Research on Computational Data Simulation of Automobile Engine Exhaust Muffler Performance

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Abstract. In this paper, the transfer matrix method is used to simulate and calculate the insertion loss of muffler. This simulation method can evaluate the acoustic characteristics of the exhaust system. After deriving the transfer matrix of six kinds of silencing units, it is applied to the calculation of insertion loss. In this paper, a mathematical model of noise attenuation is established to analyze the relationship between the characteristics of muffler and acoustic attenuation. We can take the noise reduction as the objective function to optimize the muffler design. The mathematical model of pressure loss can be used to evaluate the aerodynamic performance of muffler.

Keywords: Engine, Exhaust muffler, Data simulation,

1. Introduction

With the gradual progress of automobile technology and people's increasing attention to environmental protection, the noise control of automobile has become an important topic of environmental protection research of automobile technology[1]. Engine noise is the main source of automobile noise. We should actively carry out the research on the noise measures of the main noise sources of the engine. In this way, it is beneficial to raise the noise index of our country to the advanced level of the world[2].

At present, the design of muffler basically adopts the method of experimental research. The researchers designed several mufflers and put them on the car for experiments. The muffler that satisfies the requirements will be kept and the rest will be thrown away. Obviously, this method is lack of optimization design and waste of human and material resources[3]. Therefore, we can use advanced computer simulation technology to complete the design of muffler on the basis of improving the theoretical model of muffler[4]. This method has very important practical significance in the design of muffler.
2. Evaluation index of muffler

2.1. Evaluation index of noise elimination performance

① Insertion loss “$$L_{IL}$$”

It is defined as the difference of counting sound level measured at a fixed measuring point before and after the installation of muffler:

$$L_{IL} = L_{p1} - L_{p2}$$  \hspace{1cm} (1)

Among them, $$L_{p1}$$ and $$L_{p2}$$ are the counting sound level measured at a certain measuring point before and after the installation of muffler.

② Transmission loss “$$L_{TL}$$”

It is defined as the difference between the sound power levels at the inlet and outlet of the muffler[5]. It can reflect the ratio of the incident sound energy at the muffler inlet to the set sound energy at the outlet:

$$L_{TL} = 10 \cdot \log_{10} \left( \frac{W_1}{W_2} \right) = L_{w1} - L_{w2}$$  \hspace{1cm} (2)

$$W_1$$ and $$W_2$$ are the sound power at the inlet and outlet of muffler

$$L_{w1}$$ and $$L_{w2}$$ are the sound power levels at the inlet and outlet of the muffler

③ Noise elimination “$$\Delta L$$”

It is defined as the difference between the upper and lower sound pressure levels of the muffler[6]. It can reflect the ratio of inlet sound pressure and outlet sound pressure of muffler:

$$\Delta L = 20 \cdot \log_{10} \left( \frac{P_r}{P_c} \right) = L_{pr} - L_{pc}$$  \hspace{1cm} (3)

$$P_r$$ and $$P_c$$ are the inlet sound pressure and the outlet sound pressure of the muffler

$$L_{pr}$$ and $$L_{pc}$$ are the inlet and outlet sound pressure levels of Silencers

2.2. Evaluation index of power loss

In order to investigate the influence of exhaust muffler on engine performance, we can use the power loss ratio to evaluate them. Power loss ratio:

$$R_P = \frac{N_{\dot{e}1} - N_{\dot{e}2}}{N_{\dot{e}1}} \cdot 100\%$$  \hspace{1cm} (4)

$$p_1$$ and $$p_2$$ are the power of the engine without muffler under the standard condition and the power with muffler

3. Mathematical model of muffler's noise reduction

After calculating the inlet and outlet sound pressure in the above equation, we can calculate the muffler’s sound attenuation according to the sound pressure distribution inside the muffler. According to one-dimensional linear acoustic theory, we can calculate the pressure amplitude of the whole system according to the conservation of mass, energy and momentum.
3.1. The transmission of sound waves at the sudden expansion

The air flow at the sudden expansion is very complicated. Its boundary changes very slowly. According to the conservation principle, we can derive the conservation equations of mass, energy and momentum:

\[ [(1 + M)p_1^+ - (1 - M)p_1^-]s_1 = (s_2 + s_1M)p_2^+ - (s_2 - s_1M)p_2^- + \delta M \]
\[ [(1 + M)p_1^+ + (1 - M)p_1^-] \frac{1}{\rho_1} = [(1 + M)p_2^+ + (1 - M)p_2^-] \frac{1}{\rho_2} \]  
\[ [(1 + M)(M + 2)p_1^+ + [1 + M(M - 2)]p_1^-]s_1 + (p_2^+ + p_2^-)s_3 = [M(M + 2)p_2^+ + M(M - 2)p_2^- + \delta M^2]s_1 + (p_2^+ + p_2^-)s_2 \]

\( \rho_1 \) and \( \rho_2 \) are the average air density. \( \delta \) is a dissipative term.

3.2. The transmission of sound waves at the point of sudden contraction

The sudden contraction accords with isentropic condition. Therefore, the conservation equations of mass and energy are respectively:

\[ [(1 + M)p_1^+ - (1 - M)p_1^-]s_1 = (s_2 - s_1M)p_2^+ - (s_2 - s_1M)p_2^- \]
\[ [(1 + M)p_1^+ + (1 - M)p_1^-] \frac{1}{\rho_1} = [(1 + M)p_2^+ + (1 - M)p_2^-] \frac{1}{\rho_2} \]  
\[ [(1 + M)(M + 2)p_1^+ + [1 + M(M - 2)]p_1^-]s_1 + (p_2^+ + p_2^-)s_3 = [M(M + 2)p_2^+ + M(M - 2)p_2^- + \delta M^2]s_1 + (p_2^+ + p_2^-)s_2 \]

3.3. Sound wave transmission at the place of sudden contraction of endotracheal tube

The conservation equations of mass and energy are:

\[ (1 + \frac{s_1}{s_2}M - \frac{1 - r_s s_2}{1 + r_s s_2})p_3^+ - (1 - \frac{s_1}{s_3}M + \frac{1 - r_s s_3}{1 + r_s s_3})p_3^- = [(1 + M) - r_1(1 - M)]p_1^+ \frac{s_1}{s_3} \]
\[ (1 + M)p_3^+ + (1 - M)p_3^- = p_1^+ [(1 + M) + r_1(1 - M)] \]

3.4. Acoustic wave transmission in the place of sudden expansion of endotracheal tube

The gas flow at the sudden expansion of the cross section is very complex, which does not satisfy the isentropic condition. Therefore, we can assume that the mutation of cross section is a non-isentropic process. Therefore, the conservation equations of mass, energy and momentum are:

\[ (1 + M + \frac{s_4}{s_5}1 - r_a) \frac{p_5^+}{s_5^1 + r_a} - (1 - M - \frac{s_4}{s_5}1 - r_a) \frac{p_5^-}{s_5^1 + r_a} = \left[ (1 + M) - \frac{s_5}{s_5^1}M \right]p_3^+ - \left( 1 - \frac{s_5}{s_5^1}M \right) \frac{p_3}{s_5} \]  
\[ (1 + M)p_5^+ + (1 - M)p_5^- = (1 + M)p_3^+ + (1 - M)p_3^- - \frac{\delta}{\gamma - 1} \]

4. Mathematical model of insertion loss

The insertion loss is mainly used as the evaluation standard of muffler performance in vehicle engine. This index can reflect the characteristics of sound source, muffler and radiation impedance. The outline of rigid straight pipe is shown in Fig 1. When using the transfer matrix method to derive the
mathematical model of insertion loss, we need to make the following basic assumptions:

1. The propagation of sound wave in medium has no energy loss and medium is ideal gas.
2. The muffler is composed of a rigid wall and the sound wave will not transmit outward along the pipe wall.
3. The gas flow in the muffler is uniform.
4. The sound pressure is far less than the static pressure and the vibration speed of the particle is far less than the sound propagation speed

Mathematical model of insertion loss:

\[
IL = 20 \log \left( \frac{AZ_r + B \rho c + Z_a(CZ_r + D \rho c)}{AZ_r + B \rho c + Z_a(CZ_r + D \rho c)} \right)
\]

\(Z_a\) is the source impedance
\(Z_r\) is the tailpipe radiation impedance

\[
\Delta p_1 = \varepsilon \rho V^2 / 2
\]

\(\varepsilon\) is the local resistance coefficient

The loss of frictional resistance occurs on the pipe wall of muffler. Its size depends on the roughness of the pipe wall and the flow rate. Its expression is:

\[
\Delta p_2 = \rho y t v^2 / 2d
\]

5. Prediction of pressure loss
After meeting the requirements of insertion loss and noise reduction of muffler, we also need to predict the pressure loss to evaluate the aerodynamic performance of muffler. The magnitude of local pressure loss depends on the form of local structure, pipe diameter and air velocity. Its expression is:

\[
\Delta P_1 = \varepsilon \rho V^2 / 2
\]

6. Optimum design of muffler
By optimizing the structure parameters of muffler, the best noise reduction effect can be achieved with the smallest volume and the lowest cost. We can set the sound pressure level of the frequency band at the entrance of the muffler as \(L_{RI}\), and the sound pressure level of the frequency band at the exit as \(L_{Rf}\). The synthetic sound pressure level at the inlet is:
\[ L_R = 10 \log \sum_{i=1}^{n} 10^{L_{Ri}/10} \]  

(12)

The resultant sound pressure level at the outlet is

\[ L_C = 10 \log \sum_{j=1}^{n} 10^{L_{Cj}/10} \]  

(13)

Therefore, the objective function is:

\[ f(X) = L_Z = L_R - L_C \]  

(14)

Due to the limitation of installation space, muffler weight, material and manufacturing cost, the volume of muffler should be as small as possible and the structure should be as compact as possible. Therefore, the upper limit of muffler volume is:

\[ V = \frac{6 \times 2400}{1000} (\sqrt[4]{4 \times 4})^{-1} \times 1.809 = 6.51 \]  

(15)

7. Simulation and experimental verification of muffler performance

7.1. Performance calculation of muffler and development of optimization design program

The calculation of acoustic performance includes: calculation of insertion loss and calculation of noise reduction. The calculation of aerodynamic performance includes the calculation of local pressure loss and the calculation of pressure loss along the way. The main function of the program optimization design is to reduce the volume of muffler, reduce the cost of muffler, improve the noise reduction and reduce the worst frequency band.

7.2. Performance test of muffler

The performance test of exhaust muffler is carried out in accordance with the provisions of national standards. In the manufacturing process of muffler, we should make every effort to make the muffler conform to the requirements of all aspects of the design drawings (see Table 1). In this experiment, firstly, the noise of the diesel engine is shielded. At the rated speed, we need to measure the sound pressure level of exhaust noise frequency band of equal length straight pipe. The engine runs steadily at rated speed. After the oil temperature and water temperature are stable, we can measure the insertion loss. The spectrum is shown in Fig 2.

Table 1. Insertion loss of four kinds of mufflers

| Type of muffler | Center frequency of octave |
|----------------|---------------------------|
|                | 500 | 1000 | 2000 | 4000 | 8000 |
| A              | 28.8| 26.5 | 24.0 | 25.6 | 22.5 |
| B              | 25.0| 20.8 | 20.3 | 24.1 | 18.1 |
| C              | 21.2| 22.0 | 18.9 | 22.5 | 20.5 |
| D              | 26.6| 25.5 | 23.5 | 27.6 | 26.7 |
8. Conclusion
Through this test, we found that the exhaust noise of the car has an important impact on the noise in the car. It can be seen that the application of computer simulation technology provides a new way for the study of muffler characteristics.

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