Acoustic-structure Coupling Analysis and Optimization of Muffler

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Abstract. While the muffler attenuates the noise, the structure also withstands the impact of the airflow, in order to explore the influence of this acoustic-structure interaction on the silencing performance of mufflers. Modal superposition method is used to calculate the transmission loss of diesel exhaust muffler considering acoustic-structure coupling. The results show that the average transmission loss under acoustic-structure coupling decreases by 7.4%. The transmission loss changes abruptly in varying degrees, and the stability of muffler is seriously affected. By stiffening the dominant mode shape at the maximum frequency point of the coupling loss reduction, the transmission loss under the influence of acoustic-solid coupling is improved and the performance of muffler is strengthened.

1. Introduction

Muffler is widely used in intake and exhaust noise control of automobiles, diesel generators [1-2]. The acoustic performance of mufflers is usually described by transmission loss. Resistant mufflers are usually made of thin steel plates, when the airflows passes, the interaction between the external structure and the internal acoustic field is easy to occur, which affects the transmission loss and the performance of the muffler. Therefore, in order to reflect the actual situation of muffler more accurately, the structure and internal acoustic field of muffler should be considered simultaneously in the design and research.

At present, the research on muffler mainly focuses on the study of its exhaust noise [3-4], but there is less research on the acoustic-solid coupling of muffler. Qian Zhongchang [6] analysed the influence of fluid-structure coupling on water muffler by direct coupling method; Liu CP [5] discussed the structure-acoustic finite element coupling equation of muffler. However, there is no discussion on the change of the specific muffler performance and how to improve the muffler under the action of acoustic-structure coupling in the above article.

In this paper, a diesel engine exhaust muffler model is designed as the research object. The modal superposition method is used to calculate the exact transmission loss due to its acoustic-structure coupling effect, and further optimization measures are proposed. It provides theoretical guidance and reference for the design, use and subsequent research of muffler.
2. Model and Theory

2.1. Structure model
A diesel engine is a single-cylinder four-stroke; the displacement is 1.472 L; the rated speed is 2200 r/min, and the exhaust pipe diameter is 45 mm. According to this condition, the designed muffler expansion ratio is selected as 13; the aspect ratio \( i \) is selected as 3 according to the recommended value, and the volume is determined according to Equation 1. The total muffler structure is shown in Figure 1 and the structural parameters are table 1.

\[
V_m = \frac{QnV_L}{1000 \sqrt{\tau Z}}
\]  
(1)

Where, \( Q \) is the correction coefficient related to the muffler effect, \( n \) is the engine speed, \( V_L \) is the engine displacement, \( \tau \) and \( Z \) are the stroke and number of cylinders.

![Muffler structure](image)

**Figure 1. Muffler structure**

| Structural parameters | Dimensions (mm) | Structural parameters | Dimensions (mm) |
|-----------------------|-----------------|-----------------------|-----------------|
| \( L \)               | 400             | \( d \)               | 45              |
| \( L_1 \)             | 70              | \( L_2 \)             | 135             |
| \( L_3 \)             | 100             | \( L_4 \)             | 70              |
| \( a \)               | 83              | \( b \)               | 249             |

2.2. Acoustic-structure Coupling Basic equations
In the calculation of the acoustic-solid coupling transfer loss of the muffler, the integral coupling control equation of the system under the acoustic-structure coupling system is obtained by discrete calculation of the acoustic and structural control equations. Then, the structural unit displacement of the coupled system and the acoustic unit sound pressure are obtained by the modal superposition method. Thus calculating the transmission loss under the coupled system.

In the acoustic-structure coupling system, the acoustic field discrete wave equation of the fluid domain considering the domain action is as follows:

\[
\left[ M_s \right] \{ \dot{P}_s \} + \left[ C_s \right] \{ \dot{P}_s \} + \left[ K_s \right] \{ P_s \} = \{ F_s \} + \{ F_s^f \}
\]  
(2)

Where, \( M_s \) is the gas equivalent mass matrix; \( C_s \) is the gas equivalent damping matrix; \( K_s \) is the gas equivalent stiffness matrix; \( U \) is the gas unit node sound pressure matrix; \( P_s \) is the fluid unit node sound...
pressure vector; $F_S$ is the applied fluid load vector, $F_S^f$ is the force of the structural domain acting on the coupling surface.

Similarly, after considering the vibration effect of acoustic pressure on the structure, the structural control equation is:

$$\begin{bmatrix} K_f \end{bmatrix} \{X_f\} + \begin{bmatrix} C_f \end{bmatrix} \{\dot{X}_f\} + \begin{bmatrix} M_f \end{bmatrix} \{\ddot{X}_f\} = \{F_f\} + \{F_s^f\}$$  \(3\)

Where: $M_f$ is the structural mass matrix; $C_f$ is the structural damping matrix; $K_f$ is the structural stiffness matrix; $F_f$ is the structural external excitation force; $X_f$ is the displacement of the external system node matrix; $F_s^f$ is the acoustic fluid domain acting on the coupling surface.

System can be calculated by linear superposition of various modes of vibration modes and acoustic modes:

$$\{X_f\} = \{\psi_f\} \{\xi_f\}$$  \(4\)
$$\{P_s\} = \{\psi_s\} \{\xi_s\}$$  \(5\)

Where, $\xi_f$ is the structure modal participation factor, $\xi_s$ is the acoustic modal participation factor; Combining equations (2) ~ (5). The coupling matrix is represented by a unified matrix:

$$\begin{bmatrix} m_f & 0 \\ \rho r_s^T & m_s \end{bmatrix} \begin{bmatrix} \ddot{\xi}_f \\ \ddot{\xi}_s \end{bmatrix} + \begin{bmatrix} c_f & 0 \\ 0 & c_s \end{bmatrix} \begin{bmatrix} \dot{\xi}_f \\ \dot{\xi}_s \end{bmatrix} + \begin{bmatrix} k_f & -r_s \\ 0 & k_s \end{bmatrix} \begin{bmatrix} \xi_f \\ \xi_s \end{bmatrix} = \begin{bmatrix} f_f \\ f_s \end{bmatrix}$$  \(6\)

Where, $\{m_f\} = \{\psi_f\}^T \{M_f\} \{\psi_f\}; \{c_f\} = \{\psi_f\}^T \{C_f\} \{\psi_f\}; \{k_f\} = \{\psi_f\}^T \{K_f\} \{\psi_f\};$

$\{m_s\} = \{\psi_s\}^T \{M_s\} \{\psi_s\}; \{f_f\} = \{\psi_f\}^T \{F_f\}; \{c_s\} = \{\psi_s\}^T \{C_s\} \{\psi_s\};$

$\{r_s\} = \{\psi_f\}^T \{R_s\} \{\psi_s\}; \{f_s\} = \{\psi_s\}^T \{F_s\}; \{k_s\} = \{\psi_s\}^T \{K_s\} \{\psi_s\}.$

3. Calculation and Analysis

The structural grid and acoustic grid of the muffler are processed in hyper mesh. For acoustic grid, the size of the largest grid needs to be less than 1/6 of the minimum wavelength of the calculated frequency. The muffler structural material is Q235-A steel, density $\rho=7860$ kg/m$^3$, Poisson's ratio $\mu=0.288$; Young's modulus $E=2.01$ GPa.
3.1. Transmission Loss calculation
Muffler calculation condition setting: the inlet boundary is defined as the unit particle velocity of 1 m/s; the outlet of the muffler is defined as the characteristic impedance $\rho c$, indicated that there is no reflection of any wave at the end of the pipe.

![Graph](image)

**Figure 3.** Comparison of coupling transmission loss

From Fig.3. Under the acoustic-structure coupling effect, the overall anechoic frequency band does not change, but there is a sudden change in transmission loss at different frequency points. Such as 548Hz, the transmission loss value from 39.29dB mutation to 77.03dB, the increase of 96%; the transmission loss at 680 Hz is changed from 46.53 dB to 3.44 dB, a decrease of 92.6%. In the whole frequency band, the average transmission loss under coupling is 17.91 dB, which is 1.32 dB and 7.4% lower than that without coupling. Although the overall average transmission loss of the muffler is not greatly reduced, the sudden increase and decrease of the muffler at different frequency points affects the stability of its use. At the same time, the sudden decrease of the transmission loss of some frequency segments and frequency points causes problems such as screaming, thus affecting Overall noise reduction performance.

3.2. Structure Optimization
In order to improve the stability of the muffler performance, it is necessary to improve the sudden change of the transmission loss. In Figure 3, the maximum frequency point of the transmission loss mutation is 680 Hz, a decrease of 92.6%. In order to analyse the dominant mode generated by the acoustic-structure coupling at this frequency point, the structural mode and acoustic mode participation factor at 680 Hz are extracted as shown in Fig. 4.
As shown in Fig. 4. The multi-order acoustic modes are involved in the acoustic-structure coupling, and the 1th-order and 7th-order acoustic modes contribute a large amount. Only the 5th-order structural mode has the greatest influence on the structural mode, and the other various structural modes have almost no effect on this point. Therefore, the 5th-order structural mode at 680Hz is the dominant mode. If the mode structure mode can be suppressed or improved, it can play a key role in the coupling effect of transmission loss. Extract the 5th-order structural mode shape diagram (Figure 5).

From figure 5. The fifth mode structure mode main mode occurs at the large wall surface on both sides of the muffler expansion cavity. Therefore, the reinforcement process is performed in the middle of the muffler expansion chamber. The height of the rib is 3mm and the thickness is 5mm; the first rib is 125mm from the exit end face, and the distance between the three bars is 75mm. The summary structure is shown in Figure 6. The optimized coupling transfer loss comparison is shown in Figure 7.
Comparing the transmission loss before and after optimization, it can be seen that after the muffler is reinforced, many mutations in the transmission loss before optimization are improved. Only a small display mutation occurred in the transmission loss in the full frequency band, and the muffler transmission loss curve tends to be flat and stable, indicating the effectiveness of the reinforcement treatment.

4. Conclusion

(1) Under the action of acoustic-structure coupling, the transmission loss will be abrupt at different frequency points, the maximum mutation amplitude can reach 96%, and the average transmission loss is reduced by 7.4%. This sudden change in frequency points severely affects the stability of the overall use of the muffler. Therefore, it should be taken into account in the design analysis of the muffler.

(2) The abrupt change of transmission loss caused by frequency point is due to the dominant mode of a certain order. Structural reinforcement at the occurrence of dominant mode can effectively improve the effect of acoustic-structure coupling on transmission loss and improve the performance of muffler.

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