SIMULATION AND EXPERIMENTAL INVESTIGATION OF MUFFLER PERFORMANCE

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ABSTRACT

The purpose of the muffler is to reduce the exhaust noise produced by the engine. The main objective of this study is to simulate and investigate experimentally the muffler of the Alfa Romeo 145 vehicle. The dimensions of the muffler were used to perform the simulation. Experimentations were performed with the same muffler to develop a relationship between the noise and back pressure on muffler design. The performance of a muffler is based on Insertion loss, Transmission loss, and Back pressure. To study the performance of the muffler, simulation was carried out using GAMBIT software with FLUENT. GAMBIT was used to create a mesh surface and to define the boundary conditions of the required object, which was read and analyzed by FLUENT. The experiment on the actual muffler of Alfa Romeo 145 was conducted at different engine speed. Experimental investigation was performed on four parameters: manifold temperature, tail pipe temperature, manifold pressure and sound pressure level (SPL). Curves are drawn and analyzed using the measured parameters.

Keywords: Muffler performance, Insertion loss, Transmission loss.

INTRODUCTION

One of the components in the exhaust system of a vehicle is the muffler. Basically, the purpose of the muffler is to reduce the exhaust noise produced by the engine. The basic constructions of muffler usually consist of the tubular metal jacket, perforated tubes and the expansion chamber. The arrangement of these components will guide the exhaust gas to flow from the inlet pipe of the muffler to the outlet (tail pipe). Inside the muffler, the noise from the exhaust gas will be cancelled out by the basic physics principle on noise cancellation before the gas flows out to the atmosphere. The noise cancellation will reduce the noise that radiated by the vehicle to the surrounding. Today's vehicles are equipped with two types of muffler, either the reflective muffler (A reflective muffler consists of a number of tubular elements of different transverse dimensions joined together so as to cause, at every junction,

impedance mismatch and hence reflection of substantial part of the incident acoustic energy back to the source) or the dissipative muffler (The dissipative mufflers consist of ducts lined on the inside with acoustically absorptive materials). Both mufflers are having different construction, geometry, and principles in their application.

The main objective of this study is to simulate and investigate experimentally the muffler of the Alfa Romeo 145 vehicle. The dimensions of the muffler were used to perform the simulation. Experimentations were performed with the same muffler to develop a relationship between the noise and back pressure on muffler design.

The performance of a muffler is based on Insertion loss, Transmission loss and Back pressure[1]. Insertion loss is defined as the difference between acoustic powers radiated without any filter and that with filter [2]. Transmission loss is defined as the difference between the sound power incident (in decibel) at the entry to the muffler to that transmitted by the muffler. Transmission loss is independent of the source and presumes (or required) an anechoic termination at the downstream end. Back pressure is the extra static pressure exerted by the muffler on the engine through restrictions in the flow of exhaust gases [3].

An exhaust muffler is an acoustic filter except that waves are convected downstream by the moving medium. Inside a muffler, it contains a deceptively simple set of tubes with some holes in them. These tubes and chambers are actually designed to reflect the sound waves produced by the engine in such a way that they partially cancel themselves out. Most conventional mufflers are round or oval-shaped with an inlet and outlet pipe [4]. Some mufflers contain partitions to help reduce engine noise.

Generally an exhaust muffler should satisfy some basic requirements such as adequate insertion loss, low back pressure, ideal muffler sizing which could affect the cost and accommodation and the last one could be the durability to withstand rough conditions and extremely high temperatures. Hence some design considerations have to be taken in order to come up with an optimum muffler design.

The parameters that govern the performance of the muffler are the muffler chamber design, restrictions of the flow of the exhaust gasses and the material of the muffler itself. The relationship between the noise and the back pressure is inversely proportional; lowering the noise level at the tip will result in high back pressure. However, this relationship is undesirable as the requirement is to have a quiet muffler with a small back pressure (ideal muffler).

The higher the back pressure created by the exhaust system, the less is the net power available on the crankshaft and hence the more is the specific fuel consumption. The amount of power loss depends on many factors, but a good "rule-of-thumb" is that one inch (25.4 mm) of mercury backpressure causes approximately 1.0% loss of maximum engine power [5].

AEROACOUSTIC OF EXHAUST MUFFLER

Acoustic filters are a medium placed between a source of acoustic signal and the receiver. It consists of a set of elements which is analogous to the electrical filters or vibration isolator. An exhaust muffler is an acoustic filter except that waves are convected downstream by the moving medium, which is mean flow. Thus, exhaust muffler is classified as aeroacoustic filters. The difference between aeroacoustic and acoustic filters is that the aeroacoustic filters requires a medium, such as mean flow to transmit the waves from a point to another [2].

Sound Waves

Sound is a pressure wave formed from pulses of alternating high and low air pressure. These pulses make their way through the air at the speed of sound. In an engine, pulses are created when an exhaust valve opens and a burst of high-pressure gas suddenly enters the exhaust system. The molecules in the gas collide with the lower-pressure molecules in the pipe, causing them to stack up on each other. They in turn stack up on the molecules a little further down the pipe, leaving an area of low pressure behind. In this way, the sound wave makes its way down the pipe much faster than the actual gases do. When these pressure pulses reach our ears, the eardrum vibrates back and forth which will be interpreted as sound.

To cancel out sound, it is possible to produce a sound wave that is exactly the opposite of another wave. If two waves are in phase, they add up to a wave with the same frequency but twice the amplitude. This is called constructive interference. But, if they are exactly out of phase, they add up to zero. This is called destructive interference. At the time when the first wave is at its maximum pressure, the second wave is at its minimum, if both of these waves hit ear drum at the same time,

nothing would be heard because the two waves always add up to zero.

The design of a resonance chamber inside a muffler reflects the sound wave which is 180 degrees out of phase with the engine noise. The sound waves reflected from the wall collide with the exhaust sound waves and they cancel each other out, leaving only low-level heat to emerge from the tailpipe. The resonance chamber in the muffler reflects the sound wave from the engine as it hits the resonance chamber wall. As a result, destructive and constructive waves are formed inside the chamber with only a small fraction of the sound wave is released back to the atmosphere. The chamber length is carefully calculated to accommodate the average sound pressure level created by the engine.

The exhaust pulses are created when each cylinder in the engine is encountering an exhaust stroke, which is greatly dependant on the firing order of the engine. The more cylinders the engine has the closer the pulses are created and more sound is produced.

METHOD OF INVESTIGATION

In the present work, the Alfa Romeo 145 (1999) is used as a test subject. The muffler dimensions are taken for the simulation investigation. Mean while the actual muffler has gone through the experimental investigation.

Simulation

The simulation on muffler is carried out to determine its theoretical performance before proceeding to the experimental method. The simulation is focused on Transmission loss (TL) and Back pressure. GAMBIT, FLUENT and MATLAB are used to carry out the simulation.

GAMBIT is CAD software and is compatible with FLUENT software for running simulations based on fluid flow and heat transfer analysis. GAMBIT allows the user to create a mesh surface and define the boundary conditions of the required constructed object, which will be read and analyzed by FLUENT. The edges are meshed with spacing of 2 mm in order to have better nodes spacing and gives better results in FLUENT analysis [6]. The inlet is defined as the velocity-inlet boundary and the outlet is defined as the pressure-outlet boundary. The file is saved and exported to FLUENT for analysis [7].

MATLAB is a high-performance language for technical computing. MATLAB is used to determine the transmission loss of the simplified model muffler of Alfa Romeo. The input parameters used in the simulation are as follows according to Fig.1:

- Inlet pipe length: 0.17 m
- Outlet pipe length: 0.16 m
- Expansion chamber length: 0.44 m
- Inlet pipe diameter: 0.065 m
- Outlet pipe diameter: 0.065 m
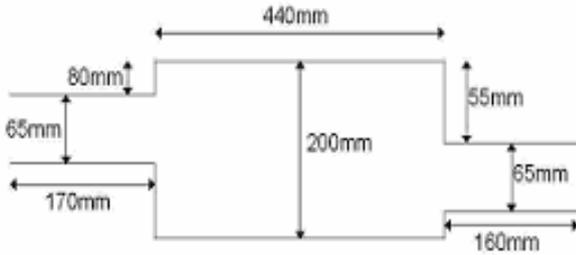
- Expansion chamber diameter: 0.2 m

Fig 1. Muffler dimension for simulation

Other input parameters are the air flow temperature and the air density.

Experimentation

An important task in constructing the experimental setup is to isolate the engine noise and the muffler sound or noise. In order to achieve this, an anechoic chamber with the holes connecting it with another anechoic chamber or just simply another good ventilated room is required for a much precise result. It is important that the chambers or rooms involved with this experimental setup has good ventilation in order to circulate the fresh air inside the room and also the removal of the combustion products released by the exhaust system. In addition, the engine also needs a constant supply of fresh air for the combustion and also the cooling process of the coolant. However, due to the limited resources, the experiment was conducted inside a small custom made wooden box that provided some isolation from the engine noise. The hole that allows the pipe passage is insulated with the clay and the end of the box has been let open to allow maximum exhaust airflow from the tailpipe.

The noise from the engine is moderately dampened by the wooden box; nevertheless the noise level itself is still high if measured by a very sensitive noise sensor. As a solution, the sound level meter that measures the noise pressure level is placed at the tip of the muffler.

Sensors used are sound level meter type 2250 (Manufacturer: Brüel & Kjær (B&K), Denmark), piezoresistive pressure transducer type 4045A10 and piezoresistive amplifier type 4618A0 (Manufacturer: Kistler Instrument AG Winterthur, Switzerland).

The sensor at the muffler tip is the thermocouple. The thermocouple is placed 15 cm from the opening of the tail pipe and supported by a custom-made sensor support. The support is specially designed to hold the sensor rigid against the exhaust gasses blowing through the tip and also to protect the sensors from high temperatures, exposed during high speed engine testing. The thermocouple is exposed to temperatures above 300°C while the sound level meter can only withstand a maximum temperature of 50°C. The sound level meter is a portable/hand held device that measures sound level. The measurement of the noise is taken at distance of 70 cm from the tailpipe opening. The reading of the noise level is taken three times for each engine speed. The duration of each reading is 30 seconds.

It is essential to shield the sensor body from the tip and also the cable connectors of the sensors from the exhaust gas temperature. In the custom-made sensor support, a piece of heat shield was used, that is made of aluminum plate. The aluminum plate is measured approximately 15cm x 15cm x 1 cm and a hole is drilled through it to make way to the thermocouple. The sensor setup at the muffler tip is located inside the wooden box (Fig. 2) that acts as the sound dampening material and also separates the engine noise and the muffler noise. The sensor is then connected to the multi-channel system, which is then connected to the workstation using local area network (LAN) port.

Two holes are made in the exhaust manifold to mount the peizoresistive pressure transducer and the thermocouple. Heat shield is used at the exhaust manifold to protect the pressure sensor body and the cable connection from the high temperatures. The heat shield used is made of an aluminum plate measures approximately 15 cm x 15 cm x 1 cm and two holes are drilled on the plate to make passage for the pressure sensor adapter and thermocouple. The tip of the thermocouple is inserted carefully so that it doesn't come in contact with the inner wall of the exhaust pipe and is placed at the centre of the exhaust pipe. This will ensure the temperature read is the temperature of the exhaust gas. The pressure sensor must be put before the thermocouple

Fig 2. Muffler tip setup

otherwise the thermocouple will affect (the velocity profile of the exhaust gas flow will change) the pressure reading measured by the pressure sensor. The thermocouple is connected directly to the IMC device. The pressure sensor is connected to the peizoresistive amplifier and then to the IMC device.

.The sensor adapter has a water circulation path within it. The coolant pipe (inlet and outlet) is connected

to the sensor adapter to cool the sensor body. The coolant system is provided by the sensor supplier (Kistler) as part of the sensor setup and it is directly connected to the water sink. The sensor body temperature can be monitored by carefully monitoring the flow of the coolant (water) coming out from the sensor adapter. It is generally safe and accepted to take the safe working condition of the sensor as long as the water that comes out is still in the liquid phase. However, as a safety precaution, the maximum temperature of the exhaust manifold is allowed to reach at 350°C. It is due to the small gap that existed in between the heat shield and the sensor body.

Experimental Procedures

1. The sensors are linked to their respective ports in the IMC (Integrated Measurement and Control) device program with Multi-Channel Synchronous System (μ-Musycs). The μ-Musycs is then linked to the workstation via the LAN cable.
2. The IMC device program is on and the sensors are initialized.
3. The sensors are set on their respective place (tailpipe and manifold), the distance between the thermocouple and the tail pipe (muffler tip) is adjusted to 150 mm.
4. The coolant (water) on the sensor adapter on the manifold is set to flow at average speed and the tube connected to the sensor adapter is checked for any leakage. The thermocouple at the manifold is positioned properly so that the tip of the thermocouple is not in contact with the exhaust pipe wall.
5. Crank the engine and set it to roam free on the idle speed. The graphs of the parameters (temperatures and manifold pressure) are plotted on the workstation. The engine is set to roam free until the parameters from the sensor are approximately constant.
6. The sound pressure level at the tail pipe is measured at the beginning of each engine speed (900 rpm, 2000 rpm, 3000 rpm and 4000 rpm) by removing the thermocouple and its support temporarily.
7. The engine speed is varied and the measurements are recorded. During the high speed variations, the coolant must not change from liquid to vapour. If this occurs, the engine must be turned off immediately. Otherwise, the pressure sensor will be damaged.
8. Measurements for required parameters are carried three (3) times for each engine speed.
9. The recorded data are tabulated and summarized.

Fig. 3 shows sample plots at 2000 rpm by the workstation for temperatures and manifold pressure with time.
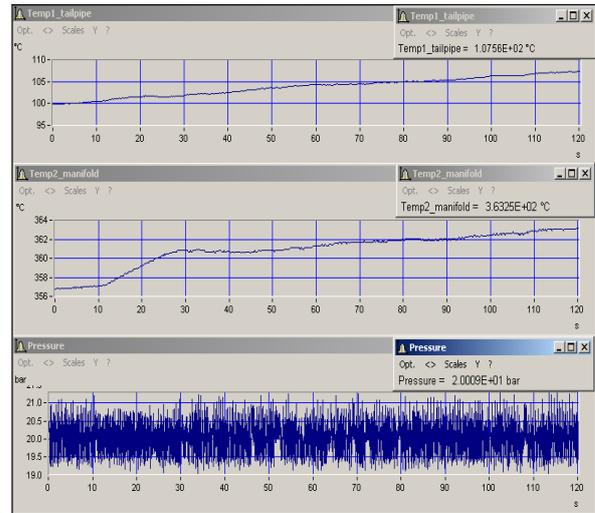

Fig 3. Variation of temperatures and manifold pressure with time (2000 rpm)

RESULTS AND DISCUSSIONS

Simulation

In Fig. 4, the static pressure distribution is indicated by various coloured contours and in Fig. 5 the static pressure distribution along the muffler is shown at 4000 rpm. The pressure rise in the expansion chamber is due to stack up of gas flow as the cross-sectional area between the chamber and the outlet pipe is changed. However, at the outlet, the velocity of exhaust gas is increased due to the high pressure in the chamber and pushes the exhaust gas out to the atmosphere.

Fig. 6 and 7 show the variation of velocity of exhaust gas flow from the inlet pipe to the outlet pipe. Both figures indicate the inverse relationship between pressure and velocity which obeys the Bernoulli principle.

Fig. 8 shows the variation of transmission loss with frequency for expansion chamber at 4000 rpm. The maximum transmission loss in the expansion chamber is 43.18 dB and the minimum transmission loss is 6.43 dB.
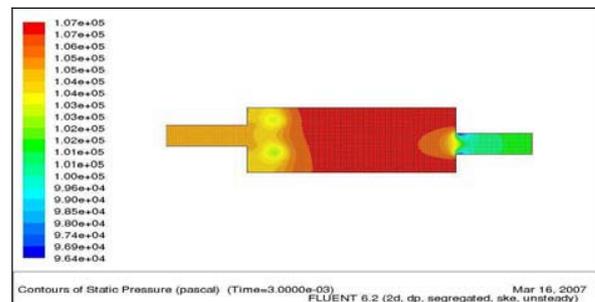

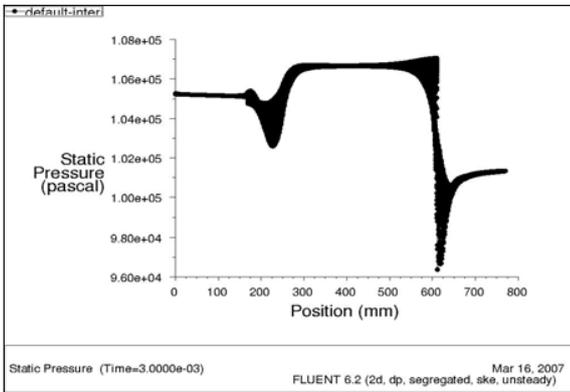Fig 4. Contours of static pressure (4000 rpm)

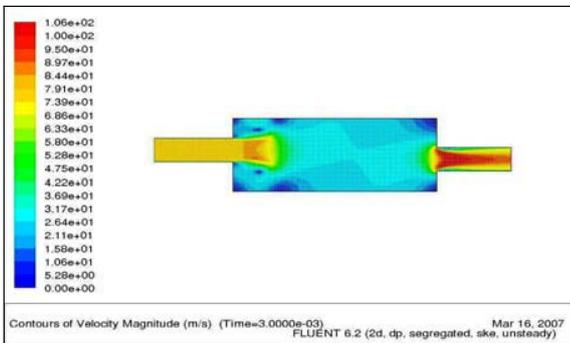Fig 5. Static pressure vs. Position in muffler
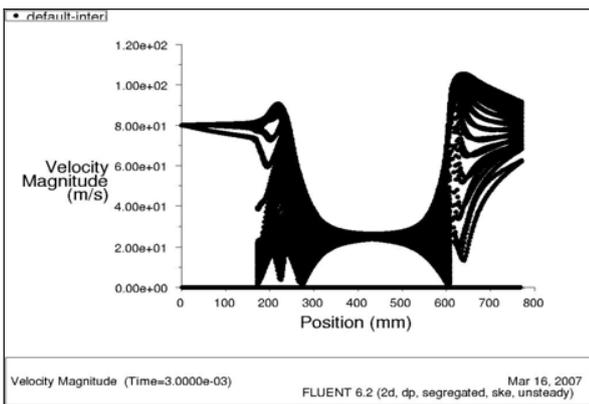

Fig 6. Contours of velocity
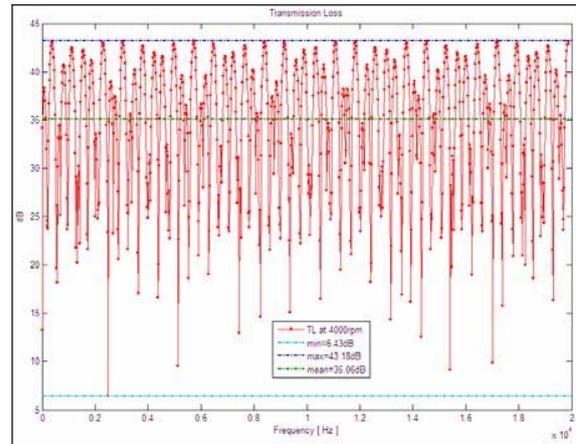

Fig 7. Velocity vs. Position in muffler

Fig 8. Transmission loss vs. Frequency (4000 rpm)

The mean transmission loss value of the muffler is 35.06 dB. As we observed, the minimum value that indicates by the graph is the lowest transmission value at low frequency range. Mainly, the transmission loss of the muffler indicates the noise cancellation in the expansion chamber is very good since the majority of the transmission loss value lies within the range of 20 dB to 43 dB.

Experimentation

The average result of the experimentation on the actual muffler of Alfa Romeo is shown in Table 1. The experiment was conducted at different engine speed without load.

Table 1: Average value of experimental results

Engine Speed (rpm)	Manifold temp.°C	Tailpipe temp. °C	Manifold Pressure (bar)	SPL (dBA)
900	210.79	58.15	19.785	71.6
2000	361.08	106.23	19.797	76.5
3000	483.54	176.88	19.882	79.1
4000	555.43	255.96	20.383	79.2

Fig. 9 shows the variation of Sound Pressure Level (SPL) with engine speed. It is evident from the figure that the SPL or also known as noise increases with the increase of engine speed. The SPL produced at 900 rpm is 71.6 dBA and the value is increased to 79.2 dBA at 4000 rpm.

The manifold pressure characteristics may be referred to Fig. 10. The manifold pressure increases with engine speed. The increase of manifold pressure intensifies as the engine speed exceeds 2400 rpm and the pressure rise continues and reaches to a large value as the speed exceeds 3000 rpm.

Comparison of SPL and manifold pressure with engine speed is shown in Fig. 11. The magnitude of both SPL

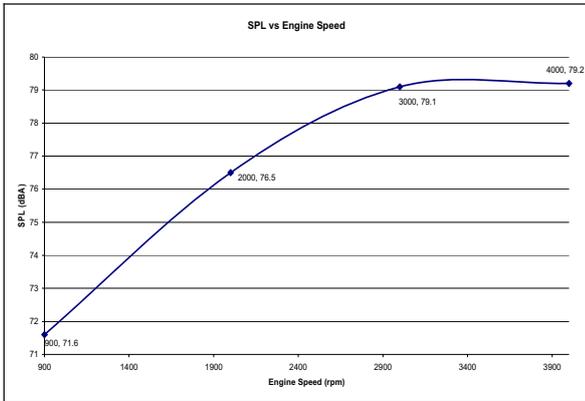and manifold pressure increases with the increase of engine speed.

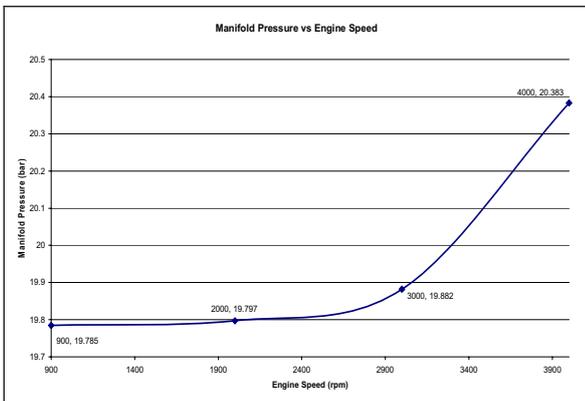Fig 9. Sound pressure level vs. Engine speed
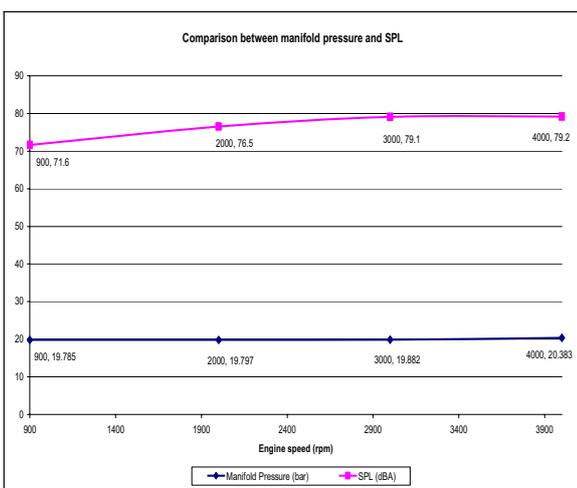

Fig 10. Manifold pressure vs. Engine speed

Fig 11. Comparison between SPL and manifold pressure

DISCUSSIONS

The flow of fluid in ducts and pipes will experience change in pressure and velocity. The fluid pressure decreases if the fluid speed increases (and vice versa). The air at inlet and outlet pipe has a greater velocity compare to the air flow in the expansion chamber which can be seen in figures 6 and 7 of simulation. The colour contour indicates the velocity of air flowing in and out of the expansion chamber and the velocity of the air in the expansion chamber as well. The simulation was carried out at different engine speed viz., 1000 rpm, 2000 rpm, 3000 rpm, 4000 rpm and 5000 rpm. The overall simulation result on the air flow in the muffler indicates that the air flow in the expansion chamber creates stagnation pressure that contributes to the back pressure for the muffler performance. The stagnation pressure is the extra static pressure that increases the pressure of air flow inside the muffler, which eventually will affect the engine performance. Back pressure represents the extra static pressure exerted by the muffler on the engine through restriction in the flow of exhaust gases which for a four-stroke-cycle engine would affect the brake power, volumetric efficiency, and hence the specific fuel consumption rate [2].

The experimental results are referred in figures 3, and 9 through 11. The difference in manifold pressure at different engine speed is small. The flow of the exhaust gas along the exhaust pipe experiences resistance inside the muffler. The construction of the muffler is also assumed to be complex as it combines the application of reactive and dissipative muffler [2]. The exhaust gas flow at high engine speed (4000 rpm) creates high pressure at the manifold.

Theoretically, the transmission loss will increase with the increase of the ratio of cross-sectional area of expansion chamber to both inlet and outlet pipe cross-sectional area. Since the dimensions of the simplified model of Alfa Romeo's muffler are constant, the results from simulation show the maximum transmission loss of the muffler is almost constant. Wilson (1993) proposed the following equation to calculate the transmission loss [8]:

$$TL = 10 \lg \left[1 + \frac{1}{4} \left(m - \frac{1}{m} \right)^2 \sin^2 kC \right]$$

Where,
$k = 2\pi/\lambda$, and
$\lambda = c/f$

The above equation predicts a transmission loss of zero when the argument of sine is 0, π, 2π, and so on, and a maximum transmission loss when the argument is $\pi/2$, $3\pi/2$, $5\pi/2$, and so on. Thus, the expansion chamber works best when length C is an odd number of quarter-

wavelength the expansion chamber is ineffective when length C is an integer number of half-wavelengths.

Referring to the transmission loss and back pressure, the requirement is to reduce the back pressure of a muffler having a good flow of exhaust gas. However, if the ratio of cross-sectional area of expansion chamber to inlet and outlet pipe is large, the muffler will provide good transmission loss. If the size of the expansion chamber is big, this will create more static pressure inside the expansion chamber, which leads to the increase in back pressure. In addition to that, the placement of plates inside expansion chamber in order to provide resonator chamber will increase in back pressure. If the muffler has high back pressure, the transmission loss will certainly be very low and the muffler ends up with filtering only small amount sound power from the source (engine). The design of muffler with extended inlet and outlet pipe inside the expansion chamber will give a better performance in terms of transmission loss [2].

CONCLUSIONS

Based on the simulation and experimentation, the following conclusions are made:

- The muffler design requirement is based on the adequate insertion loss, back pressure, size, durability, sound quality, breakout noise from muffler shell and the flow generated noise.
- The muffler noise and backpressure contradict each other.
- The noise level and the pressure in the manifold start to increase at higher engine speed.
- Experimental results could be improved by conducting the experiments in anechoic chambers.

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NOMENCLATURE

Symbol	Meaning	Unit
TL	Transmission loss	(dB)
m	Ratio of expansion chamber cross-sectional area to inlet and outlet pipe cross-sectional area	
k	Wave number	
λ	Wave length	(m)
c	Speed of sound	(m/s)
f	Frequency	(Hz)
C	Length of expansion chamber	(m)