length will not affect the transmission loss but the frequency range will be affected. A shorter chamber length will increase the number of the dome while longer chamber increases the number dome and increases the frequency range coverage. Therefore, changing the muffler length is very effective and efficient to attenuate a wide band frequency noise [11].

The baffle positioning also affected the transmission loss. By changing the baffle positioning, it can enhance the attenuation at high frequency [12] and small baffle spacing (small volume) can create a resonator effect [9, 12]. Other than that, increasing the extended inlet and outlet muffler will increase the number of resonant peaks. By choosing the correct length can provide a great acoustic attenuation [13]. The attenuation becomes irregular and the number of peaks increase as the pipe radius increased [14].

To reduce the back pressure, the perforated muffler is introduced [12]. The perforation can improve the flow and reduction in the pressure drop [15]. The chosen type of muffler for this study is the combination of expansion chambers, side-resonant type, and diffusing type. The 4-stroke engine that will be used is Proton Iriz 1.6L engine. The study will be conducted in 1D simulation. This because the study focused on the low noise frequency. In low noise frequency, the plane wave theory is in plane, but at high frequencies, the plane wave theory is no longer in plane [16, 17]. Furthermore, the 1D analysis is faster than the 3D analysis and this can save time [18-23].

2.0 METHODOLOGY

2.1 Modelling and Simulation

The simulation is applied on one-dimension muffler model which involves manipulation of certain specific parameters. The muffler is operated on the Proton Iriz 1.6L model engine. The engine model is already constructed in GT-Power by the previous researcher based on actual design, scale, dimensions and parameters [24]. During the engine modelling process, it is important to make sure the differences between the measured and simulated data less than 5% for exhaust manifold pressure and 2% for intake manifold pressure. The result from the previous studies were compared with actual experimental result.

The muffler design is validated by determining the acceptable exhaust system backpressure on the engine after the muffler design is assembled with engine model. The backpressure result from the previous research is used as the baseline to validate the muffler design. The result of backpressure after the muffler assembly should not be more than 5% difference from the baseline backpressure. If the muffler produced more than 5% difference from the baseline backpressure, other muffler type model shall be constructed.

To construct the 1D muffler model, a three-dimensional model must first be built by using GEM3D in GT-Power engine simulation software as shown in Figure 1. The selected muffler design will be named Muffler 1.

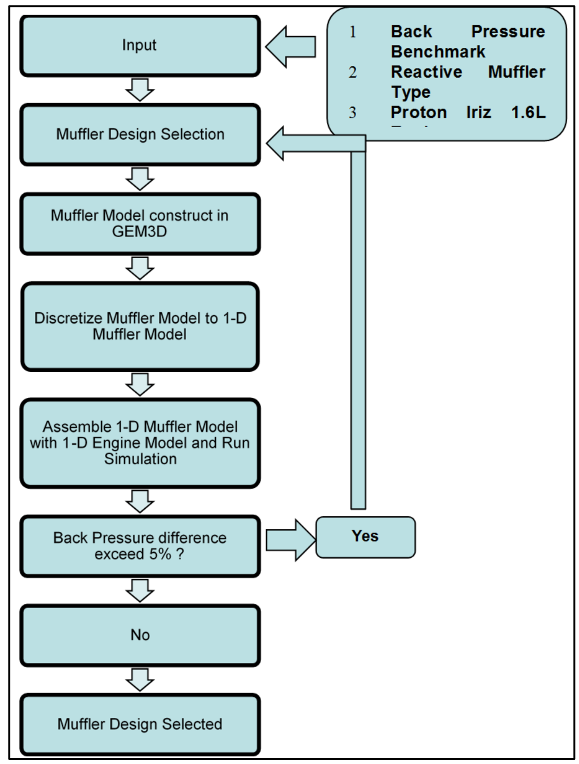


Figure 1 Process flowchart on muffler design selection

The selected muffler design, Muffler 1, is then discretized into 1D model using GEM3D as depicted in Figure 2. The 1D muffler model is then placed into the 1D engine model in GT-ISE.

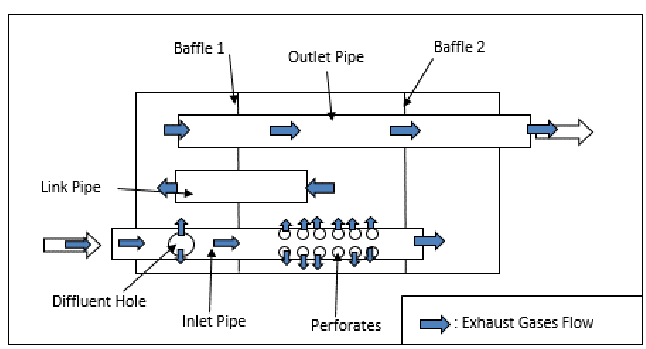


Figure 2 Muffler 1 Layout

This simulation is carried out at full load condition. During the simulation, results were deemed valid only when the engine is running from 1,000 rpm to 6,000 rpm. The SPL at tail pipe is measured using a microphone which is placed at a strategic location, i.e., 45° angle with a distance of 500 mm [25]. The transmission loss for every engine speed is known to be different and the selected engine speed transmission loss was determined by the highest SPL (in dBA).

2.2 Parameter Study

For Muffler 1, several muffler parameters were assigned as shown in Table 1. Table 2 shows a description of the modifications being made on Muffler 1 based on various groupings (colored). Four group of parameters were chosen to determine their effects on the SPL and transmission loss.

Table 1 Muffler 1 Specification

Shell Volume Muffler (L)	15
Inlet Diameter (mm)	40
Outlet Diameter (mm)	40
Link Pipe Diameter (mm)	40
Perforates Diameter at pipe (mm)	4.5
Number of Perforates at pipe	500
Perforates Length (mm)	130
Baffle 1 Position (mm)	115
Baffle 2 Position (mm)	275

Table 2 Description on the modification of Muffler 1 (compare to Table 1)

Model	Description (compared to muffler 1)	Group
A	Perforate size = 10mm Perforates number = 100	Perforates Parameter
B	Perforate number = 100 Perforate length = 50	Perforates Parameter
C	Perforate size = 2mm Perforates number = 1000	Perforates Parameter
D	Baffle 1 position = 60mm	Baffles Position
E	Baffle 1 position = 160mm	Baffles Position
F	Baffle 2 position = 330mm	Baffles Position
G	Inlet Pipe Diameter = 50mm	Pipe Diameter
H	Muffler size = 13L	Muffler Size
I	Muffler size = 17L	Muffler Size
J	Outlet pipe diameter = 50mm	Pipe Diameter
K	Baffle 1 position = 100mm Baffle 2 position = 230mm	Baffles Position
L	Baffle 1 = 125mm Baffle 2 = 230mm	Baffles Position
M	Inlet pipe diameter = 50mm Link Pipe Diameter = 50mm	Pipe Diameter
N	Perforates size = 2mm Perforates length = 50mm	Perforates Parameter
O	Muffler Size = 11L	Muffler Size
P	Link Pipe diameter = 50mm	Pipe Diameter

Perforates at the pipe as depicted in Figure 3 is a side resonant type diffuser. It usually located at the inlet pipe because it is the first muffler part to receive the high-pressure exhaust gases. Some muffler uses a sleeve at perforates and wool to reduce the noise. Perforates contain a few more parameters such as perforates size, perforates number and perforates length.

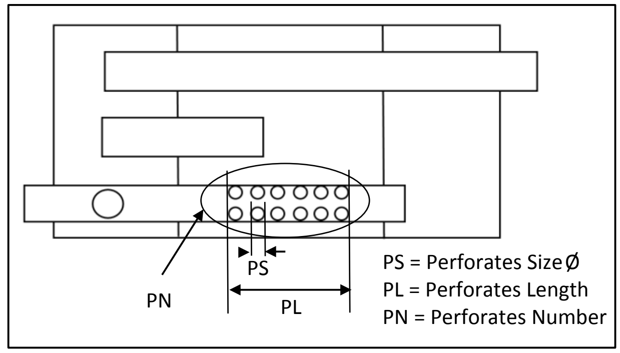


Figure 3 Perforates Parameter

Baffles used to allocate the chamber inside the muffler. The existence of the baffles is to allow more destructive interference of the sound wave, thus facilitating noise being reduced. Muffler 1 contain two baffles. These two baffles position will be adjusted along the z-axis, as shown in Figure 4. The baffles position also determines the size of each chamber in the muffler. The baffles position changed are not entering the perforate area. The pipe inside the muffler is used to flow the exhaust gases in and out from the muffler. For muffler 1 model, to study the pipe parameter effect on sound pressure level, the pipe diameter of inlet, outlet and link are modified as shown in Figure 5.

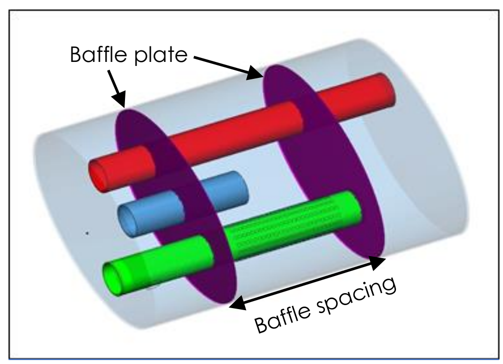


Figure 4 Baffles position

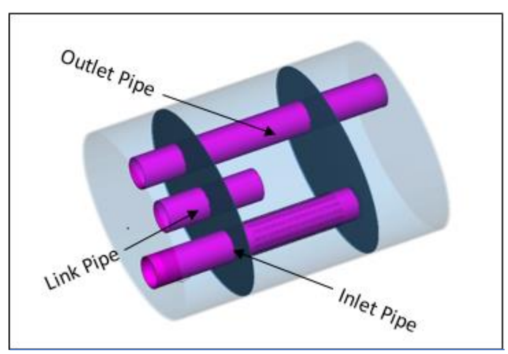


Figure 5 Muffler pipes

The last parameter that was considered in studying the effect on the SPL is the muffler shell size or volume. The muffler shell that used in Muffler 1 model is an elliptical cylinder shell. Other types of muffler shell can be in the form of cylindrical shell or others. In this study, the muffler shell size are modified accordingly to smaller or bigger sizes

2.3 Simulation Reference

Benchmark results are those that are obtained through experimental means and usually compared with the simulation results to validate the model. In this study, all muffler model must be validated by achieving the backpressure differences by not more than 5% compared to the benchmark backpressure as shown in Figure 6.

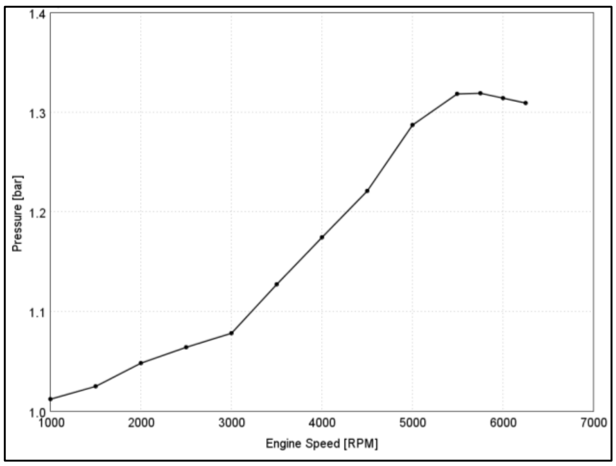


Figure 6 Benchmark Backpressure (bar) vs Engine Speed (RPM)

The benchmark backpressure can be obtained from the engine model constructed by the previous researcher, where the research was based on experiment.

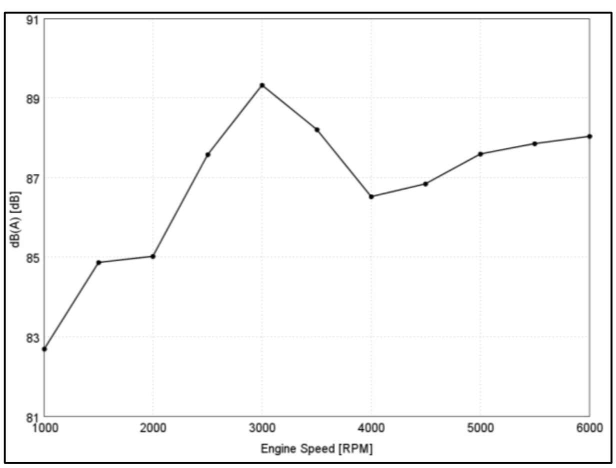


Figure 7 Benchmark SPL vs Engine Speed

To determine the benchmark result for SPL, Muffler 1 was assembled on the engine model. The SPL of a-weighted was then recorded. The a-weighted SPL is the noise that correspond to human hearing. Figure 7 shows the result for SPL. To analyse the transmission loss (TL), the result is taken at 3000 RPM (Figure 8). This is because from the benchmark SPL at 3,000 rpm, it produces the highest SPL. Thus, only TL at 3,000 rpm is analysed.

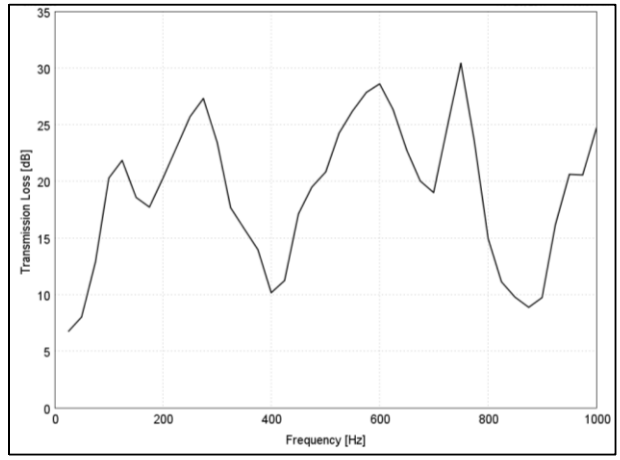


Figure 8 Benchmark Transmission loss vs Frequency

3.0 RESULTS AND DISCUSSIONS

The summary of results is presented in Tables 3 and 4.

Table 3 Comparison of percentage difference of backpressure and SPL

Muffler Model	Percentage difference of backpressure (%)	Percentage difference of sound pressure level (%)
Model A	1.38	-0.29
Model B	0.35	-3.07
Model C	1.42	-1.73
Model N	0.19	-2.29
Model D	1.32	3.18
Model E	1.04	0.38
Model F	1.49	-0.26
Model K	1.01	1.87
Model L	1.13	2.25
Model G	2.82	-2.76
Model J	2.04	0.56
Model M	4.52	1.93
Model P	2.73	3.27
Model H	1.85	2.3
Model I	1.44	-0.81
Model O	1.29	3.64

Table 4 Transmission loss for all muffler at 3000 RPM

Muffler Model	Highest TL (dB)	Frequency at highest TL (Hz)
Model A	29	750
Model B	34.2	1000
Model C	36	275
Model N	33.2	1000
Model D	21.06	225
Model E	38.27	350
Model F	34.23	275
Model K	32.99	275
Model L	34	600
Model G	33.77	675
Model J	34.84	625
Model M	25.88	650
Model P	39.24	1000
Model H	30.13	550
Model I	39.69	275
Model O	33.37	675

3.1 Backpressure Comparison

Before selecting the muffler model, it must achieve the requirement of backpressure difference of not more than 5% from the benchmarked value. If the modified muffler model exceeds 5% difference, another model need to be used or modified. Only backpressure at 5,000 rpm until 6,000 rpm are analysed.

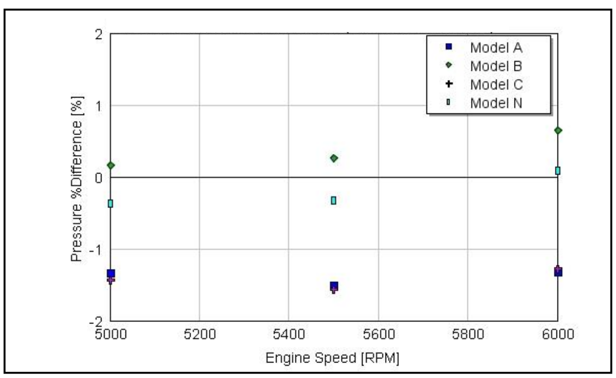


Figure 9 Percentage difference of Back Pressure vs RPM for different perforates parameter

For model A, the average percentage different between 5000 RPM until 6000 RPM is 1.38% lower than the benchmark backpressure (Figure 9). Meanwhile for model B, the results show that the average percentage difference is 0.35%. Model C shows and average percentage difference of backpressure of about 1.42% lower from the benchmarked value. For Model N, the average percentage difference of the back pressure is only 0.19%. Model N gives the smallest percentage difference compared to another model. However, Model C gives the highest percentage difference among all models in perforates parameter group. Since, all muffler model in perforates parameter do not exceed the 5% difference of backpressure, this model is deemed valid for simulation.

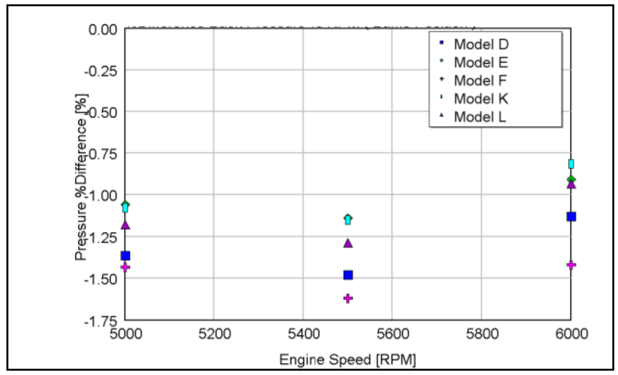


Figure 10 Percentage Difference Back Pressure vs RPM for different baffles positions

For Model D, the average percentage difference is 1.32% (Figure 10). The percentage difference backpressure for Model E is 1.04% while Model F show percentage difference of 1.49%. Model K and L show results of the percentage different not exceeding 5% compared to the benchmarked figure. Thus, all models in this group are valid for simulation test.

For Model H, the percentage different of backpressure is 1.35% while 1.44% is the percentages difference for model I (Figure 11). Model O shows the percentage difference back pressure of 1.29%. All muffler models in the muffler size group are valid for the simulation test. Model I produces higher percentage than model H. Meanwhile model O produces even lower percentage than Model I and H.

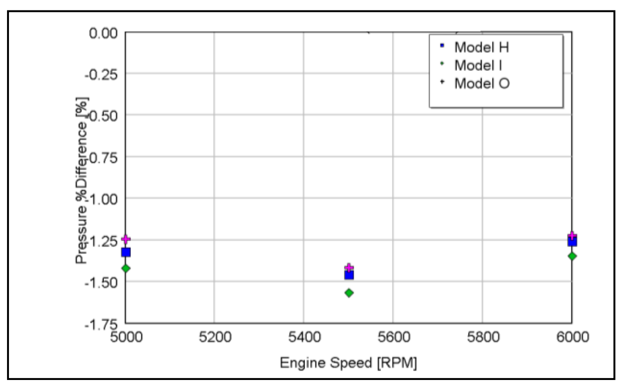


Figure 11 Percentage Difference Back Pressure vs RPM for different muffler size

3.2 Sound Pressure Level Comparison

SPL result obtained shows the effect of changing the parameter of the Muffler 1 model. From the result, the effect of changing the parameter can be known whether it increases the SPL or reducing it.

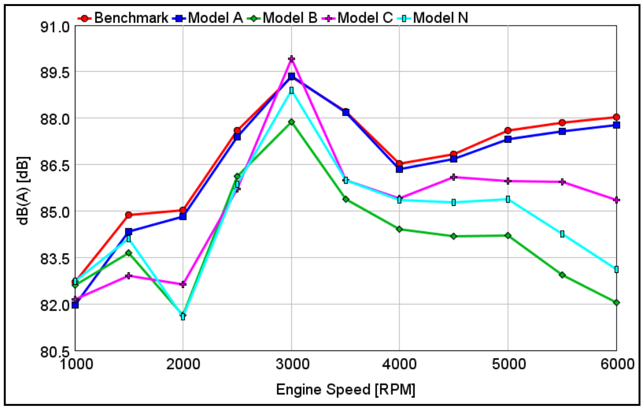


Figure 12 Sound Pressure Level dB(A) for perforates parameter

Muffler Model A shows the smallest percentage difference of SPL compared to the benchmarked value (Figures 12 & 13). By increasing the perforate size to 10 mm and reducing the perforate number to 100, it reduces the SPL by an average of 0.29% lower than the benchmarked value. Other than that, Model B produces the biggest percentage difference of noise reduction from 3,000 RPM until 6,000 RPM. The total average percentage difference of SPL for Model B is 3.07%. For model C and N, they both produce an average SPL percentage difference of 1.73% and 2.29% respectively.

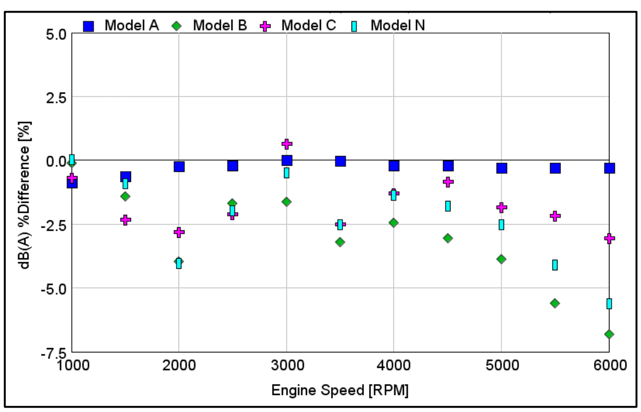


Figure 13 Percentage Difference of SPL for Perforates Parameter

For model D, the SPL produced is higher than the benchmark. Its average percentage difference is 3.18% higher than the benchmarked value (Figures 14 and 15). According to the graph shown, the results for Model E and F are 0.38% higher and 0.26% lower. The SPL percentage difference for model K is 1.87% higher than the benchmarked counterpart, while Model L is 2.25% higher.

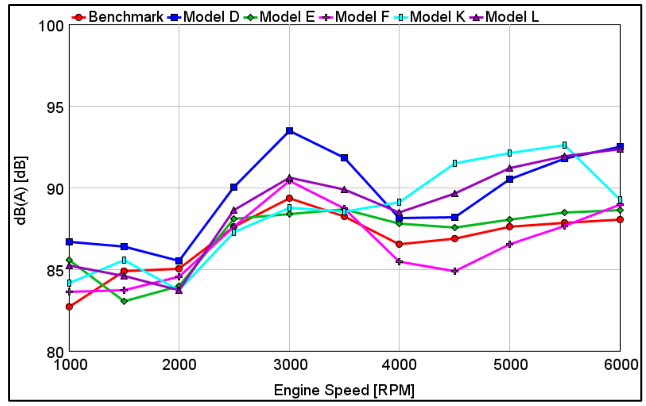


Figure 14 Sound pressure level dB(A) for Baffles Position

Model G manage to reduce the SPL with average percentage difference of 2.76% lower than the benchmarked figure (Figures 16 and 17). Furthermore, Model J only manages to reduce SPL at 2,000 rpm until 3,500 rpm. Its average percentage difference is only 0.56% higher than the benchmark. Meanwhile for model M and model P, their SPL percentages difference are 1.93% and 3.27%, higher than the benchmarked value.

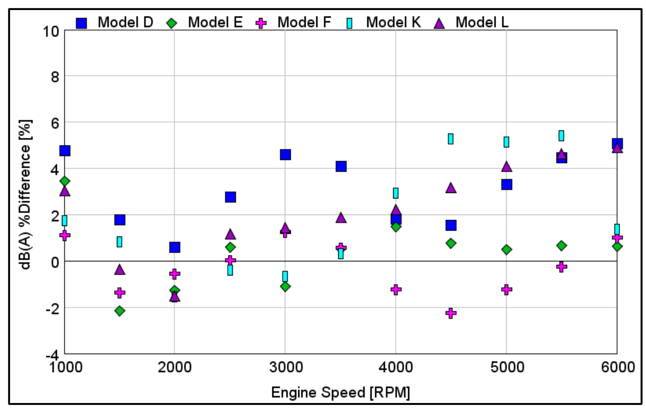


Figure 15 Percentage difference of SPL Baffles Position

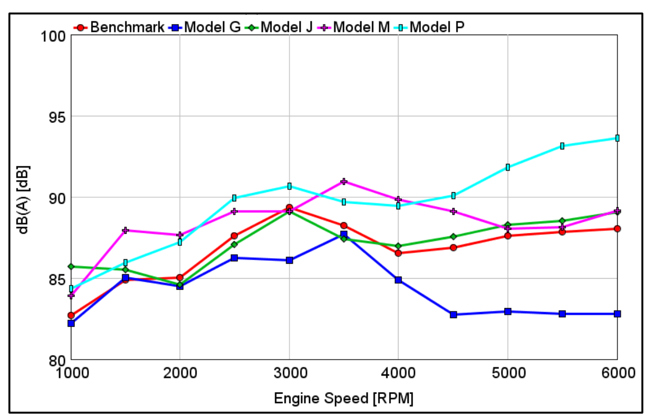


Figure 16 Sound Pressure Level dB(A) for Pipe Diameter

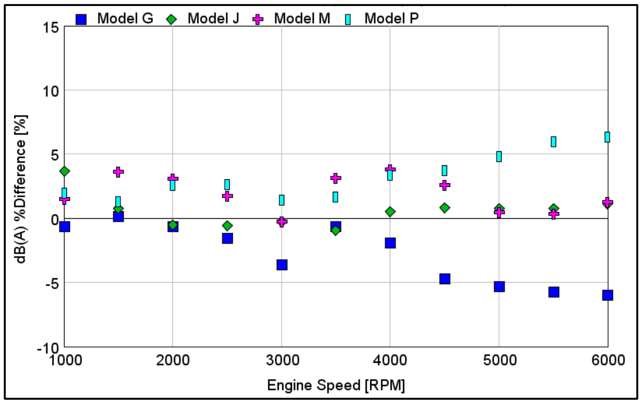


Figure 17 Percentage Difference of SPL for Pipe Diameter

The average percentage difference of SPL for Model H is 2.3% higher than benchmarked value (Figures 18 & 19). Meanwhile for model I, the average of SPL percentage difference is 0.81% lower from the benchmarked value. For model O, its average percentage difference is 3.64% higher than the benchmarked. Smaller size of muffler producing a higher SPL.

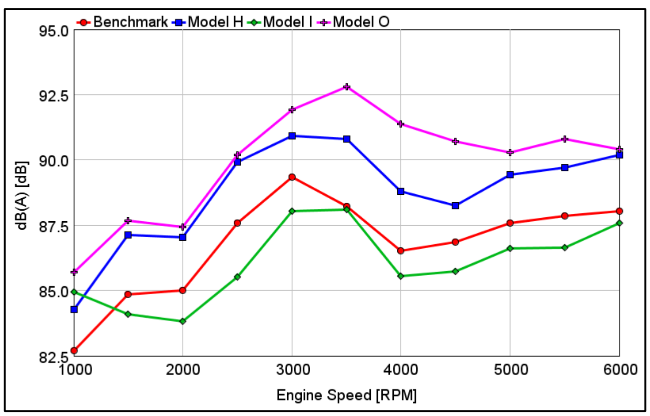


Figure 18 Sound Pressure Level dB(A) for Muffler Size

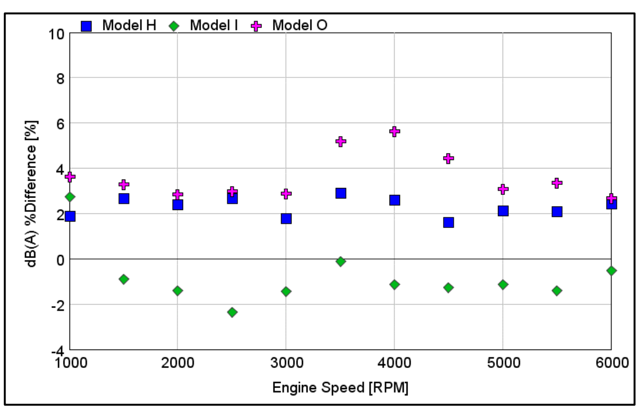


Figure 19 Percentage Difference of SPL for Muffler Size

3.3 Transmission Loss Analysis

The transmission loss is taken at an engine speed of 3,000 rpm due to a high SPL produced for almost all muffler models. The TL that are considered for all models are only until 1,000 Hz. This is because the accuracy of this simulation software is limited to 1,000 Hz. A frequency more than 1,000 Hz produce less accurate results. This is because in 1D simulation, the wave is assumed to be in plane wave theory. However, at the middle and higher frequency, the wave is no longer in plane [16, 17].

TL for all the muffler models in perforates parameter produce almost similar pattern from the benchmarked TL (Figure 20). Model A produces its highest TL at 750Hz with 29 dB loss. The highest TL produced by Model C is 36 dB at 275 Hz. Meanwhile for model B, its highest TL produced is 34.2 dB at frequency of 1000 Hz. For model N, the highest TL shown is 33.2 dB at frequency of 1,000 Hz. Every model in this group is having lowest TL at 25 Hz frequency.

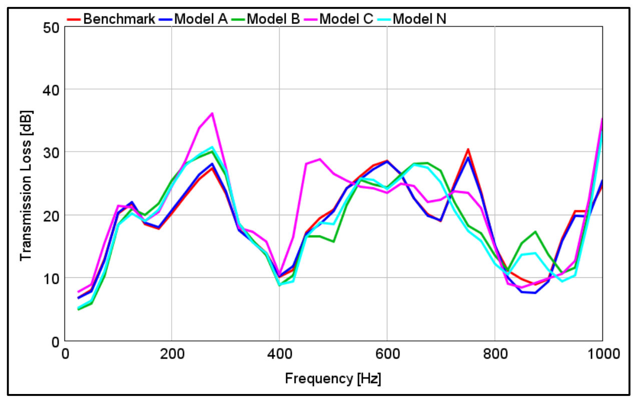


Figure 20 Transmission Loss for different perforates

The trends of the TL curves for each model are different. For Model D, the highest TL produced is 21.06 dB at 225 Hz (Figure 21). Meanwhile, the highest TL produced by Model E is 38.27 dB at 350 Hz. Other than that, the highest TL for Model F is 34.23 dB at 275 Hz. Model K produces its highest TL of 32.99 dB at 275 Hz while Model L produces highest TL at a frequency of 600 Hz with TL at 34 dB. Somehow, only Model E has a negative TL at 975 Hz.

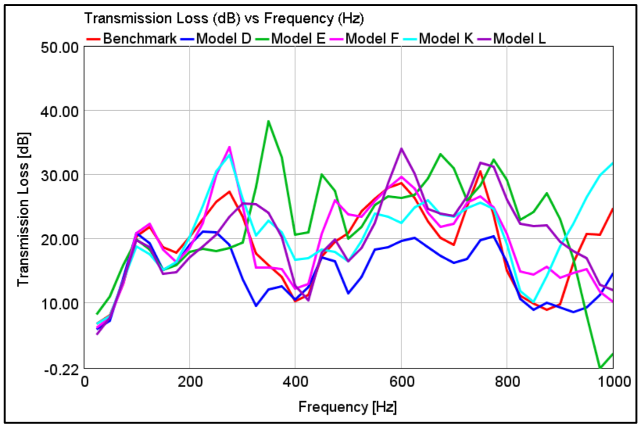


Figure 21 Transmission Loss for Baffles Position

In every muffler models, the TL are different from each other. From the graphs of Figure 22, the highest TL produced by Model G is 33.77 dB at frequency of 675 dB.

Model J highest TL value is 34.84 dB located at frequency of 625 Hz. According to the graphs obtained, the highest TL for model M is 25.88 dB at 650 Hz frequency. Model P has the highest TL at frequency of 1,000 Hz with TL value of 39.24 dB.

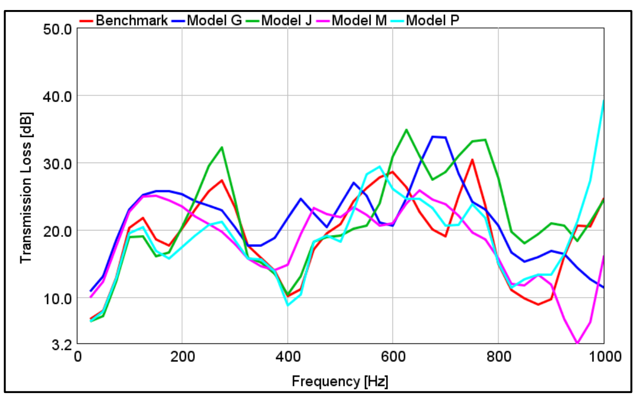


Figure 22 Transmission loss for Pipe Diameter

The lowest TL is produced by Model P at frequency of 950 Hz with 3.2 dB TL. Each of the muffler model in this group produces different pattern of graph compared to benchmark TL as shown in Figure 23. The highest TL produced by Model H is 30.13 dB at frequency of 550 Hz. Meanwhile for Model I, the highest TL is 39.69 dB at frequency of 275 Hz. Other than that, Model O is producing its highest TL at frequency of 675 Hz with TL value of 33.37 dB. Unfortunately, Model H is the only model that is producing a negative TL at 1,000 Hz frequency.

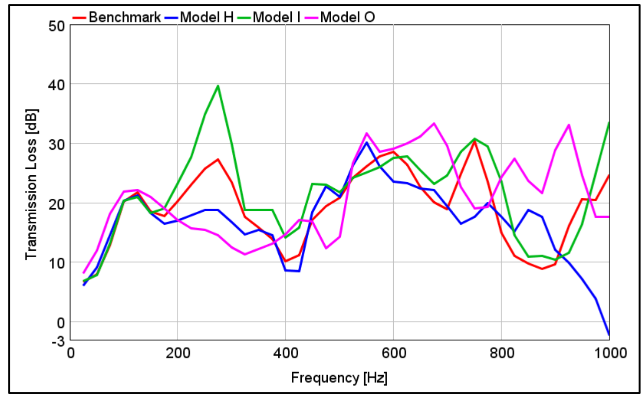


Figure 23 Transmission Loss for Muffler Size

4.0 CONCLUSIONS

According to the simulation study, every muffler parameter has an effect on the SPL and transmission loss (TL). It is imperative to know the effects of muffler parameters on the system performances when designing a muffler. As for reducing the tail pipe noise, perforates parameter is the most preferable parameter to be used. For baffles position group, Model F is the only model in the group that manages to reduce the noise. Meanwhile, for the pipe diameter group, Model G is the only model that manages to reduce the noise. Moreover, for muffler size group, the bigger the size, the more capable it has to reduce the noise at the tail pipe. Thus, only Model I is able to reduce the noise because it has the biggest size. While it is important to reduce the noise, there should not be too much backpressure difference; otherwise, the net power will be reduced if the back pressure difference is too high or too low. From all the models used, Model B is the best muffler to be used for reducing the tail pipe noise. Model B manages to reduce the noise by an average of 3.07% in comparison to the benchmarked figure with an average backpressure difference of 0.35%.

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