Optimal Design of a 3D Printed Composite Micro-Perforated Silencer for Engine Intake Noise Control

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Abstract. Micro-perforated panel (MPP) is a new sound-absorbing material with wide frequency band and high absorption characteristics. In this paper, to reduce medium-high frequency intake noise of a car engine under accelerating working conditions, a composite MPP silencer with a serial-parallel coupling mode is presented. Moreover, based on the numerical calculation method of the presented MPP silencer, the Isight software is utilized to integrate relevant simulation software, and then the multi-island genetic algorithm (MIGA) is adopted to optimize the average transmission loss of the silencer. Finally, the optimized silencer is 3D printed for impedance tube testing and vehicle testing. The results demonstrate that the optimization design process of the proposed composite MPP silencer is reasonable; and after adopting the optimized silencer, the objective wideband intake noise is effectively attenuated and the sound pressure level is reduced by 8 dB(A) when the engine is at 3525 r/min, providing a promising way of vehicle noise control.

1. Introduction

Intake noise is one of the main noise sources of internal combustion engine and has recently received more and more attention for its great contribution to in-car noise level. Generally, the engine intake noise is mainly caused by intake pulsation and high-speed airflow, which correspond to low frequency intake noise and medium-high frequency intake noise, respectively. The medium-high frequency wideband noise component accounts for a large proportion of the overall intake noise when the engine at high speed, but it tends to be difficult for attenuation, unlike the low-medium frequency noise component, which could be obviously reduced by traditional intake silencers such as air filter, Helmholtz resonator and quarter wave tube. And alternative dissipative silencers are not yet appropriate here because of engine cleaning requirement. Therefore, a micro-perforated panel (MPP) silencer may be utilized to attenuate the medium-high frequency wideband noise component.

MPP is of wide absorption bandwidth and high absorption coefficient and was firstly investigated by Maa [1]. Currently, this kind of material has been widely applied in duct silencing as MPP silencers [2]. The silencing frequency range of traditional single-cavity MPP silencers is certainly wider than that of resonance-type silencers, however due to the Helmholtz resonance mechanism, such MPP silencers still have single peak and are effective only in a narrowband range around the resonance peak. Accordingly, to obtain better noise reduction effect under the condition of low pressure loss, the serial coupled MPP
silencers [3] and parallel coupled MPP silencers [4, 5], which respectively adopt the MPP serial coupling mode and MPP parallel coupling mode, are proposed.

Actually, serial coupled MPP silencers and parallel coupled MPP silencers both have the wider silencing bandwidth and larger noise reduction amount than traditional single-cavity MPP silencers due to the increase of resonance peaks, which has been demonstrated by many researches. Furthermore, Qian [6] recently concluded that it could obviously widen silencing bandwidth by combining the serial and parallel coupling modes, and our subsequent study [7] came to the same conclusion. On the other hand, taking into account the limited space in the engine compartment and installation position requirement of MPP silencer (the used MPP silencer should be placed behind the air filter to avoid clogging the perforations), a multi-layer serial coupled MPP silencers or a multi-chamber parallel coupled MPP silencers is not proper to be used here. As a consequence, aiming at reducing the medium-high frequency wideband intake noise, a composite MPP silencer integrating double-layer serial and two-chamber parallel coupling modes would be an excellent solution.

The composite MPP silencer has great potential in obtaining good silencing performance, but its parametric design would be complex. Therefore, it needs to utilize an optimization means to determine optimal combination of structure parameters. The transmission loss (TL) is an indicator for evaluating the acoustic performance of a silencer [2-5] and its value is determined by structure parameters of the silencer, and thus in this study, the TL is still focused and its average value is used as the objective function for optimization. Besides, the presented composite MPP silencer is used in the engine intake system, thus the silencer made of metal material will be not suitable here. Liu et al. [8, 9] introduced a new processing method for MPP, namely 3D printing technology, and they verified the effectiveness of this approach. Based on this, the whole optimized composite MPP silencer is also 3D printed for later experiment verification.

In this paper, to attenuate the medium-high frequency wideband engine intake noise, a composite MPP silencer integrating serial and parallel coupling modes is presented, and its TL numerical calculation method is investigated. Moreover, the multi-island genetic algorithm (MIGA) is adopted to optimize average TL value of the silencer in objective frequency range. In addition, the optimized silencer is 3D printed for experimental investigation.

2. Engine Intake Noise Analysis

Engine intake silencers are usually composed of an air filter, several Helmholtz resonators and quarter wave tubes. The air filter could be used to attenuate broadband intake noise, however, the noise reduction is very low due to its limited area expansion ratio. And the Helmholtz resonators and quarter wave tubes are effective only for low or medium frequency narrowband intake noise. Figure 1 shows the original intake silencing system of a car engine, which includes an air filter, three independent Helmholtz resonators (the corresponding frequencies are 73 Hz, 110 Hz and 320 Hz, respectively) and three adjacent Helmholtz resonators (the corresponding frequencies are 90 Hz, 183 Hz and 360 Hz, respectively). The pipe segment in dashed box is reserved for later application of a composite MPP silencer.

Figure 2a and 2b shows frequency spectrum of intake orifice noise when the original intake silencing system without and with the six Helmholtz resonators, respectively. During the test of intake orifice noise, the test vehicle runs on the rolling drum in a semi-anechoic room and accelerates from 1000 to 5000 r/min under the third-gear and full-throttle working condition. The distance between the microphone and intake orifice is about 10 cm. And the LMS SCADAS data acquisition system and LMS TestLab software are used to acquire and process the noise signals. According to the measured data, it shows that the intake noise component below 400 Hz is obviously reduced but that of 600-1800 Hz is not. No doubt this is because the intake silencers of original intake silencing system are aimed at low frequency noise control. Therefore, a compact silencer needs to be introduced here that can guarantee both good wideband noise reduction of 600-1800 Hz and low pressure loss.
Figure 1. Original intake silencing system.

Figure 2. Frequency spectrum of intake orifice noise: (a) with original intake silencing system removing the Helmholtz resonators, (b) with original intake silencing system.

3. Composite MPP Silencer

3.1. Structural Form

MPP is a thin panel with many sub-millimeter micropores, as shown in figure 3, where t, d and b are respectively the panel thickness, hole diameter and hole spacing between two adjacent micropores. Figure 4 illustrates the schematic diagram of proposed composite MPP silencer. The whole silencer is cylindrical and includes three circular tubular MPPs. MPP1 and MPP2 are arranged in series, and MPP1 and MPP3 as two sections of the main pipe of the silencer are arranged in parallel. The radius of the main pipe is R. The radial distance between MPP1 and MPP2, MPP2 and the shell, and MPP3 and the shell are D1, D2 and D3, respectively. The axial length of MPP1 and MPP3 are respectively L1 and L2 and only L1=L2 is investigated in this study. Such a MPP silencer that integrates the double-layer serial and two-chamber parallel coupling modes would have tremendous potential in obtaining wider silencing bandwidth and larger noise reduction amount relative to traditional MPP silencers.

3.2. Numerical Calculation

The TL value of the composite MPP silencer could be calculated using finite element method (FEM). During calculation, the TL value of the silencer is partially determined by acoustic transfer impedance of the MPPs. So the acoustic transfer impedance of a MPP is introduced here first. Based on the theory of Maa [1], the specific acoustic impedance of a micropore can be written as
Figure 3. Schematic diagram of MPP.

Figure 4. Schematic diagram of composite MPP silencer.

\[ Z_i = R + j\omega M \]  \hspace{1cm} (1)

with

\[ R = \frac{32\eta t}{d^2} \left[ \sqrt{1 + \frac{k^2}{32}} + \frac{\sqrt{2}k}{8} \frac{d}{t} \right], \quad \omega M = \omega_{opt} \left[ 1 + \frac{1}{9 + \frac{k^2}{2}} + 0.85 \frac{d}{t} \right] \]  \hspace{1cm} (2)

and

\[ k = \frac{d}{2} \sqrt{\frac{\omega \rho}{\eta}} \]  \hspace{1cm} (3)

where \( R \) denotes the specific acoustic resistance of the micropore; \( \omega M \) denotes specific acoustic reactance of the micropore; \( \eta \) denotes the dynamic viscosity; \( \rho \) denotes the density of air; and \( \omega = 2\pi f \) denotes the angular frequency corresponding to the frequency \( f \) of incident acoustic wave.

Regarding an MPP as a parallel set of many micropores, then its acoustic transfer impedance can be expressed as

\[ Z_{MP} = Z_i / \sigma \]  \hspace{1cm} (4)

where \( \sigma \) denotes the microperforation rate of the MPP and when the micropores of the MPP are circular and arranged in a square shape, \( \sigma = \pi d^2 / (4b^2) \).

While performing the simulation calculation, suppose the MPPs are rigid enough so that the panel vibration can be ignored under acoustic loading. Figure 5 illustrates the finite element model of a composite MPP silencer, where the sound cavities of the silencer are meshed but the MPPs are not. The three pairs of separated sound cavities are linked by means of the three transfer impedance interfaces, which are formed by Coupling surfaces 1 and 2, Coupling surfaces 3 and 4, and Coupling surfaces 5 and 6, respectively. As a result, the relationship of the sound pressure and particle velocity between each pair of separated sound cavities is determined [10]. The used acoustic transfer impedances are based on the complicated calculation of equations (1)-(4). The TL value of the silencer is available after the harmonic response is performed.

4. Optimization Design of the Composite MPP Silencer

By combining the serial and parallel coupling modes, a composite MPP silencer with a smaller volume may achieve considerable wideband noise reduction, so that the silencer would be quite suitable as an engine intake silencer. However, the parametric design of the silencer still shows complexity due to the number of structural parameters. Thus an optimization method is presented here to achieve the maximum average transmission loss in the objective frequency range.
Figure 5. Finite element model of a composite MPP silencer.

4.1. Optimization Preparation
To ensure low pressure loss, the radius $R$ of main pipe of the composite MPP silencer is given by 27mm as the radius of the intake pipe. Considering limited installation space, the radial distance $D_3$ is given by 37 mm and the axial lengths $L_1$ and $L_2$ are given by 85 mm. In addition, the panel thickness of the MPPs is given by 2 mm. Accordingly, there are seven decision variables for the composite MPP silencer, which are the hole diameters, $d_1$, $d_2$, and $d_3$; the hole spacings, $b_1$, $b_2$, and $b_3$; and the radial spacing, $D_1$. And the hole diameters and hole spacings of the MPPs are constrained as follows:

$$0.5 \text{ mm} \leq d_1, d_2, \text{ and } d_3 \leq 1 \text{ mm}; \ 2 \text{ mm} \leq b_1, b_2, \text{ and } b_3 \leq 12 \text{ mm} \quad (5)$$

To make the optimization process more easily be realized on the premise of a certain optimization effect, $D_1$ is given by 5, 10, 15, 20, 25, or 30 mm, thereby $D_2= 35\text{ mm }- D_1$. According to the six different values of $D_1$, there are six corresponding composite MPP silencer models, namely M1, M2, M3, M4, M5, and M6. For each composite MPP silencer model, the number of decision variables changes from seven to six due to the exclusion of $D_1$.

Prior to optimization, the finite element model of each composite MPP silencer model should be prepared (the maximum element size of the finite element model is given by 5 mm) and initial values of the decision variables should be also given first (the initial values of $d_1$, $d_2$, and $d_3$ are set to 0.8 mm; the initial values of $b_1$, $b_2$, and $b_3$ are set to 5 mm).

4.2. Optimization by the MIGA
Based on the numerical calculation method in Section 3.2, the Isight software is utilized to integrate the Actran and MATLAB softwares so that the average transmission loss of each composite MPP silencer model is optimized and then the best combination of structure parameters within given ranges may be obtained. The optimization process is shown in figure 6. The adopted optimization algorithm is the multi-island genetic algorithm (MIGA), which has better global optimization capability than any traditional GA and has been successfully used to optimize the multi-size MPP absorbers [11]. Table 1 lists the defined simulation and optimization parameters. The objective function, namely the average transmission loss is expressed as

Figure 6. Optimization process.
Table 1. Values of simulation and optimization parameters.

| Parameter                                | Numerical simulation based on FEM | Optimization based on the MIGA |
|------------------------------------------|----------------------------------|--------------------------------|
| Air density (kg/m³)                      | 1.225                            | Island size                    |
| Speed of sound (m/s)                     | 340                              | Number of islands              |
| Dynamic viscosity (kg/(m/s))             | 1.79x10⁻⁵                        | Evolution generations          |
| Lower limit frequency (Hz)               | 600                              | Crossover rate                 |
| Upper limit frequency (Hz)               | 1800                             | Mutation rate                  |
| Step size (Hz)                           | 20                               | Migration rate                 |

Maximize: \( \bar{TL} = \frac{1}{N_0} \sum_{i=1}^{N_0} TL(f_i) \), \( i = 1, 2, 3..., N_0 \) (6)

where \( TL(f_i) \) represents the TL value corresponding to the frequency \( f_i \) and \( N_0 \) represents the number of calculated frequency points, which equals the ratio of the difference between the upper and lower limit frequencies to the step size.

The optimized bandwidth is set to 600-1800 Hz. And the frequency step size is given by 20 Hz for reduction of optimization time. Through our six optimization simulations, the optimized results of the composite MPP silencer models corresponding to \( D_1 \) with different values are obtained, as shown in table 2, and their TL curves are shown in figure 7. It indicates that the optimized composite MPP silencer models all have considerable noise attenuation capability within the objective bandwidth, which may owe to the great contribution that the composite coupling mode provides to their acoustic performance. Furthermore, the results show that the optimized silencer models have similar TL values in the same frequency range, indicating that no matter how much the structure parameter \( D_1 \) is, to some extent the composite MPP silencer may obtain optimal acoustic performance through optimization of MPP structure parameters. According to the average transmission loss \( \bar{TL} \), the composite MPP silencer model (M4) corresponding to \( D_1=20 \) mm, seems slightly superior to the others, thus it is selected to reduce the wideband intake orifice noise of 600-1800 Hz.

Table 2. Optimized results of six composite MPP silencer models.

| Parameter  | \( d_1 \) (mm) | \( b_1 \) (mm) | \( d_2 \) (mm) | \( b_2 \) (mm) | \( d_3 \) (mm) | \( b_3 \) (mm) | \( TL \) (dB) |
|------------|----------------|----------------|----------------|----------------|----------------|----------------|--------------|
| M1 (\( D_1=5 \) mm) | 0.98            | 3.12           | 0.96           | 2.28           | 0.80           | 2.89           | 34.461       |
| M2 (\( D_1=10 \) mm) | 0.99            | 3.27           | 0.98           | 2.22           | 0.76           | 2.84           | 34.358       |
| M3 (\( D_1=15 \) mm) | 0.89            | 3.06           | 1              | 2.63           | 0.90           | 3.39           | 34.498       |
| M4 (\( D_1=20 \) mm) | 0.99            | 3.62           | 1              | 2.03           | 0.99           | 3.94           | 34.862       |
| M5 (\( D_1=25 \) mm) | 0.99            | 3.39           | 0.86           | 3.29           | 0.94           | 3.46           | 34.520       |
| M6 (\( D_1=30 \) mm) | 0.98            | 3.75           | 0.93           | 2.65           | 0.85           | 3.09           | 34.840       |

Figure 7. Optimized TL curves of six composite MPP silencer models.
5. Experimental Study

5.1. Validation of Transmission Loss

The selected optimal composite MPP silencer is made by the 3D printing technology according to the obtained optimized parameters, as shown in figure 8a. Based on the two-load method [12, 13], the TL value of the silencer is measured with the impedance tube, which is a cylindrical stainless steel tube of the inner diameter 54 mm and effective measurement bandwidth of 50-3650 Hz. Figure 8b illustrates the test bench. Figure 9 shows comparison of optimized and measured TL curves for the composite MPP silencer. It reveals that the optimized TL curve agrees well with the measured TL curve and demonstrates that the proposed optimization design process is practicable to the acoustic performance optimization of a composite MPP silencer.

![Figure 8. (a) Silencer sample, (b) Test bench.](image)

![Figure 9. Comparison of optimized and measured TL curves for the composite MPP silencer.](image)

5.2. Validation of Silencing Effect

To verify the silencing performance of the optimized composite MPP silencer, a further test is conducted. Figure 10a shows the whole intake silencing system including the original intake silencing system in Section 2 and the optimized composite MPP silencer. Figure 10b shows noise test of the intake orifice in the semi-anechoic room. Finally, the frequency spectrum of intake orifice noise with the optimized composite MPP silencer and comparison of sound pressure level (SPL) of the intake orifice noise with and without the optimized composite MPP silencer are shown in figures 11 and 12, respectively. It indicates that the intake noise component of 600–1800 Hz is significantly reduced by introducing the optimized composite MPP silencer, and when the engine is at 3525 r/min, the maximum attenuation amount of A-weighted SPL is up to 8 dB, proving that the presented composite MPP silencer has a great silencing effect for engine intake noise control.
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Figure 10. (a) Intake silencing system with the optimized composite MPP silencer, (b) Intake orifice noise test with the optimized composite MPP silencer.

Figure 11. Frequency spectrum of intake orifice noise with the optimized composite MPP silencer.

Figure 12. Comparison of SPL of the intake orifice noise with and without the optimized composite MPP silencer.

6. Conclusion
Aiming at reducing medium-high frequency intake noise of a car engine at high speeds, a composite MPP silencer is proposed and its TL numerical calculation method is investigated. Moreover, the average transmission loss of the silencer is optimized by using the Isight software to integrate relevant simulation softwares and adopting the MIGA to determine optimal values of the structure parameters. Finally, the optimized composite MPP silencer is 3D printed for validation of transmission loss and validation of silencing effect. The results show that the optimization design process of the presented composite MPP silencer is practicable, and the composite MPP silencer with a smaller volume has great wideband noise reduction effect, which may contribute to engine intake noise control.

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