Noise Quality and Muffler Design of A Formula SAE Racecar

A Masa’id, Ubaidillah, B W Lenggana, D R Pratama, E T Maharani and F R Sinaga

Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia

Abstract. Mufflers are an essential part of the engine system and commonly used in the exhaust system to minimize sound transmissions caused by exhaust flow. The primary objective of a muffler is to reduce engine noise emission. Mufflers have a sophisticated design that affects fuel efficiency, noise characteristics and emission of engine. In the selection of a muffler for an internal combustion engine of a Formula SAE, several functional requirements should be considered, which include both acoustic and non-acoustical design issues. Attention must also be given to problems of space availability and configuration. The best material for the purpose must be chosen. Equally important is the most economical utilization of this material, both from the standpoint of original availability and cost, as well as the practical aspect of ease of production. Not only the basic acoustical design but also some of the problems of fabrication and attachment will be discussed.

1. Introduction
Vehicle performance has been the main focus of the automobile industry. For example, the suspension system, such as a damper [1-4] is needed to maintain the dynamic performance of a vehicle. At the same time, a muffler is needed for the engine and drivetrain system in a vehicle. The main purpose of an automotive muffler is to reduce engine noise emissions. The use of mufflers when the car is running gives a significant difference in the level of noise. Suppose the vehicle does not have a muffler, there will be unbearable engine exhaust noise in our environment. Noise is defined as an unwanted sound. Sound is a pressure wave formed from alternating high and low air pulses. In automotive engines, pressure waves are generated when the exhaust valve repeatedly opens and allows high-pressure airflow to enter the exhaust system.

The sound emitted has a higher frequency when the engine speed and pressure fluctuations increase [5,6]. This pulse is the sound that can be heard. Each muffler has a set of parameters or regulations, such as noise level. Noise emitted by the car does not come from the exhaust system. Other contributors to vehicle noise emission include mechanical, intake noise and vibration-induced noise from the transmission and engine body. Exhaust gasses must be passed through the automotive muffler while restricting the transfer of the sound [6].

The Formula SAE® competition objective is to promote research, innovation and ingenuity in all aspects of the project, particularly concerning the design and integration of vehicle elements. The optimization of each component and sub-system in the context of the overarching vehicle system is fundamental to achieving the maximum performance potential of the car within the competition rules [7]. Some of the 2020 Formula SAE® competition rules identified as being relevant to this project. At idle, the maximum allowable sound level is 103 dB; While at any other engine speed up to and including
the maximum test speed (7000 rpm based on the current vehicle engine), the maximum allowable sound level is 110 dB [8].

2. Muffler Design
There are many variations of the mufflers, and the two main types of muffler designs commonly used, namely reactive and absorptive techniques. Generally, automotive mufflers have both absorptive and reactive properties. Noise reduction assesses using reactive or reflective mufflers with the destructive interference phenomena. Destructive interference of sound means that the muffler are designed to cancel sound from the engine out of the mufflers. Reflected pressure waves of the same amplitude and 180 degrees of phase need to collide with the transmitted pressure wave so that destructive interference completely occurs.

Reflections happen where there is a change in area discontinuity or geometry. As shown in Figure 1, a reactive muffler generally consists of a series of expansion and resonating chambers designed to reduce the sound pressure level at specific frequencies. The inlet and outlet pipes are generally offset and have perforations that allow sound pulses to scatter out in many directions inside a chamber, so that causes destructive interference.

![Figure 1. Typical reactive automotive muffler [6]](image)

Reactive type mufflers are commonly used in vehicle exhaust systems where the emission varies with time and the exhaust gas flow. It can reduce noise at various frequencies because many chambers and changes in geometry that the exhaust gasses are forced to pass through. The disadvantage of reactive mufflers is that they create large backpressures. Reactive techniques are effective at the low-mid frequency [5].

A dissipative or absorptive muffler, as shown in Figure 2, uses absorption to minimize the sound energy. Sound waves decrease because the energy is converted into heat in the absorptive material. A typical dissipative muffler consists of a circular, perforated and straight pipe that is covered in a larger steel housing. Between the casing and the perforated pipe is a layer of sound absorptive material that absorbs several pulses of the pressure. Dissipative techniques are effective at the mid-high frequency [5].

![Figure 2. Absorptive automotive muffler [6]](image)
Dissipative mufflers make less backpressure than reactive mufflers. However, it does not reduce noise too. It is impossible to design mufflers that achieve complete destructive interference, although some designs are possible. The noise spectrum variation makes the muffler design quite complicated, and testing is the only sure way to determine whether the muffler is performing well at all engine speeds. However, as a general rule, exhaust noise is generally limited to the first few harmonics and basic frequency, which can be calculated. Therefore, the frequency must be used as a starting point for the initial muffler design.

A practical way to determine the frequency range to be controlled is to measure the engine noise that is not affected. This measured spectrum can be used to identify the frequency at which higher noise levels occur. High-frequency noise levels must be treated with proper noise control to achieve overall noise reduction. There is always another way to design mufflers for specific applications. Nevertheless, the designer has succeeded if the muffler is designed practically, achieves the necessary noise reduction and meets all functional requirements.

3. Functional Requirements Formula SAE Exhaust Muffler

Many functional requirements should be considered when designing a muffler for Formula SAE Racing Car. Adequate insertion losses, size, backpressure, durability, desired sound, cost, style and shape are examples of functional requirements. The details of functional requirements are written below, especially the functional automotive muffler requirements.

3.1. Adequate insertion loss

"Muffler" or attenuated the sound is the main function of a muffler. The reduction of sound pressure from the noise source to the required level is the result of an effective exhaust application. In terms of the automotive muffler, noise in the exhaust system produced by the engine must be reduced. Insertion loss or transmission loss is the definition of muffler performance or attenuating ability. Insertion loss is the difference between acoustic power emission without and with muffler installation. This calculation was measured energy of sound (in decibels) released through to the atmosphere and comparing it with the sound released passage through the muffler [9].

The insertion loss is needed so that the style of the muffler can be designed according to specific purposes. Meanwhile, transmission loss is the difference (in decibels) between the sound power induced when entering the muffler transmitted by the muffler. Transmission loss measurement considers the pressure differential in the logarithmic equation and the muffler impedance of the center inlet of the muffler and its outlet [10]. Transmission loss is the ratio power that can transmit measuring the use of many approaches like two loadings [11], two sources [9], and breaking waves [12–14]. The use of reactive mufflers with a lot of area discontinuities to achieve great attenuation is the principle used to design mufflers. The muffler attenuation capacity can be increased by adding sound-absorbing material that placed appropriately.

3.2. BackPressure

Static pressure from the muffler on the engine through exhaust gas flow restrictions is the kind of backpressure. In general, the more backpressure produced make muffler attenuates the sound better. Excellent attenuation in the reactive muffler assesses when the reduction in engine power output is made by forcing the exhaust gasses to go through many geometric changes so that sufficient backpressure be generating.

Power losses, especially for performance vehicles, can be avoided by keeping back pressure to a minimum. Changing the direction of additional backpressure is made every time the exhaust gas is forced. Backpressure must be kept in minimum value to limit changes in geometry, for example, is a "straight-through " absorption silencer. The exhaust gas passes unimpeded through a straight to the perforated pipe.
3.3. Size
Muffler size is affected by space availability. Optimal attenuation according to the design of the muffler geometry. If a muffler size is large, then it affects its weight. Heavier muffler has more manufacturing cost. The weight of the muffler is highly considered in light of open-wheel racing vehicles because it affects the acceleration or the performance of the vehicles. Therefore, a small muffler is used to get a lightweight.

Mufflers with large size are difficult to be supported with design. Muffler mounting is used to support the muffler weight, but it also used to isolate vibrations so that the vibrations are not transferred to the chassis and passenger cabin from the exhaust system. Hard rubber inserts and brackets are usually used to isolate vibrations from the muffler to the chassis.

3.4. Durability
Another important functional requirement is the life expectancy of the muffler, especially when dealing with hot exhaust gases and absorptive silencers found in performance vehicles. The insertion loss is due to the blockage of absorbent material by hot exhaust gases. However, some materials that are resistant to these undesirable effects, such as mineral wool, fiberglass, sintered metal composites and white wool. Without the use of absorbent materials on the reactive type, mufflers are very durable, and its performance is quite good.

There is various kind of materials to make mufflers. Temperatures up to 500 °C typically use aluminized steel or mild steel, temperatures up to 700 °C use type 409 stainless steel, and higher temperatures use type 321 stainless steel. Generally, corrosion-resistant materials such as aluminum or stainless steel are used to make mufflers because automotive exhaust gas temperatures are around 750 °C.

3.5. Desired sound
The general function of the muffler is to reduce the sound of a combustion engine to the desired level, reduce noise pollution, and provide driver comfort. Reduce exhaust noise meaning must reduce sound pressure. The internal combustion engine produces high pressure. The difference in pressure level creates a sound whose intensity needs to reduce [15].

The reduction in characteristics that interfere with untreated exhaust noise, such as low-frequency rumble, is the aim of the muffler design. Generally, performance and sound are the two reasons for muffler modifications of a stock vehicle. Noise control performance of the vehicle from the factory floor is usually not optimal.

Replacement of a standard reactive muffler to a straight-through absorption silencer is carried out to minimize backpressure and hence improve vehicle performance and aesthetics. In most cases, vehicle owners want a noticeable deep rumble in the exhaust system. However, according to government regulations, the emission produced by the main muffler is only allowed to be heard in the passenger cabin.

Breakout noise from the muffler shell may be a problem and should be minimized together with flow-generated noise, especially when designing a muffler for a high insertion loss. But noise reduction is reduced can be solved by controlling the propagation path and sound barriers for noise reduction purposes [16].

3.6. Cost
Cost to consumers is a major factor. Not only have an effective performance as a silencer, but muffler prices must also be affordable in order to be acceptable to the marketplace. Aftermarket car muffler prices range around $ 90 to $ 700 depending on design integrity, materials used in muffler construction, muffler durability and labor costs of muffler makers. The development of high safety vehicle and production costs were carried out by engineers [17].
3.7. Style and Shape
There are various shapes, styles and sizes of mufflers depending on the application. Inlet and outlet tubes separated by a larger oval or round chamber are part of an automotive muffler. The desired sound and aesthetics, regardless of what is in the room is what the muffler’s user wants. Therefore, ensuring that the muffler is functional and also marketable is the task of the muffler designer.

4. Measured performance of an absorption style muffler

4.1. FSAE Muffler Design
The muffler used the specification of the KTM 450 SX-F. The standard muffler and the FSAE design muffled exhaust comparison of the KTM 450 SX-F Formula SAE vehicle can be seen in Figure 3 and Figure 4. The inner diameter and outer diameter are 57 mm and 112 mm with a 457 mm muffler length. Whereas, 1.6 mm perforated tube runs from the inlet to the outlet pipe with 1160 perforations whose diameter is 3.2 mm. The location layer of absorption material is between the perforated tube and the outer casing. The illustration of muffler configuration is shown in Figure 5.

4.2. Measurement method and result
A microphone of Precision Sound Level Analyzer was used to measure exhaust noise, with parameters from the end part of the exhaust outlet are 0.5 m and 45 degrees that can be seen in Figure 6. The measurement of muffler insertion loss is shown in Figure 7 and Table 1.
Measurement of the muffler force and its attenuation characteristics carried out on the insertion loss of an absorptive muffler that fitted to a Formula SAE racecar. A straight-through dissipative muffler that provides 97 dB attenuation at 1500 rpm (idle) and 101 dB at 7000 rpm was used for the vehicle performance. In addition, this muffler is lightweight and produces minimal back pressure to improve engine performance.

According to measurement results, the absorbent muffler that was used for the vehicle is a good broadband attenuator. In addition, this absorbent muffler can control noise at low or high frequencies. Attenuation of the high frequency of the muffler is obtained from the use of absorbent material, while the medium to low frequency controlled by the central chamber. After all, it is ideal for such applications.
because it provides the necessary attenuation, is light and produces less back pressure to improve engine performance.

5. Conclusion
Formula SAE Racing car exhausts must be designed to meet all functional requirements, as mentioned above, i.e., adequate loss of insertion, minimal backpressure, space constraints, long-lasting, producing the desired sound, cost-effective and aesthetic. The muffler design could achieve 97 dB at idle (1500 rpm) and 101 dB at 7000 rpm according to the testing of the proposed muffler design. In the future, there are many possible muffler design solutions for specific situations and many possible ways to predict muffler insertion loss. Still, its performance on the car proves the design.

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