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The research on semi-active muffler device of controlling the exhaust pipe's low-frequency noise

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ABSTRACT

In order to control low frequency noise in exhaust pipe, this paper puts forward a new concept of H-Q tube based semi-active muffler device. The semi-active muffler device and bench testing system have been designed and operated. Finite element simulation study on semi-active muffler and experimental study on semi-active muffler and passive muffler have been carried on. The effect of simulation and experiment are consistent. The semi-active muffler device acts well in low frequency band, especially between 50 Hz and 150 Hz. The average level of noise reduction is around 35 dB, which is much better than passive muffler. Between 150 Hz and 350 Hz, semi-active muffler has a better performance than passive muffler; above 350 Hz, it has worse performance compared with the passive muffler.

1. Introduction

In spite of the convenience of car travelling, the noise produced by car bother both drivers and passengers. Car noise not only lower the ride comfort, but also easily stress drivers out, cause agitation, fatigue and distraction, etc. It is harmful to human health, and buries hidden dangers for riding safety.

Mounting researches showed that the noise in cars is mainly under 200 Hz, which has bad influence on ride comfort. This noise mainly comes from low frequency noise of internal combustion engine. High pressure cylinder gas erupts and impacts exhaust pipe near gas valve while internal combustion engine exhaust valve open. The pressure wave generated by drastic changes in barometric will stimulate low frequency noise.

Choosing a suitable muffler is vital to control noise in cars, especially for diesel trucks and large buses. The roaring during travelling not only have negative effects on drivers and passengers, but also pollute environment severely. Traditional passive muffler has a good performance on middle and high frequency noise. But it has a poor performance on low frequency noise. Active noise reduction technology by introducing a secondary sound source makes it generate an opposite phase sound wave to interfere noise wave destructively. It has a good performance on noise reduction [1,2]. However, if the airflow is hot and corrosive, components such as error sensors and secondary sound sources of active muffler device which are exposed to the air will easily get damaged. Moreover, in order to generate a high power and low frequency secondary sound wave, the secondary sound source size is inevitable larger, which will occupy rather larger space in actual use.

Based on above analysis, in order to solve the poor performance of passive muffler in low frequency noise reduction and technical problems in active muffler such as complex, fragile. In this paper, a new H-Q tube based semi-active muffler device is designed and operated, and the finite element simulation and experimental study are carried on [3,4]. In addition, in order to evaluate advantages and disadvantages of the semi-active muffler device objectively, the noise reduction performance of passive muffler is also studied and comparatively analyzed in this paper.

2. Noise reduction mechanism of semi-active muffler device

When two same frequency sound waves meet in the space, the necessary interference condition is: (1) same frequency; (2) fixed phase difference. There are various kinds of wave interference. If two opposite phase waves interfere, then it will cause minimum amplitude, that is fully destructive interference. The concept of H-Q tube is put forward based on one-dimensional wave fully destructive interference theory. The structure shows in diagram 1. Sound waves at position I separate into two parts, move forward respectively in the main tube and bypass tube, and then flow together at position II [5,6]. If two sound waves have same pressure

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but opposite phase at junction, they will offset and eliminate noise completely.

As shown in Fig. 1, A is cross sectional area of tube. P is sound pressure amplitude. L is sound wave path length. "+" means sound waves move forward in the tube, and "−" means the reflected wave move on the opposite way. According to the continuity of sound pressure in the acoustic boundary condition, sound pressure balance equation at position I is

$$P_{1+} + P_{1-} = P_{2+} + P_{2-} = P_{3+} + P_{3-} \tag{1}$$

Sound pressure balance equation at position II is

$$P_{2+}e^{-ikl_2} + P_{2-}e^{ikl_2} = P_{3+}e^{-ikl_3} + P_{3-}e^{ikl_3} = P_{4+} + P_{4-} \tag{2}$$

According to the conservation of the volume flow in the tube, the volume flow balance equation at position I is

$$\mathrm{A}_1(P_{1+} - P_{1-}) = \mathrm{A}_2(P_{2+} - P_{2-}) + \mathrm{A}_3(P_{3+} - P_{3-}) \tag{3}$$

Volume flow rate balance equation at position II is

$$\begin{aligned} A_4(\mathrm{P}_{4+} - P_{4-}) = A_2\left(\mathrm{P}_{2+}\mathrm{e}^{-ikl_2} - P_{2-}\mathrm{e}^{ikl_2}\right) \\ + A_3\left(\mathrm{P}_{3+}\mathrm{e}^{-ikl_3} - P_{3-}\mathrm{e}^{ikl_3}\right) \end{aligned} \tag{4}$$

Sound transmission loss on H-Q tube is

$$TL = 10\log_{10}\left|\frac{P_{1+}}{P_{4+}}\right|^2 \tag{5}$$

To sum up Eqs. (1)–(3), as there is no reflection at the exit of the tube, where the reflected sound pressure is $P_{4-} = 0$. The cross sectional area of the inlet and outlet of tube is equal, $A_1 = A_4$, so

$$\frac{P_{1+}}{P_{1-}} = -\frac{A_2\alpha_2 + A_3\alpha_3}{A_1} + \frac{(A_1 + A_2\Phi_2 + A_3\Phi_3)^2}{4A_1(A_2\alpha_2 + A_3\alpha_3)} \tag{6}$$

where

$$\alpha_j = \frac{e^{-ikl_j}}{1 - e^{-2ikl_j}}, \quad \Phi_j = \frac{1 + e^{-2ikl_j}}{1 - e^{-2ikl_j}}, \quad k = \frac{2\pi f}{c_0}$$

f: frequency of sound wave, c_0: the speed of sound.

The formula (6) into (5), the sound transmission loss of expression of H-Q could be obtained for

$$TL = 10\log_{10}\left|-\frac{A_2\alpha_2 + A_3\alpha_3}{A_1} + \frac{(A_1 + A_2\Phi_2 + A_3\Phi_3)^2}{4A_1(A_2\alpha_2 + A_3\alpha_3)}\right|^2 \tag{7}$$

By formula (7), to get the maximum attenuation performance of equal cross sectional area H-Q tube, that means two different paths waves have opposite phase at junction. It requires [7–11]

$$\mathrm{f}_m = \left(m - \frac{1}{2}\right)\frac{c_0}{L_3 - L_2}, \quad m = 1, 2, 3\ldots \tag{8}$$

or

$$\mathrm{f}_\mathrm{n} = \mathrm{n}\frac{c_0}{L_3 + L_2}, \quad n = 1, 2, 3\ldots \tag{9}$$

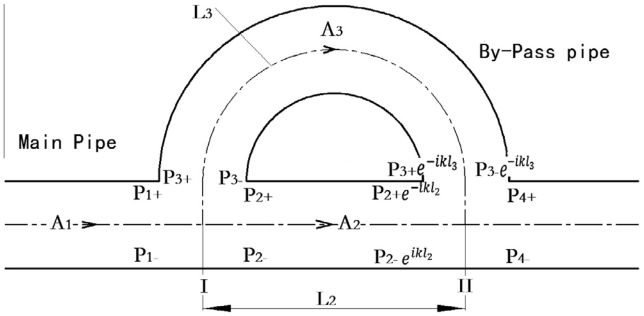

Fig. 1. The schematic diagram of H-Q pipe.

3. Structure designing and operation processing of semi-active muffler device

The semi-active muffler device presented in this paper was achieved by the following technical scheme: As shown in Diagram 2, a sensor connected with a controller by wire was set up at the entrance, and the controller was connected with stepper motor and the electromagnetic valves. The output shaft of the stepping motor was connected to the reciprocating screw, whose screw nut was connected with a shifting fork which was connected with the end of the two telescopic bypass tubes of the movable tube. Bearing supported both sides of reciprocating screw. A dissipative muffler was installed at the exit to eliminate middle and high frequency noise. Four branch bypass tubes, the number of which can be increased or decreased according to the noise frequency component that is going to be eliminated.

The sensor at entrance sampling the frequency of noise signal and pass it to controller. According to formula (8) and (9), Corresponding path difference can be calculated by controller and can be achieved by adjusting closed position of solenoid valve and bypass tube telescopic length. The sound wave from entrance into main tube partially go into bypass tube at position I, partially move forward along the main tube, then flow together at position II. The two opposite phase waves offset due to fully destructive interference, so as to eliminate noise.

As to this semi-active muffler device, the path difference of main tube and bypass tube can be changed rapidly by adjusting bypass tube solenoid valve. The length of telescopic bypass tube can be adjusted precisely by step motor and screw. Path difference can be changed rapidly and accurately corresponding to the changing of noise frequency by connecting branch bypass tube and telescopic bypass tube.

The difference between the longest and shortest length of telescopic bypass tube is designed to be as same as the distance between two adjacent branch bypass tubes. For example, dealing with the continuous change of noise frequency, when one branch bypass tube is removed, by changing closed position of solenoid valve①at entrance of telescopic bypass tube, the telescopic bypass tube transmission path can be changed from the shortest to longest instantaneously. The path loss due to a lack of branch bypass tube thus can be compensated. Therefore, the continuous variation of muffler tube length can be achieved, which can ensure the continuity of noise reduction frequency.

4. Simulation research on noise elimination performance of semi-active muffler device

Before the semi-active muffler performance is going to be explored through experiments, first of all, A Finite Element Simulation should be carried on to detect preliminary problems and improve semi-active muffler design.

As shown in Fig. 2, the structure of the semi-active muffler device is complex. In order to facilitate the finite element simulation study and further experiment on noise reduction performance, in this paper, its structure was simplified. In Fig. 2, Double telescopic tubes were simplified into single telescopic tube. Adjusting the length of the bypass tube by solenoid valve was seen as tube increase or decrease in a certain length.

The semi-active muffler device model is constantly changing according to the input sound wave frequency. Therefore, there are hundreds processes need to be repeated when the finite element software is used to analyze the noise reduction performance of the semi-active muffler. In order to reduce workload and improve work efficiency, APDL parametric modeling and analysis is introduced to study the semi-active noise muffler device. Every