Design of Racing Car Muffler in FSAE Based on GT-Power

Zhengming Wang¹,a, Jialun Pan²,b, Wei Su³,c

¹School of International Education, Wuhan University of Technology, Wuhan, China
²School of International Education, Wuhan University of Technology, Wuhan, China
³School of International Education, Wuhan University of Technology, Wuhan, China

*a3341667548@qq.com, ballen.poon@whut.edu.cn, csuwei@whut.edu.cn

Abstract—Muffler plays a very important role in the internal combustion engine vehicle, and plays a key role in reducing noise. Formula SAE (FSAE) also has strict rules for noise, so the proper muffler is very important. Using GT-Power series software to optimize the internal structure of muffler is a common solution at present. Through the cooperation of resistance structure and resistance structure, noise loss can reach 20%, and finally the design scheme meeting the target is obtained. At the same time, the resistive structure is conducive to improve the exhaust back pressure, so as to improve the torque output of the vehicle at low speed. Through the simulation analysis of the software and the coupling analysis of dynamic performance and noise value, a muffler suitable for FSAE can be obtained.

1. INTRODUCTION

With the continuous development of FSAE, the research and improvement of single project has gradually become the object of everyone's pursuit. More and more motorcades have used self-developed mufflers, but there is no set of detailed procedures and research methods. Many self-developed mufflers are not only complex in structure and heavy in weight, but also have limited noise elimination effect. For the design of muffler, we should not only consider the regulation of noise value, but also analyze the influence of muffler structure on exhaust pressure to ensure that the output power of engine is not affected.

2. RELEVANT BACKGROUND

Formula SAE (FSAE) automobile competition is an automobile design and manufacturing competition sponsored by American Automobile Engineering Society and participated by college teachers and students. The FSAE competition requires each team to design and manufacture a single seat mini car with excellent performance in power, braking, handling stability and fuel economy within one year according to the competition rules and racing car manufacturing standards, and complete all competitions.

So far, FSAE has become a global automobile design and manufacturing competition with great influence for college students. China first introduced the event in 2010, known as the Formula SAE of China (FSC), which is held once a year. The purpose of the competition is to cultivate college students' abilities in automobile design and manufacturing, cost control, marketing and communication coordination, so as to lay a talent foundation for the long-term development of automobile industry in China.
In the FSC competition, according to the situation of the 2019 season, more than 50% of the participating teams use exhaust mufflers for direct purchase, only a small number of teams use their own muffler, the effect is generally general, and there is no variable internal channel structure. The noise of many teams does not meet the requirements of the race. The upper limit of noise level required by the FSC is shown in Table 1.

|                     | C-weighted |
|---------------------|------------|
| Idle speed          | 103        |
| other speed         | 110        |

Racing car team of Wuhan University of Technology (WUT) uses the CBR600 engine, which is a high speed engine. At high speed, the straight through exhaust is beneficial to its dynamic performance, while the exhaust with back pressure device is conducive to increase the torque at low speed and improve the dynamic response at low rotation speed.

3. Research Status of the World

3.1 Research Status in China

According to the situation of the 2019 season, more than 50% of the teams adopt the muffler purchased directly, as shown in Figure 2 which does not match the racing car well, which makes the noise test result not ideal. Moreover, due to the single exhaust path, it is unable to obtain the best engine power under all working conditions.

Figure 1. Muffler purchased directly

3.2 Research Status in Overseas

The research of muffler abroad began at the beginning of 20th century. It mainly introduces the theory of pipe acoustics and transfer matrix. After many years of practice and exploration, the theory of muffler noise control has developed from the original pure acoustic theory to the present acoustic field and acoustic structure coupling field analysis, forming two basic analysis methods in time domain and frequency domain. Frequency domain methods mainly include plane wave theory, three-dimensional analytical method, finite element method and boundary element method, which are used to solve acoustic control equations in frequency domain.
4. THE RESEARCH CONTENT OF THIS PAPER
Using the simulation software GT-Power to build a complete CBR600 engine system, through the accumulation of literature and experience, using frequency domain analysis method to obtain the basic structure suitable for racing car, and then using the GEM3D modeling module of GT series software, after establishing the model, it is directly dispersed into the GT-suite module. Through setting up the running environment with the real situation, the simulation operation is carried out, and the map diagram shows that the model is feasible by adding the original microphone, the exhaust noise value at a specific speed can be directly obtained. Through the experience accumulated in literature and papers, the structure is improved continuously and the internal structure with the lowest noise is obtained through repeated testing.

After the operation is completed, we can adjust the power torque diagram of the engine in the GT-post module. By changing the internal structure of the muffler, the power and torque will also change correspondingly. A variable schedule structure is designed to make the engine get the best dynamic performance at high and low speed. The way to change the exhaust passage is to add a switchable electric control in the muffler. Valve structure.

Finally, a muffler suitable for FSAE racing car is obtained.

5. THEORETICAL SOURCE AND TECHNICAL BACKGROUND

5.1 Selection of Muffler Structure
The basic types of muffler can be divided into reactive muffler, resistive muffler and impedance composite muffler [1].

5.1.1 Reactive muffler
The principle of the reactive muffler is that when the expansion chamber, resonance chamber and other sound elimination units are composed of internal parts such as pipes and clapboards, the acoustic wave will reflect and interfere when it propagates, so as to reduce the sound energy and achieve the purpose of noise elimination. The frequency band of reactive mufflers is limited, which usually has good effect on low and medium frequency band, but poor at high frequency band. Figure 2 shows the BMW X3M rear muffler.

![Figure 2. The BMW X3M rear muffler](image)

5.1.2 Resistive muffler
The resistive muffler is a kind of muffler which is filled with sound absorption material around the pipe through which the internal exhaust passes to absorb the sound energy and achieve the purpose of noise
elimination. It has good noise reduction effect on medium and high frequency, and it is seldom used for passenger cars only. It is usually combined with reactive muffler.

5.1.3 Impedance composite muffler
Impedance composite muffler is a kind of muffler composed of resistance silencing unit and sound absorption material, which has the common characteristics of resistance and resistance muffler. It has good effect on low, medium and high frequency noise.

After analysis, in order to achieve the best noise reduction effect and increase the back pressure of the exhaust system at low speed, we adopt the impedance composite muffler [2].

5.2 Theoretical Background of Back Pressure Structure
In the design of automobile powertrain, the engine is one of the most important points. There are many factors affecting the engine performance, such as engine displacement, in cylinder stroke, piston diameter, compression ratio, intake form and so on. Among them, the exhaust system has a significant impact on the performance of the engine.

The combustion state of the engine at low speed: due to the low speed, the temperature of the mixture is not high enough, resulting in insufficient combustion of the mixture. Generally, when the speed of gasoline engine is 3000, the combustion is not enough. When the engine is ignited, the piston starts radial force stroke, and the exhaust valve will open before the piston reaches bottom dead center. When the valves overlap, the multi-carbon molecules which do not fully release energy will be squeezed into the intake port and exhaust valve, and then be instantaneously sucked into the cylinder by the piston to participate in the next combustion stroke. Compared with fresh gasoline molecules, the multi carbon molecules left over from the last combustion are easier to ignite because they have fewer carbon chains and smaller molecules. Therefore, under the condition of low speed, the exhaust system without back pressure or too small back pressure (straight through or too smooth exhaust system) will lead to low torque and high fuel consumption. Therefore, most of the original vehicles adopt back pressure exhaust pipe, which mainly depends on the grid muffler in the pipe or the volume change of the pipe to generate a pressure that will return to the cylinder [3].

In the high-speed state, the mixture is fully burned when the engine is running at high speed, which basically produces useless exhaust gas. It is not conducive to the combustion work in the next cycle. When the original factory exhaust is used, the exhaust system will prevent these useless exhaust gases from discharging and produce certain back pressure. Because the exhaust passage is not smooth, a certain amount of useless exhaust gas will be pressed into the intake port when the valves overlap, and then be sucked into the cylinder again. Due to the inhaling of non combustible exhaust gas, the volume (volume) of combustible fresh mixture gas entering the cylinder is reduced. Therefore, at high speed, straight exhaust is more conducive to the dynamic performance of the engine.
Figure 4. Straight through muffler for refitted vehicle

It can be seen from the above that the exhaust with back pressure device is beneficial to the performance of low speed torque, while the straight through exhaust is more conducive to the dynamic performance at high speed.

Figure 5. Variable muffler for performance vehicle

6. DESIGN OF SPECIFIC INTERNAL STRUCTURE

6.1 Technical Route
The technical route of this paper is as follows:
(1) Consulting the data and literature and determining the type of muffler.
(2) Determining the appropriate muffler length and diameter
(3) Determining the internal structure and quantity of anechoic chamber and the volume of expansion chamber
(4) Creating muffler model in GEM3D module of series software
(5) Obtaining The first group of power, torque and noise values by suing simulation calculation
(6) Optimizing the torque performance of the straight type at high speed and the performance of the back pressure type at low speed.
(7) Optimizing the performance under the condition that the noise value meets the standard

6.2 Detailed Research Process

6.2.1 Volume and overall dimensions
According to the formula:
In formula (1), \( V \) is muffler volume, \( n \) is rated engine speed, \( i \) is number of engine cylinders, \( \tau \) is number of strokes, \( V_{st} \) is engine displacement. \( Q \) is the correction coefficient, generally taken as 2 \( \sim \) 6 (the higher the noise elimination effect, the greater the \( Q \) value).

The external dimensions of the muffler should consider other parts of the rear of the car, such as the layout of the rear suspension and the placement of the rear aerodynamic device. In addition to the calculation of muffler volume, the final size of muffler shell is determined as 120mm in diameter and 600mm in length.

### 6.2.2 Internal structure design

According to the engine displacement, we need to determine the total number of cavities [4].

| Muffler type | A   | B   | C   | D   |
|--------------|-----|-----|-----|-----|
| Noise reduction | 10-14 | 15-19 | 20-24 | \( \geq 25 \) |
| Number of chambers | 2-3 | 3-4 | \( \geq 4 \) | \( \geq 4 \) |

According to the requirements, the noise at 3000rpm shall not be higher than 103dB under c-weighting, and the noise at 10500rpm shall not be higher than 110dB under C-weighted. According to the noise without muffler, the muffler type is preliminarily determined as class C, that is, the muffler with four chambers.

According to the formula

\[
V = Q \times n \times V_{st} \times \frac{1}{1000} \times (\tau \times i) \times \frac{1}{2} \tag{1}
\]

Where \( V \) is muffler volume, \( n \) is rated engine speed, \( i \) is number of engine cylinders, \( \tau \) is number of strokes, \( V_{st} \) is engine displacement. \( Q \) is the correction coefficient, generally taken as 2 \( \sim \) 6 (the higher the noise elimination effect, the greater the \( Q \) value).

The external dimensions of the muffler should consider other parts of the rear of the car, such as the layout of the rear suspension and the placement of the rear aerodynamic device. In addition to the calculation of muffler volume, the final size of muffler shell is determined as 120mm in diameter and 600mm in length.

According to the requirements, the noise at 3000rpm shall not be higher than 103dB under c-weighting, and the noise at 10500rpm shall not be higher than 110dB under C-weighted. According to the noise without muffler, the muffler type is preliminarily determined as class C, that is, the muffler with four chambers.

According to the formula

\[
f_k = \frac{knz}{60r}
\]

Where \( f_k \) is the \( k \)-th harmonic frequency, when \( k=1 \), it is the corresponding fundamental frequency. \( n \) is the engine speed, which unit is r/min. \( z \) is the number of internal combustion engine cylinders. \( \tau \) is the stroke coefficient, \( \tau = 2 \) when number of stroke is 4. In addition to the fundamental frequency, the exhaust noise of the second and third harmonics is also obvious. With the increase of the harmonic frequency, the amplitude of the corresponding component becomes smaller and smaller [5].

The corresponding relationship between order and harmonic frequency in noise analysis is as follows:

\[
f_{k\text{order}} = \frac{\tau f_k}{z}
\]

For combustion engine with four strokes and four cylinders, the peak value of exhaust noise occurs at the second, fourth and sixth order frequencies. According to the calculation, the frequencies of 2nd, 4th and 6th order are 200Hz, 400Hz and 600Hz respectively at 3000rpm.

The impedance composite muffler is designed because of the consideration of high frequency and low frequency. Tentatively, the first and fourth cavities are resistance silencing, and the second and third cavities are resistance silencing. The results show that the resistance muffler has good effect on high frequency and poor low frequency; the reactive muffler has good effect on low frequency and poor high frequency.
For the expansion chamber, the larger the expansion ratio, the greater the amount of noise elimination. The number and arrangement of outlet pipes have no effect on the muffler performance below the upper limit frequency, but after the upper limit frequency, the greater the distance between multiple outlets and outlets, the better the muffler performance. Therefore, two outlet pipes and one inlet pipe are arranged in the third chamber of the muffler. At the same time, the muffler performance is optimized. A perforated unit is added to the inlet and outlet pipe of the expansion chamber to further improve the noise elimination effect of the muffler. The two kinds of back pressure structures are shown in Figure 6.

![Figure 6. Back pressure structure](image1)

![Figure 6. Back pressure structure](image2)

Figure 7. Comparison of simulation values

![Figure 7. Comparison of simulation values](image3)
According to the formula:

$$f = \frac{c}{2\pi} \sqrt{\frac{\varepsilon}{t(d + 0.8r)}}$$ (4)

Where $c$ is the local sound velocity, $\varepsilon$ is the perforation rate of the perforated section, $t$ is the length of the perforated section, $d$ is the thickness of the perforated pipe, $r$ is the perforation radius (m). Through calculation, the hole diameter is 4 mm, the perforation rate is 20%, and the length of perforation section is 100 mm.

For resonators, Helmholtz resonators follow the following formula:

$$f_r = \frac{c}{2\pi} \sqrt{\frac{G}{V}}$$ (5)

$c$ is sound velocity, $c = 340 \text{ m/s}$. $V$ is chamber volume, $V = 0.1695 \text{ m}^3$. $G$ is conductivity, a physical parameter with length dimension, which is defined as the ratio of sectional area of cervical foramen to effective length, as follows:

$$G = \frac{S_c}{t_c}$$ (6)

$t_c$ is the effective length of the connecting short pipe, $t_c = t + \frac{md}{4}$, $d$ is the inner diameter of the connecting pipe, $S_c$ is the cross-sectional area of the connecting short pipe.

The length of the resonant chamber is 200 mm, the inner diameter of the connecting pipe is 40 mm and the length of the connecting pipe is 3.1 mm.

Finally, in order to enhance the effect of noise reduction in low frequency region, a bend pipe is added at the exit of the last expansion chamber to further optimize the noise elimination effect. At the same time, the space is used to make the fourth chamber more easily arranged.

![Figure 8. Final design of muffler structure](image)

6.2.3 Function summary of structure

The first chamber: filled with silencing cotton, which is of pure resistance structure, is used to absorb the energy from the high-speed exhaust sound wave of the engine. Silencing cotton is the most suitable material for calculation and simulation [6].

The second chamber: expansion cavity, using the sudden increase of cross-sectional area, disturbs the air flow and counteracts the acoustic energy.

The third chamber: back pressure chamber, used to improve exhaust back pressure, improve the torque performance of the engine at low speed.

The fourth chamber: it is still a pure resistive structure, absorbing noise energy.
At the same time, the influence of exhaust back pressure on engine power performance should be considered deeply, and the noise should not be reduced simply at the cost of sacrificing output power.

6.2.4 Simulation test results
The noise reduction effect of the muffler is obvious, which meets the target of 100 dB under 3000 rpm mentioned in the design goal. The final test result is 98 dB, and the test value of noise at high speed is 102 dB, which is far lower than the formula rule standard of college students. The structure of the reactive muffler is beneficial to the noise isolation of high to high frequency, and the sound absorption material can effectively absorb the energy of exhaust. The designed expansion cavity can disturb the air flow and counteract the acoustic energy by using the sudden increase of cross-sectional area. The noise elimination effect is remarkable.

It can be seen from the analysis that the back pressure muffler channel can increase the torque by 8%. However, in the case of high speed, the torque increase caused by the straight through exhaust is relatively small, but it is reflected in the power. There is a difference of 1 horsepower at 10000 rpm. Straight exhaust is more conducive to engine power output.

![Comparison of noise values](image1)

**Figure 9.** Noise comparison before and after adding muffler

![Torque comparison](image2)

**Figure 10.** Torque comparison before and after adding muffler

7. Realization of Key Technologies
Using GEM3D module, the three-dimensional model of muffler was successfully established, and the internal structure of muffler calculated by theory was successfully established as a model, and it was discretized into two-dimensional diagram, which was imported into GT-Suite for simulation [7].
Clicking on the shell, selecting shellcuff, and setting the first partition plate to be 100 mm away from the outer circular surface of the muffler.

After selecting the partition, clicking the officebuffle option to punch the partition. Selecting a circle of appropriate size in the Cross Section and the appropriate hole location in the location below. When the selection is complete, the required vent will appear in the model.
After selecting the round pipe, clicking the OrificePipe option, entering 1 in the origin diameter, and selecting the distance between the circular plate and the pipe to generate a circular diaphragm.

Selecting the straight pipe and clicking the perfref option, selecting the appropriate punching rate and length. The designed punching area can be obtained.
If we choose a reasonable size of discretization and the grid is too small, the internal structure will not be covered completely. If the grid is too small, it will slow down the process of discretization and calculation and lose efficiency. Therefore, it is very important to choose the appropriate size of the grid.

WUT team of Wuhan University of Technology has GT-Power model of CBR600 engine. According to the debugging of team members in recent years, the error between simulation data and actual test data has been controlled within 3%. Therefore, after the muffler model is integrated into the engine model, the data obtained are completely credible.
Open the discrete 2D structure diagram of muffler in ST-ISE and connect it after the exhaust pipe.

By setting the microphone components, the noise reduction effect can be tested intuitively. According to the test requirements of the competition, the muffler is arranged 50 cm away from the exhaust outlet and 45° away from the outlet.
After setting, the simulation steps are carried out, and the simulation parameters are set. The simulation operation point is from 3000 rpm to 16000 rpm, and a case is set every 500 rpm. The ambient temperature is set at 400 k to simulate the temperature of the exhaust air when the engine is running.

Figure 20. Setting of simulation situation

Figure 21. Setting of simulation process
Figure 22. Setting of GT-Post results

Setting the simulation step size to 20 steps per cycle and selecting the default periodic option. The simulation is carried out according to the above settings.

After the simulation is finished, open the result file automatically generated after simulation in GT-Post, which is convenient to view the effect after adding muffler, establishing XY coordinate diagram, setting abscissa as speed RPM, ordinate as total noise value with C-weighted.

Finally we get a noise curve, according to the requirements of the race and the team's goal, analyze whether the results meet the standard.

8. ENTITY TEST

According to the design of the software, the team purchased materials for processing, produced the same physical object as the design sample, and put it into the 2020 racing car for testing.

Figure 23. Entity processing
Through practical reference, design and simulation, we know that exhaust muffler has a very significant effect on the noise reduction of internal combustion engine, and its internal structure design is very important in this process. For a high-performance racing car, the muffler should have the internal structure of resistance resistance combination to achieve the ideal noise reduction effect. At the same time, we should pay attention to the coupling analysis with the engine power. We can not blindly reduce the noise at the expense of the engine torque and power. Through the experimental analysis, we know that a certain resistance structure can reduce the noise and improve the torque of the engine at low speed, and in the case of high speed, the resistant silencing cotton plays a very important role in noise reduction.

9. PROSPECT ANALYSIS
With the progress of domestic FSC, more and more new technologies are used, and more scientific research and design are practiced in each team's racing cars. In order to meet the needs of racing cars and obtain better noise test results, more teams begin to design mufflers by themselves and use advanced software similar to GT power for simulation calculation.

Internal combustion engine muffler design in China started too late. College students participate in muffler design in the learning stage can be conducive to their own hands-on ability and scientific research ability, which is also more conducive to the development of the whole industry.

REFERENCES
[1] J. Zeng, L. Liao, Z. Wang, et al. “Effect of Geometric Structure Parameters on the Acoustic Performance of Automobile Engine Exhaust Muffler,” Journal of East China Jiaotong University, vol. 34, pp.116-123, 2017.
[2] J. Zhang. “Optimization Design of Automobile Exhaust Muffler Based on GT-Power,” Agricultural Equipment & Vehicle Engineering, vol. 55, pp.78-81, 2017.
[3] J. Ma, J. Liu, H. Chen. “Study in Influence of Valve Overlap Angle on Engine Performance,” Modern Vehicle Power, vol. 1, pp. 32-38, 2017.
[4] S. Biswas, "Combination muffler is more effective than reactive muffler even in small size," Frontiers in Automobile and Mechanical Engineering -2010, Chennai, 2010, pp. 344-349.
[5] G. Cui, S. Qiu. “Research on Engine Exhaust Order Noise Control,” Small Internal Combustion Engine and Motorcycle, vol. 48, pp. 63-68, 2019.
[6] C. Tian, X. Hou, Z. Liu, et al. “The Effect of Noise Absorption Material on Muffler,” Automobile Science & Technology, vol. 6, pp. 8-10, 2008.
[7] X. Hou, T. Wang, C. Tian, et al. “Design of Passenger Vehicle Muffler Based on GT-Power,” Transactions of Beijing Institute of Technology, vol. 30, pp. 161-165, 2010.