This paper develops a tunable dual-band perfect sound absorber to improve the low-frequency absorption based on the polyurethane foam. First, we propose a hybrid sound absorber composed of the polyurethane foam and Helmholtz resonator. The impedances of the Helmholtz resonator and the polyurethane foam are derived by the Helmholtz resonator theory and Delany-Bazley empirical formulations. Then the equivalent network is applied to present the impedance of the hybrid sound absorber. Next, numerical applications are implemented using MATLAB to predict the sound absorption coefficients of the hybrid sound absorber. It shows that the hybrid sound absorber can provide more sound absorption than the polyurethane foam in low frequency, while in high frequency, it provides more than the Helmholtz resonator. It also implies that the hybrid sound absorber is a tunable sound absorber in low frequency. Finally, experiments have been done by the two-microphone impedance tube method to validate the theoretical results.

Keywords: Polyurethane foams; Helmholtz resonator; sound absorption coefficient; impedance tube; equivalent network
1. Introduction

Over the past decades, sound absorbers are widely applied in the acoustic design of buildings, aircrafts, vehicles, ships and marines. Conventional sound absorbers are mainly divided into two categories based on their sound absorbing mechanism, i.e. the porous sound absorber and the resonance sound absorber. The porous sound absorbers have the advantages of small specific gravity and high sound absorption coefficient in high frequency. However, they are not suitable for sound absorbing in low frequency. In contrast, the resonance sound absorption structure provides high sound absorption coefficient in low frequency. The conventional porous sound absorbers may be used to control the noise of the environment [1–4], but the control effects in low frequency region are prone to be unsatisfactory. As a results, significant efforts have been directed towards the combination of the porous sound absorber and the resonance sound absorber.

To improve the absorption performance of the micro-perforated panel (MPP) in low frequency, an array of Helmholtz resonators are used to reduce the low frequency noise by Li [5]. Then, Wang [6] presented a theoretical study of the sound propagation in one-dimensional duct with identical side-branch resonators mounted periodically. To enhance the frequency bandwidth of the sound absorption, Wang and Huang [7] proposed an absorber array consisting of three parallel-arranged MPP absorbers with different cavity depths. Similarly, MPP absorbers backed by Helmholtz resonators are introduced to solve the sound absorption in low frequency by Park [8, 9]. Besides, the MPP absorbers associated with different Helmholtz resonators are also studied in [10]. However, up to now, there is no research to investigate the polyurethane foams combined with Helmholtz resonators, and this mechanism of sound absorption structure has not been well presented in the literature.

This paper proposes a new dual-band sound absorber called hybrid sound absorber composed of the polyurethane foam and the Helmholtz resonator to present an enhanced sound absorption performance. Next its acoustic properties are investigated. In Section 2, the structure of the proposed sound absorber is introduced and the relevant formulations are derived. Numerical examples are applied in Section 3. Finally, experiments are done by two-microphone transfer function method to validate the numerical examples and then the results are discussed.

2. Description and theoretical formulation

2.1 Description of the hybrid sound absorber

To illustrate the idea of the hybrid sound absorber in parallel with Helmholtz resonators, we start from the one-resonator case. Here, the structure of the hybrid sound absorber is illustrated in Figure 1. The parameters $d_1$, $d_2$ and $d_3$ represent the diameters of the cavity, sample and neck respectively, and $l_1$ and $l_2$ are respectively the length of the sample and neck. It is made up of polyurethane material and polyvinyl chloride resonator. Note that there is no fundamental difference between one and multiple parallel Helmholtz resonators. Multiple ones may achieve high absorption coefficients with different resonant frequencies. The resonant frequencymay be expressed as[11]

$$f_0 = \frac{c}{2\pi} \sqrt{\frac{S}{(d_2+0.73d_3)V}} \quad (1)$$
Figure 1. Structural diagram of the hybrid sound absorber with a single Helmholtz resonator in parallel where

\[ c \] is the sound speed in the air;
\[ S \] is the cross sectional area of the neck;
\[ V \] is the volume of the Helmholtz resonator cavity.

### 2.2 Theoretical formulation

Figure 2. The equivalent circuit of the hybrid sound absorber with (a) one or (b) multiple Helmholtz resonators

The key component of the hybrid sound absorber is the acoustic impedance that characterizes acoustic properties of the absorber. The electro-acoustic analogy may be applied to obtain it. Figure 2 (a) and (b) show the equivalent circuit of the hybrid sound absorber with one (a) or multiple (b) Helmholtz resonators in parallel. Based on the impedance type of the electro-acoustic analogy, the acoustic impedance of the hybrid sound absorber with a Helmholtz resonator is given by

\[
\frac{1}{Z} = \frac{1}{Z_P} + \frac{1}{Z_H}
\]

where \( Z, Z_P \) and \( Z_H \) are the acoustic impedance of the hybrid sound absorber, the polyurethane foam and the Helmholtz resonator, respectively. The acoustic impedance of the polyurethane foam can be expressed by Delany-Bazley power-law function [12] in terms of coefficients \( C_1 \) to \( C_4 \) as follows.

\[
Z_P = \rho c \left[ 1 + C_1 \left( \frac{\rho f}{\rho_f} \right)^2 - j C_3 \left( \frac{\rho f}{\rho_f} \right)^4 \right]
\]

The acoustic impedance of the Helmholtz resonator is calculated as follows [13].

\[
Z_H = R_H + j \omega M_H - \frac{j}{\omega C_H}
\]

\[
R_H = \frac{l_2}{\pi (d_3/2)^3} \sqrt{2 \eta \rho \omega}
\]

\[
M_H = \rho \left( l_2 + 0.73d_3 \right)
\]

\[
C_H = \frac{V}{\rho c^2}
\]

where
\( \rho \) is the air density;
\( f \) is the frequency;
\( r_f \) is the airflow resistivity;
\( k = \omega / c \) is the wave number;
\( \eta \) is the coefficient of viscosity of the air;
\( R_H, M_H \) and \( R_H \) are acoustic resistance, acoustic mass and acoustic capacitance of Helmholtz resonators.

For the polyurethane foam with multiple parallel Helmholtz resonators, the acoustic impedance of the hybrid sound absorber can be derived by

\[
\frac{1}{Z} = \frac{1}{Z_P} + \frac{1}{Z_{H_1}} + \cdots + \frac{1}{Z_{H_i}} + \cdots + \frac{1}{Z_{H_n}} \tag{8}
\]

where \( Z_{H_i} \) is the acoustic impedance of \( i \)th Helmholtz resonator.

The absorption coefficient of the hybrid sound absorber can be calculated by the well-known formula as [14]

\[
\alpha = \frac{4R_e(Z)}{[1+R_e(Z)]^2+[I_m(Z)]^2} \tag{9}
\]

3. Numerical examples

Table. 1. The structural parameters of the sample

<table>
<thead>
<tr>
<th>Structural parameter</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
<th>( l_1 )</th>
<th>( l_2 )</th>
<th>( l_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>46 mm</td>
<td>100 mm</td>
<td>18 mm</td>
<td>60 mm</td>
<td>25/31/46/50 mm</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

Table. 2. Delany-Bazley function coefficients for the power-law function.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
<th>( r_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.3759</td>
<td>-2.3020</td>
<td>0.9418</td>
<td>2.8896</td>
<td>1920.936</td>
</tr>
</tbody>
</table>

In this section, numerical applications are implemented in MATLAB software, and there are several examples illustrating the predicted sound absorption coefficients of the hybrid sound absorbers. These examples include the hybrid sound absorbers with a single Helmholtz resonator of different neck lengths \( l_2 \) (25 mm, 31 mm, 46 mm and 50 mm), the hybrid sound absorber with four Helmholtz resonators of different neck lengths \( l_2 \) (25 mm, 31 mm, 46 mm and 50 mm) and the polyurethane foam with no Helmholtz resonator. The parameters of the examples are illustrated in Table. 1. The polyurethane foam is the polyurethane foam used in this study, and its impedance is calculated by Delany-Bazley power-law function. The unknown coefficients of Delany-Bazley function may be obtained by experimentally measuring the characteristic impedance and fitting the data to Eq. (3). Table. 2 lists the relevant coefficients.
Figure 3 depicts the predicted sound absorption coefficient of the hybrid sound absorbers with a single Helmholtz resonator of different neck lengths $l_2$ (25 mm, 31 mm, 46 mm and 50 mm). ‘Theoretical abc’ is the polyurethane foam without the Helmholtz resonator, and ‘Theoretical abc_hm_25mm’ is the hybrid sound absorber with a 25mm-neck Helmholtz resonator, the other and so on. ‘Theoretical abc_multi-hm’ is the hybrid sound absorber with our Helmholtz resonators of different neck lengths $l_2$ (25 mm, 31 mm, 46 mm and 50 mm). From the results, it can be seen that the sound absorption coefficients of the hybrid sound absorbers are much higher than the pure polyurethane foam, especially in 400-600Hz. The hybrid sound absorbers have a near-perfect absorption peak of >99% at the resonant frequency. It also shows that the increment of the neck length $l_2$ can result in the decrement of the peak frequency, which is consistent with the resonant frequency calculation formula in section 2.1. According to the calculation formula, the sound absorption peak can also move along with the cross sectional area $S_0$ and the volume $V$. It implies that the position of the sound absorption peak may be adjusted by changing the structural parameters of the Helmholtz resonator. The curve of ‘Theoretical abc_multi-hm’ demonstrates that the hybrid sound absorber with multiple parallel Helmholtz resonators can obtain multiple sound absorption peaks and the sound absorption frequency band is broadened. Therefore, it is concluded that the hybrid sound absorber has the sound absorption characteristics of both the porous sound absorption material and the resonance sound absorption structure, which means that it not only retains the original high-frequency sound absorption characteristics, but also has the resonance sound absorption characteristics and it can improve the sound absorption coefficient of different low frequencies and extend the sound absorption frequency band.

4. Experiments and discussion

To validate the numerical examples in Section 3, the two-microphone transfer function method has been applied to measure the sound absorption coefficients of the samples through the impedance tube. Due to the limitation of the tube size, we are only able to measure the absorption coefficient of the hybrid sound absorber with a single Helmholtz resonator. In this section, there just are the comparisons of the hybrid sound absorber with a single Helmholtz resonator between the experiment and the prediction.
1.1 Absorption coefficient measurement

![Image](a) (b)

Figure 4. Measurement setup in the laboratory (a) and schematic of two-microphone transfer function method (b)

Measurement equipment is set up as shown in Figure 4, where the impedance tube and Pulse Labshop of Bruel and Kjær are used. The samples are put into the impedance tube and the measurements are done with the two-microphone transfer function method. In this method, the impedance and the complex sound reflection coefficient $R$ of the measured sample is derived by the transfer function $H_{12}$, according to Chung and Blaser’s research [15, 16].

$$ R = \frac{H_{12} - H_i}{H_r - H_{12}} e^{2jks(l+s)} $$  

(10)

where

- $l$ is the distance between the first microphone location and the front of the sample;
- $s$ is the spacing between two microphones;
- $H_i$ is the frequency response function associated with the incident component;
- $H_r$ is the frequency response function associated with the reflected component.

Using the value of the reflection coefficient, the specific impedance ratio $z$ and the sound absorption coefficient $\alpha$ can be calculated from the following equations:

$$ Z = \frac{1+R}{1-R} $$  

(11)

$$ \alpha = 1 - |R|^2 $$  

(12)

It should be noted that the acoustic impedance $Z$ is calculated by $Z= z\rho c$.

1.2 Experiment results

Figure 5 plots the measurement results. It can be observed that all the hybrid sound absorbers have two peak frequencies. The low frequency peak is mainly caused by the Helmholtz resonator, while the high frequency peak is close to the one of the polyurethane foam without the Helmholtz resonator. With the of the neck length of the Helmholtz resonator decreasing, the low frequency peak moves toward the high frequency direction, which is consistent with the theoretical predictions.

![Figure 5. Measurements: absorption coefficients of the proposed absorber with and without different Helmholtz resonator neck lengths](image)
Figure 6 (a) and (b) compare the sound absorption coefficients of the experiment results and the theoretical predictions. In the figure, it can be seen that the trends of the experimental data are in good agreement with theoretical values. The low frequency peak almost appears in the same frequency calculated by the theoretical formula. However, there are some differences between the experiments and the predictions in values. In the theoretical predictions, the impedance of the polyurethane foam is derived by Delany-Bazley power-law function which is just an empirical formula. And the empirical expressions are unable to sufficiently encapsulate the acoustical behavior of the polyurethane foam to be regarded as universally applicable, which is the main reason that causes the difference between the experimental data and the theoretical prediction. Although the theoretical predictions do not perfectly coincide with the experimental data, it demonstrates that the proposed hybrid sound absorber can obtain more sound absorption than the polyurethane foam in low frequency range and the Helmholtz resonator in high frequency range.

![Figure 6](image)

Figure 6. Comparisons of the experimental and the predicted sound absorption coefficient of different proposed absorbers.

5. **Conclusions**

In this study, a hybrid sound absorber for both the low-frequency and the high-frequency has been successfully proposed. Based on the empirical formula, Helmholtz resonator theory and electro-acoustic equivalent network, the sound absorption coefficients of the hybrid sound absorber have been calculated. Numerical applications and experimental results demonstrate that the hybrid sound absorber has two peak frequencies in low and high frequency respectively, and the low frequency peak moves to low frequency with the increment of the neck length when other parameters keep unchanged, which implies that the position of the sound absorption peak may be adjusted by changing the structural parameters of the Helmholtz resonator. Moreover, the hybrid sound absorber with multiple parallel Helmholtz resonators may provide more sound absorption peaks than the one with a single Helmholtz resonator in low frequency range. By adjusting appropriate number and parameters of Helmholtz resonator, the hybrid sound absorber can achieve a wider sound absorption bandwidth.

**REFERENCES**


