Optimization of Low Frequency Acoustic Absorption Characteristics of Underwater Acoustic Cover Based on Nelder-Mead Simplex Method

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Abstract. In order to solve the low frequency sound absorption problem of acoustic covering layer, the local resonant cavity covering layer is established. The geometric parameters and material parameters of the composite structure are taken as optimization variables, the maximum sound absorption coefficient in the frequency band of 10-2000Hz is taken as optimization objective, and the Nelder-Mead simplicated method was used as optimization method to optimize the established model. The optimization results show that the sound absorption coefficient of the composite structure is increased by 13% and 24% respectively after the optimization of geometric parameters and material parameters. The sound pressure level of the sound wave emitted into the water area is reduced by about 3dB after the optimization, and the power loss is equivalent to increasing by half. Therefore, the sound absorption performance is improved. The research results can provide a theoretical basis for the design of acoustic coating.

Keywords: Local resonance; Cavity structure; Nelder-Mead simplex method; Optimization.

1. Introduction

Acoustic cover is a key technology affecting the acoustic stealth of underwater weapons. It can absorb the incident sound wave and reduce the radiation of its own noise [1]. At present, for several cave-type covering layers, such as cylindrical or conical cavity covering layer [2-4] and composite cavity covering layer [5], etc., the sound absorption and noise reduction performance for medium and high frequency sound waves is mainly improved by the isolation of the covering layer. But its ability to absorb low frequency sound waves is limited. The emergence of locally resonant thin film materials [6-7] provides a new research idea for solving this problem. However, local resonance thin film materials have the problem of narrow acoustic band for the absorption of low frequency sound waves. Therefore, it is of great significance to develop acoustic coatings with structural and material diversity and good low frequency sound absorption performance for improving the acoustic stealth performance of underwater weapons.

In engineering design, the optimal solution of a research problem is to choose the most reasonable one among many feasible schemes. The commonly used optimization methods include genetic algorithm [8], heuristic algorithm [9], simulated annealing method [10], etc. In recent years, Zhao Honggang et al. [11] and Yu Yilun et al. [12] have used genetic algorithm to optimize the sound absorption characteristics of acoustic covering layer in frequency band above 1kHz, and the optimization effect has been significantly improved. Chen Jingchao et al. [13] and Ma Xianchao et al. [14] used the differential evolution method of heuristic algorithm to optimize the sound absorption characteristics of the cavity rubber layer. Most of these optimization studies focused on the middle and high frequency band above 1kHz, and few studies were conducted on the low frequency band below 1kHz. The optimization of low frequency sound
The absorption characteristics of underwater sound absorption structure is of great significance to the acoustic stealth performance of underwater vehicle. There are two kinds of algorithms in the optimization module of COMSOL Multiphysics simulation software. One is gradient algorithm, which requires the derivative of the objective function. Another non-gradient algorithm, such as Bobyqa, Cobyla, etc., is suitable for the case that the objective function is discontinuous or has errors. As one of the heuristic algorithms, Nelder-Mead simplex method is a direct search method based on comparison, with strong robustness and no gradient, and can be used to solve the problem of finding the optimal solution of the optimization target in multi-dimensional space [15]. Therefore, this paper adopts this method as the optimization algorithm in this paper.

In this paper, a composite structure with a local resonance structure embedded in the cavity overburden is established. The geometric parameters and material parameters of the composite structure are taken as optimization variables respectively, the maximum sound absorption coefficient in the 10-2000Hz frequency band is taken as optimization objective, and the Nelder-Mead simplex method is used as optimization method. The optimization results are analyzed and compared. In order to analyze the reasons for the amelioration of sound absorption characteristics, the sound pressure level and the kinetic energy density of the structure before and after the optimization were compared and analyzed.

2. Method

2.1. The Establishment of Finite Element Model

Considering the feature that the frame is fixed around the thin film in the local resonance structure, the local resonance cavity overburden is established. The film material is embedded into the cavity, so that the rubber covering layer around the cavity provides support for the local resonance structure. The view of the finite element model cut up along the diagonal section is shown in Figure 1. According to the spatial geometrical characteristics of the composite structure model, only one unit of acoustic covering layer is needed to be established and Floquet periodic boundary conditions are set on the four sides of the whole model to simulate the infinite extension of the composite structure in XY plane.

![Figure 1. Comparison of structure diagram.](image)

2.2. Calculation of Sound Absorption Coefficient in COMSOL

In the background pressure field, if the incident sound pressure is $p_{in}$, then the incident sound intensity is

$$I_{in} = \frac{p_{in}}{2\rho_o c_0} \quad (1)$$

Where $\rho_o c_0$ is impedance of the incident sound field. Then the incident sound power is

$$W_{in} = \int_{S_1} I_{in} dx dy \quad (2)$$
Where, $S_i$ is the interface between the second water layer and the third rubber covering layer in Fig. 1. Similarly, the transmitted sound power is

$$W_{out} = \iiint_{S_2} I_{out} \, dx \, dy$$

(3)

Where, $S_2$ is the lower surface of the fourth layer hull in Fig. 1, and $I_{out}$ is the transmitted sound intensity at the surface $S_2$. When the sound wave is perpendicular incident to the interface of the water rubber coating, the impedance difference between the two is large, reflecting energy

$$W_{refl} = W_{in} - \iiint_{S_1} I_{in} \, dx \, dy$$

(4)

Where, $-I_{in}$ is the sound intensity of the surface $S_1$ incident into the rubber covering along the negative axis. According to the law of conservation of energy, the sound absorption coefficient is

$$\alpha = \frac{W_{in} - W_{refl} - W_{out}}{W_{in}}$$

(5)

2.3. Optimization of Sound Absorption Performance

In this section, geometric parameters and material parameters were taken as the control variables, the maximum sum of the acoustic absorptivity of the complex structure was taken as the optimization objective, the Nelder-Mead simplex method in the optimization module was adopted as the optimization method, and the optimization frequency band range was 10-2000Hz. The change of the sound absorption coefficient after optimization was compared and analyzed with that before optimization.

According to the model structure, the cavity size and the film size can be adjusted simultaneously by adjusting the perforation rate, so one of the control variables is the perforation rate $\tau$, cavity height $h$ and overburden thickness $H$. With the structural parameters as the initial parameters unchanged, the material parameters of the rubber coating including Young’s modulus $E$, Poisson’s ratio $\nu$ and loss factor $\eta$ as the control variables. The constraint conditions of the control variable are set as

$$\begin{align*}
\tau & \in [0.1, 0.5] \\
h & \in [5, 20] \\
H & \in [10, 30]
\end{align*}$$

$$\begin{align*}
E & \in [1e6, 3e8] \\
\nu & \in [0.4, 0.6] \\
\eta & \in [0.2, 0.8]
\end{align*}$$

After optimization by Nelder-Mead simplex method, the geometric parameters are

$$\begin{align*}
\tau & = 0.16005 \\
h & = 6.0[mm] \\
H & = 24.995[mm]
\end{align*}$$

$$\begin{align*}
E & = 1.99950 \times 10^6[Pa] \\
\nu & = 0.49992 \\
\eta & = 0.8
\end{align*}$$

After optimization by Nelder-Mead simplex method, the geometric parameters are

$$\begin{align*}
\tau & = 0.16005 \\
h & = 6.0[mm] \\
H & = 24.995[mm]
\end{align*}$$

After optimization by Nelder-Mead simplex method, the geometric parameters are

$$\begin{align*}
\tau & = 0.16005 \\
h & = 6.0[mm] \\
H & = 24.995[mm]
\end{align*}$$

Compared with the initial parameters, the cavity height is reduced by 10mm relative to the thickness of the entire overburden layer. The underwater sound-absorbing material deforms under the action of water pressure, which weakens the sound-absorbing performance of the material. The thicker the rubber material around the cavity, the smaller the deformation will be, and the smaller the influence on the sound-absorbing performance will be. Therefore, the optimized geometric structure has a more stable sound-absorbing performance than the initial structure. The optimized sound absorption coefficient is shown in Figure 2. Within the frequency band of 10-1000Hz, the sound absorption coefficient is increased by 13%. The peak frequency of sound absorption has been moved from 1330Hz to 750Hz now.

It is worth noting that in the simulation process, due to the influence of finite element mesh generation
and the inaccuracy of the solution average value, the calculation results have small errors. In addition, in engineering practice, the error caused by material parameters and the influence of external environment such as water pressure cannot be ignored.

![Figure 2. Optimized result of geometric parameters.](image)

Compared with the initial parameters, the loss factor changed greatly, while Young's modulus and Poisson's ratio changed little. On the one hand, it shows that the loss factor of rubber layer material has a greater influence on the sound absorption performance. Under the premise of variable loss factor of material, the larger the loss factor is, the better the low frequency sound absorption characteristics of the structure will be. The optimization results of sound absorptivity are shown in Figure 3. Overall, the sound absorptivity has been greatly improved, with the average sound absorption coefficient increasing by 24%.

### 2.4. Principle Analysis of Sound Absorption Performance Improvement

In order to analyze the reasons for the improvement of the sound absorption performance, the sound pressure level of the sound wave radiated into the water by the optimized composite structure was compared with that before the optimization. Before optimization, the sound pressure level reflected into the water area is shown in Fig. 4, with a maximum of 93dB. After optimization of material parameters, the sound absorption peak is about 750Hz, and the sound pressure level in the water area is shown in Fig. 5, with a maximum of 90.2dB, a decrease of about 3dB, and the power loss is equivalent to an increase of half. Before and after the optimization of geometric parameters, the sound pressure level was also reduced by about 3dB, which will not be described here.

![Figure 4. Sound pressure levels in pre-optimized waters.](image)

![Figure 5. Sound pressure levels in the optimized waters.](image)

### 3. Conclusion

In this paper, based on the multi-physics field simulation software COMSOL Multiphysics, the composite structure of local resonance structure embedded in the cavity overburden is established. The geometric parameters and material parameters are respectively taken as the control variables, and the maximum sum of the acoustic absorption coefficient is taken as the optimization objective. The optimization method of Nelder-Mead simplex method is adopted. The optimized structure shows that: (1) The average acoustic absorptivity of the complex structure is increased by 13% in the frequency band of 10-1000Hz after geometric optimization, and the sound absorption performance is weakened after
the frequency band of 10-1000Hz. 
(2) After the material optimization, the average sound absorption performance in the 10-2000 band is improved by about 24%.
(3) Taking the optimization of material parameters as an example, it is analyzed that the sound pressure level in the optimized water area is reduced by about 3dB, and the power consumption is increased by about half, so the sound absorption performance is improved.

The optimization results of local resonance sound absorption overlay have great reference value for engineering practice.

References

[1] ZHU B L, HUANG X C. The key technology of submarine stealth-design of acoustic overlay[M].Shanghai: Publishing house of Shanghai Jiaotong University, 2012.
[2] TAO M, TANG W L. Analysis on the Mechanism of Alberich type sound absorption coating at low frequency[J]. Journal of vibration and shock, 2011,30(1):56-60.
[3] LIU G Q, LOU J J, HE S P. Analysis of sound absorption characteristics of multilayer material based on COMSOL[J]. Ship Science and Technology, 2016,38(4):35-37.
[4] Valentin L, Anatoly S, Maxime L, et al. Super-Absorption of Acoustic Waves with Bubble Meta-Screens. Physical Review B: Condensed matter and materials physics, American Physical Society, 2015, pp.020301(R).
[5] KE L J, LIU C Y, FANG Z. Acoustic performance analysis of composite cavity structure acoustic overlay based on COMSOL[J]. Journal of research on Chinese ship. 2020, DOI: 10.19693/j.issn.1673-3185.01673.
[6] Naify C J, Chang C M, Mcknight G, et al. Membrane-type metamaterials: transmission loss of multi-celled arrays[J]. Journal of Applied Physics, 2011, 109: 104902.
[7] Ma G, Yang M, Xiao S, et al. Acoustic meta-surface with hybrid resonances[J]. Nature Materials, 2014, 13(9):873-878.
[8] MA Y, JIA J F. A review of genetic algorithms [J]. Journal of Shanxi Datong University, 2007,23(3).
[9] HE Y. Overview of Hyper-heuristic Algorithms[J]. Digital Technology and Application, 2020,38(9):94-95.
[10] CHEN P S, ZHANG Y T, TANG D Y, ZHUANG Y. Study on simulated annealing method and coupled finite element inversion[J]. Modern Tunneling Technology, 2013,50(04):76-83.
[11] ZHAO H G, WEN J H, YANG H B, et al. A sound absorption mechanism and optimization of a rubber layer containing a cylindrical cavity structure [J]. Journal of Physics, 2014,63(13):35-37:134303.
[12] YU Y L, XU H L, XIE X, et al. Optimization design of structural parameters of underwater acoustic absorbing cladding based on multi-population genetic algorithm[J].Science Technology and Engineering, 2017,17(02).
[13] CHEN J C, ZHAO H G, ZHONG J, et al. A sound absorption mechanism and optimization of rubber layer in a single period cylindrical cavity [C]. The 27th National Conference on Vibration and Noise Applications.
[14] MA X C, ZHAO H G. Optimization of sound absorption of rubber layer with embedded double-period cavities [J]. Technical Acoustics, 2018,37(6):119-120.
[15] MENG X H, SHI B C, HU X S. Dynamic sensitivity analysis of linear programming simplex method and its application[J]. Applied Mathematics, 2018,31(3):697-703.