A Sandwich Coating Containing Micro-perforated Panel for Underwater Sound Absorption

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Abstract. This paper focuses on the underwater application of Micro-perforated panel (MPP) for broadband sound absorption. In this paper, MPP-rubber coating (MPPRC), a novel sandwich anechoic coating embedded with MPP in high-viscosity condition, is proposed. The acoustic impedance for MPP is derived from Maa’s equation and vibration modal modification, while the acoustic propagation property of the viscoelastic rubber layer is obtained by the wave propagation equation. The theoretical calculation for the absorbency of the composite structure is conducted based on electro-acoustic analogy method and transfer matrix approach. The sound absorption validation is carried out in a hydroacoustic impedance tube filled with water, and the experimental results match with the theoretical model. Compared with the equal-thickness rubber, the MPPRC performances better at a lower frequency of 1.6 kHz ~15 kHz due to MPP, which shows the potential to be utilized as an underwater anechoic coating.

1. Introduction

A micro-perforated panel (MPP), a thin plate with distributed apertures of sub-millimeter scale, has long been regarded as a substituted structure for porous materials. Compared with traditional porous materials, the MPP requires small space to achieve high sound absorption in the low-frequency domain. The construction of MPP resonant absorber originates from Maa’s research [1, 2], which initially proposes the approximate theory to predict the impedance of MPP and the resonance absorption peak at a low frequency. In previous theoretical analyses, researches have been improving low-frequency and broadband-frequency sound absorbency in various methods, including ultra-micro perforations [3], arbitrary cross-sectional perforations [4], parallel-arranged cavities of various depths [5], panel vibration effect [6, 7]. Tang [8] proposed an ultra-lightweight honeycomb-corrugation hybrid cored sandwich panel with heterogeneously perforated faceplate and perforated corrugation, which shows good acoustic and mechanical properties at the same time. Meng [9] studies the acoustic influence of surface roughness on cylindrical micro-tubes from both viscous effect and thermal effect, which shows the potential of improving the MPP absorbency by enlarging the surface roughness. Other valuable researches are also impressive, including tube mufflers [10], the combination with mechanical impedance plates [11, 12] and hybrid passive-active modification [13, 14].
Compared with the plentiful research for MPP in air medium, the investigation on MPP underwater is much fewer, and the underwater application is much more complicated. Since the impedance of water is about 3600 times than that of air, the MPP structure matching the impedance of air extremely mismatch the impedance of water. Bai [15] and Tong [16] studied the feasibility of MPP for underwater usage by electro-acoustic analogy analysis and hydroacoustic measurement, which demonstrates that the MPP can only be used underwater on condition of submillimeter-scale perforation and centimeter-level panel thickness. Wang [17, 18] even investigated the underwater transmission characteristics of MPP based on transfer matrix method and equivalent model. All these works indicate that the MPP suitable in the air cannot be applied underwater for sound absorption directly.

The inspiring progress of underwater MPP comes with significant structural modifications. Instead of the parametric adjustments of MPP, Wang [19] set an MPP in the condition of castor oil and demonstrated that the MPP works much better in high-viscosity propagation medium because of the considerable viscous dissipation caused by castor oil. Luo [20] combines the MPP resonance sound absorption mechanism with the absorbing mechanism of the mature Alberich coating [21, 22], and achieves absorbency of 0.7 at the broad bandwidth of 3 kHz ~ 12 kHz. As for underwater, sound absorption, rubber-based anechoic layers [23-26] are widely used and extensively studied as submarine acoustic coatings. The low-frequency resonance absorbency of MPP may bring inspiring absorption peak for the traditional rubber layer.

In this paper, we investigated the sound absorption characteristics of the sandwich-structured MPP-rubber coating (MPPRC) consisting of rubber plates and MPP in castor oil. The absorption coefficient of the composite anechoic coating are theoretically analyzed based on electro-acoustic analogy method and the transfer matrix approach and verified experimentally based on the combination of the transfer function method and pulse-echo method. Accordingly, the influence of the MPP parameters for the absorption of MPPRC is investigated.

2. Theoretical calculations
As shown in Fig. 1, the MPPRC consisted of three sections: the front rubber, the MPP in castor oil, and the backing rubber. The incident soundwave enters the composite structure from water at an angle of \( \theta_i \), and propagates through the MPPRC before it reaches the rigid backing condition. We can also choose other backing conditions based on actual requirements, such as impedance-matching condition and pressure-release condition.

![Figure 1. Sketch of MPPRC backed with rigid wall](image)

2.1. Acoustic equivalence for a flexible MPP
The structure of MPP with backing rubber can be considered as multi-parallel Helmholtz resonators. The microspores acted as masses, and the backing rubber worked as the stiffness of the Helmholtz
resonators. The absorbency of the MPP system depends upon the dimensions such as panel thickness, aperture diameter, porosity and the depth of the backing layer. The acoustic impedance in rigid MPP for the normal incident wave can be derived from Maa’s theory [2]:

\[ R = \frac{\mu L_p}{\sigma_p d_f^2} \left( \sqrt{\frac{K^2}{32} + \frac{\sqrt{2}}{32} K d_p + \frac{d_p}{t_p}} \right) \]  

\[ M = \frac{\rho L_p}{\sigma_p} \left( 1 + \frac{1}{\sqrt{9 + K^2 / 2}} + 0.85 \frac{d_p}{t_p} \right) \]  

\[ Z_{p,\text{rigid}} = R + j \omega M \]  

where \( \mu_c \) and \( \rho_c \) are the kinetic viscosity coefficient and the density of castor oil respectively, \( t_p \) is the panel thickness, \( \sigma_p = \pi d_f^2 / 2 \sqrt{3} L^2 \) is the perforation rate of MPP in a triangular arrangement, \( d \) is the diameter of the holes, \( L \) is the center distance between the adjacent apertures, and \( K = \frac{\pi f}{\rho c d_f^2 / 2 \mu} \) is the perforated panel constant.

The vibration effect of the aluminum panel can be regarded as impedance in parallel with the rigid MPP. The equivalent impedance of the vibration effect of the panel is [6]:

\[ Z_v = \left( \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{\rho^{2}}{\eta_{m,n} Z_{m,n} S} \right)^{-1} \]  

where \( \epsilon_{m,n} \) is mode damping ratio, \( \eta_{m,n} = \int \omega_{m,n} \rho(r, \theta) d \theta \) is the weighting factors of modal velocity amplitude of vibration, \( S \) is the area of the cross-section, \( Z_{m,n} = \rho_v (\epsilon_{m,n} \omega_{m,n} + j(\omega^2 - \omega_{m,n}^2)) / \omega \) is mode impedance, \( \omega_{m,n} \) is mode frequency obtained by structural modal simulation based on finite element software. The clamping of the rubber plate and the viscous damping of castor oil immensely weaken the vibration effect [27], which makes \( Z_v \) large enough to be ignored compared with the impedance of the MPP. The equivalent impedance of the flexible MPP is:

\[ Z_p = \left( \frac{1}{Z_{p,\text{rigid}}} + \frac{1}{Z_v} \right)^{-1} \]  

2.2. Calculations based on electro-acoustic analogy

The infiltrating layers are set in rubber surfaces in touch with MPP to sustain the castor-oil-saturated condition for MPP. The hybrid structure of the front rubber is regarded as a connection of two parallel circuitual branches, as shown in Fig. 2. Branch 1 is a total-rubber layer, and Branch 2 is a serial connection of the cylindrical rubber layer and a castor oil layer. \( C_{f,0}, C_{f,r}, C_{f,c} \) are the acoustic capacitances of parallel rubber branch, serial rubber part, and serial castor-oil part.
The equivalent capacitance and impedance of an isotropous layer are

$$C_i = \frac{\tan(k_i t_i)}{\sigma_i \omega \rho_i c_i}, Z_i = \frac{1}{j \omega C_i}$$

(6)

where the subscript i represents the propagation medium (r for rubber, c for castor oil), $k_i = \omega/c_i$, $\rho_i$, $c_i$, are the wavenumber, layer thickness, density and sound speed, respectively; the subscript ii (including f, f0, fc, fr, as shown in Fig. 2) represents the different propagation layer; $\sigma_i$ represents the cross-section area ratio of each parallel branch. The acoustical equivalence of the front rubber and the backing rubber are:

$$Z_f = \left(\frac{1}{Z_{f,0}} + \frac{1}{Z_{f,r} + Z_{f,c}}\right)^{-1}, Z_b = \left(\frac{1}{Z_{b,0}} + \frac{1}{Z_{b,r} + Z_{b,c}}\right)^{-1}$$

(7)

where $Z_{f,0}$, $Z_{f,r}$, $Z_{b,c}$ can be similarly derived from (6). The equivalent circuit diagram of the MPPRC based on electro-acoustic analogy method is shown in Fig. 3.

$$Z_{\text{MPPRC}} = \left(\frac{1}{Z_f} + \frac{1}{Z_p + Z_b}\right)^{-1}$$

(8)

The reflection coefficient $R$ is:
\[ R = \frac{Z_{\text{MPPRC}} - \rho_w c_w / \cos(\theta_i)}{Z_{\text{MPPRC}} + \rho_w c_w / \cos(\theta_i)} \]  

(9)

where \( \rho_w \) is the density of water, \( c_w \) is the sound speed in the water. According to Snell's refraction law, the refraction angle in rubber is very close to the incident angle in water, so we just use neglect the angle change in rubber, and just use \( \theta_i \) for short. Respectively the echo reduction and the absorption coefficient of the MPPRC are:

\[ ER = 20 \log R, \quad \alpha = 1 - |R|^2 \]

(10)

2.3. Calculations based on transfer matrix approach

For the multi-layered structure of MPPRC, the total transfer matrix \( T_{\text{MPPRC}} \) can be obtained by connecting the individual transfer matrices in order:

\[ [T_{\text{MPPRC}}] = [T_c][T_p][T_b] = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \]

(11)

where \([T_c] \), \([T_p] \), \([T_b] \) are transfer matrices of the front rubber, MPP and the backing rubber, respectively.

Considering the approximate acoustic impedance between castor oil and rubber, the 2-millimeter-thick infiltrating layer can be neglected. Consequently, the front rubber and backing rubber is simplified as a homogeneous rubber plate. The two-dimensional transfer matrices of the MPP and the two rubber plates can be derived from:

\[ [T_c] = \begin{bmatrix} 1 & Z_p \\ 0 & 1 \end{bmatrix} \]

(12)

\[ [T_f] = \begin{bmatrix} \cos k_t t_i & j \rho_f c_i \sin k_t t_i \\ j \sin k_t t_i / \rho_f c_i & \cos k_t t_i \end{bmatrix} \]

(13)

\[ [T_b] = \begin{bmatrix} \cos k_b t_b & j \rho_b c_i \sin k_b t_b \\ j \sin k_b t_b / \rho_b c_i & \cos k_b t_b \end{bmatrix} \]

(14)

where the subscript \( r \), \( f \), \( b \) represent rubber material, front rubber, and backing rubber, respectively.

The surface acoustic impedance of the MPPRC derived from the total transfer matrix of MPPRC:

\[ Z_{\text{MPPRC}} = t_{11} / t_{21} \]

(15)

Substituting (11) ~ (15) into (9) and (10), we can get the absorption coefficient based on the transfer matrix method.

3. Results and discussion

3.1. Experimental verification

The sound absorption coefficient measurement is conducted in a five-meter-long hydroacoustic impedance tube based on the combination of transfer function method and pulse-echo method [28]. The internal structure of the MPPRC specimen is shown in Fig. 4. The involved materials parameters at 5 °C are: \( \rho_w = 1000 \text{ kg/m}^3 \), \( c_w = 1500 \text{ m/s} \), \( \rho_t = 1039 \text{ kg/m}^3 \), \( c_t = 1470 \times (1+0.245j) \text{ m/s} \), \( \rho_c = 972 \text{ kg/m}^3 \).
c_s=1447 m/s, \mu_s=1.42 \text{ Pa·s}. The dimension parameters of the test specimens are: t_f=15 \text{ mm}, t_p=1 \text{ mm}, t_b =30 \text{ mm}, t_{fb} =t_{bi} =2 \text{ mm}, d_p =1 \text{ mm}, \sigma_p =0.031. The thickness of the equal-thickness rubber for comparison is t_e =46 \text{ mm}.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{Structure OF MPRC specimen}
\end{figure}

Fig. 5 shows the comparison of the sound absorption graphs of the experimental results and the theoretical predictions, including calculations by transfer matrix method (TMM) and electro-acoustic analogy (EAA) method. The trend of the theoretical predictions agrees with that of the experimental data, while the specific value shows a slight difference. The absorption coefficient climbs up as the frequency increases within 0.5 kHz ~5 kHz; after the first peak at about 5 kHz ~6.3 kHz, the absorption coefficient moves down a little and then increases again.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{Comparisons between the theoretical predictions and the experimental results.}
\end{figure}

Although acquired from different approaches, the absorption performances of MPRC (red lines in Fig. 5) are always better than that of equal-thickness rubber (black/blue lines in Fig. 5) at the bandwidth at above 1.6 kHz. Compared with equal-thickness rubber, the MPRC achieves better performance of the lower frequency absorption peak and higher absorption peak value, which shows the favorable influence of the MPP in castor oil.

The absorbency difference between MPRC and rubber from the experiment is much less remarkable compared with that from theoretical calculations. Besides, the calculation data for MPRC are not quite the same: compared with the experimental curve of MPRC (red dot line in Fig. 5), the calculation from equivalence method of the MPRC (red dashed line in Fig. 5) moves to a lower frequency by about 1/6 octave. All these errors mainly come from two parts: the test specimen with additional 2-mm-thick aluminum box used for sealing requirement increases the reflection of MPRC; besides, the parametric deviation of the rubber materials also causes the error to some extent.

The calculation results for rubber from the different method are in agreement with each other, implying that the calculation methods for rubber are effective and valid. As for the calculations of MPRC, the calculation result from transfer matrix method (red line in Fig. 5) shows slight movement towards lower frequency compared with that from equivalence method (red dashed line in Fig. 5), because of the neglect of the thin infiltrating layer.

3.2. Influence rule of the MPP
Considering of the Limited space for MPP and the limited changing range of viscosity of castor oil, the aperture diameter and perforation ratio are the only two influence factors in sound absorbency of
MPP. We investigated the influence of these two parameters by experiments of MPPRC specimens, where the unspecified parameters are selected as shown in Section 3.1. The test results are shown in Fig. 6.

![Figure 6. The acoustic influence of MPP parameters for MPPRC](image)

(a) The influence of the aperture diameter  
(b) The influence of the perforation ratio

As shown in Fig. 6(a), with the increase of the perforation diameter, the absorption peak moves to a lower frequency leading to the absorbency reduction at 3.15 kHz ~ 6.3 kHz. As shown in Fig. 6(b), with the increase of the perforation ratio of MPP, the absorption peak moves to a higher frequency, and the peak value moves up. The significant influence rules of the two parameters can be used to acquire better performance of MPPRC.

4. Conclusion
In this paper, we proposed an MPP-embedded rubber structure for underwater sound absorption, and establish its calculation model based on Maa’s theory, electro-acoustic equivalence and transfer matrix method. We also measure the sound absorption coefficient for validation. The experimental results are in good agreement with the theoretical predictions, demonstrating the low-frequency improvement of sound absorption characteristic provided by MPP. The influence of MPP parameters are also investigated by experiment, showing the potential of absorbing improvement by adjusting the MPP parameters. All these innovative work may inspire further researches on the combination of MPP with a more effective structure to form a broadband underwater absorber in a lower frequency.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (no. 51575201) and the Fundamental Research Funds for the Central Universities, HUST, China (Grant no. 2018JYCXJJ039). The authors gratefully acknowledge all of these supports.

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