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Design of drag reduction and water pressure resistant skin layer of underwater vehicle based on mechanical metamaterials

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Abstract. Developing high-speed and large working depth underwater vehicles has gradually become a hot topic. Various drag-reduction skins and water pressure-resistant structures have been proposed to reduce surface resistance interference and increase the working water depth. Mechanical metamaterials can exhibit extraordinary static mechanical and quasi-static mechanical properties. It provides possibilities for achieving excellent static water pressure resistance and drag reduction simultaneously. This paper proposed an underwater elastic skin based on metamaterials and drag-reducing grooves. A composite functional skin was obtained by combining the negative Poisson's ratio design of metamaterials with the V-groove drag reduction design. Analysis based on the COMSOL finite element simulation shows that lower flow resistance during high-speed and low-speed navigation and stronger pressure resistance can be achieved simultaneously. By comparing different drag reduction models, the drag reduction characteristics of the composite skin are analyzed. The results provide new ideas for the design of thin-layer multifunctional integrated underwater skins for UUV.

1. Introduction

Driven by the development of deep-sea technology and artificial intelligence technology, unmanned undersea vehicles (UUV) are demonstrating advantages such as high cost-effectiveness, good stealth performance, and wide applications, gradually becoming important equipment in future ocean development and naval warfare that can perform multiple types of complex tasks [1-2]. With the advancement of propulsion and control technology, UUV is gradually becoming larger in scale. The influence of flow resistance and noise on its speed, agility, and stealth performance is becoming increasingly apparent, and the work depth has significantly increased. Therefore, the research of their skins with drag reduction and water pressure resistance enhancing effects has gradually become a new hotspot in UUV research.

Since Kramer discovered the drag reduction effect of elastic coatings [3], researchers have proposed drag reduction design theories of underwater skins based on flexible walls, aquatic biomimetic structures, and water cloaks [4-8]. Kramer proposed a design to delay the flow turbulence transition by simulating the dolphin skin using a flexible structure layer. Dai et al. analyzed the impact of shark and dolphin skin structures on fluid viscosity and their drag reduction effect [4-5]. Riley et al. [6] proposed a skin structure with uniformly distributed elastic support, finding that it can effectively suppress disturbances in the flow field. Then, the study of the drag reduction effect and mechanism of thin elastic films containing microstructures was conducted [7]. Underwater skins can reduce navigation resistance by absorbing pressure fluctuations in turbulent flow fields while effectively suppressing flow noise. Due to the advantages of not requiring changes to the structure of the undersea vehicles and being suitable for most shell shapes, it has gradually become a hot topic in underwater drag reduction research.

At present, various drag-reduction skins for submarines have been designed. However, compared with submarines, UUV have a smaller size and a wider range of working water depth variations, and thinner skin thickness and stronger pressure resistance are required. It proposes a serious challenge to the design of underwater skins. Mechanical metamaterials are a novel type of artificial materials developed in recent years [9]. It is composed of artificial microstructure units arranged periodically. By designing microstructure unit arrays at the mesoscale, it can exhibit extraordinary physical properties that natural materials do not possess. Mechanical metamaterials can exhibit extraordinary static and quasi-static mechanical properties such as negative Poisson's ratio. Meanwhile, anomalous elastic wave modulation characteristics such as low-frequency elastic wave bandgap and super damping can be achieved [10-11]. Based on the idea of regulating mechanical properties through microstructure units rather than material components, it is possible to simultaneously achieve an optimized design for static water pressure resistance and vibration reduction performance. Based on the pressure resistance and shock absorption characteristics brought by the negative Poisson ratio of mechanical metamaterials and the drag reduction effect of the flexible skin on the v-groove surface, this paper proposes the design scheme of UUV skin with good pressure resistance and drag reduction performance. Moreover, the combination of mechanical metamaterials and the flexible skin of the v-groove surface can enhance the drag reduction performance of the flexible skin of the v-groove surface to a certain extent. Analysis based on the COMSOL finite element simulation shows that lower flow resistance during high-speed and low-speed navigation and stronger pressure resistance can be achieved simultaneously. The drag reduction mechanisms of the composite skin are analyzed by comparing different drag reduction models. The results provide new ideas for the design of thin-layer multifunctional integrated underwater skins for UUV.

2. Models and theory

We consider a flexible skin model with V-shaped groove contours on the surface to facilitate comprehension. A typical negative Poisson's ratio mechanical metamaterial is introduced to form a composite multifunctional skin structure, as shown in Figure 1(a). Here, polyurethane (density 928Kg/m^3, Young's modulus 0.001 GPa, Poisson's ratio 0.40) is used to fabricate the flexible skin, the thickness of the skin is 2mm, the V-shaped groove is formed by periodic extension of the contour of an isosceles triangle, which has a base length and height of 0.082mm each, just as shown in Figure.1(b). Such flexible skins can absorb the pressure pulsation in the early stage of turbulence burst, reduce the frequency of turbulence burst, and achieve the effect of suppressing pulsating pressure and reducing flow resistance. The structure of the negative Poisson's ratio metamaterials is shown in Figure 1(c), which adopts a honeycomb structure with a periodic arrangement of concave configuration units. Each unit is composed of thin ribs and connecting hinges. The ribs are made of aluminum alloy (density 2180Kg/m^3, Young's modulus 68.9 GPa, Poisson's ratio 0.33), and the thickness of it is 2mm. The concave structure of the unit inevitably undergoes in-plane rotation of the diagonal rod under tension and compression, resulting in the metamaterial exhibiting negative Poisson's ratio characteristics as a whole, leading to extraordinary pressure resistance characteristics. In this paper, four configurations, including U-shaped honeycomb, V-shaped honeycomb, folded honeycomb, and honeycomb sandwich panel, were designed, as shown in Figure. 1(d). The variation of pressure resistance performance with configuration is analyzed to study structural optimization.

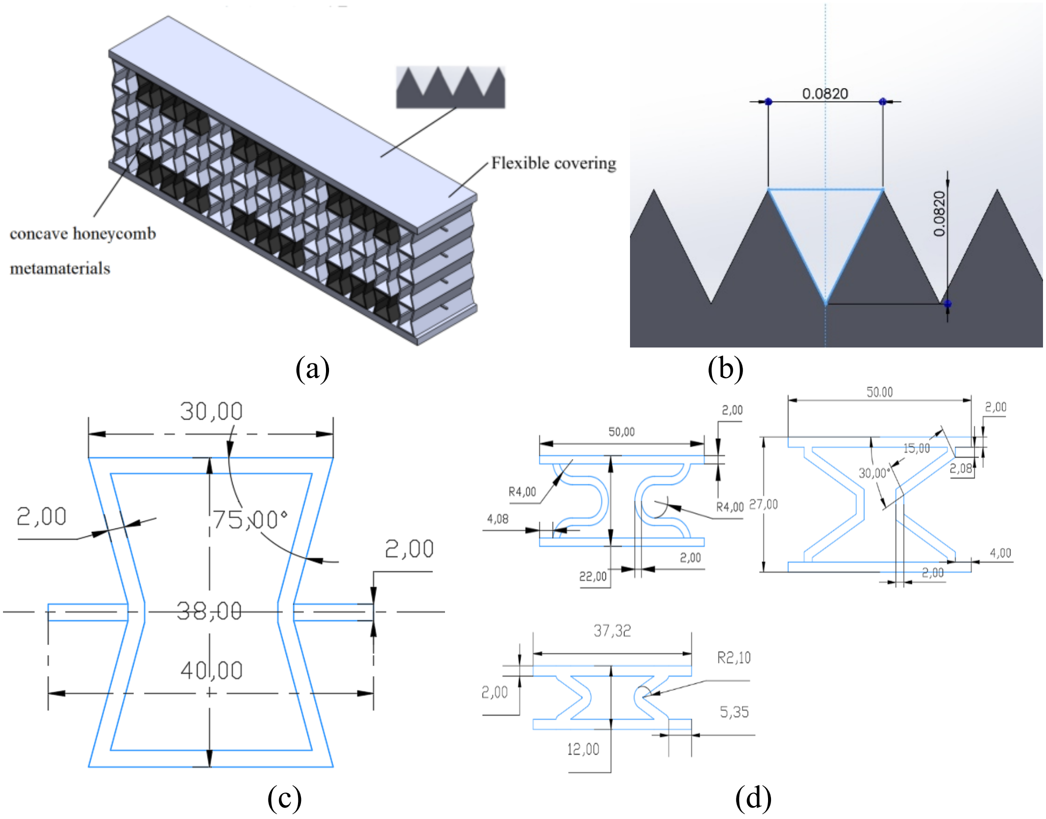


Figure 1. The skin layer of the underwater vehicle based on mechanical metamaterials. (a) schematic diagram of composite skin; (b) groove contours on the surface of composite skin; (c) concave mechanical metamaterials unit; (d) different configurations of mechanical metamaterials units.

The composite skin's flow resistance and pressure resistance characteristics in a fluid-structure coupling model are analyzed. Due to the need for large-scale calculations in flow resistance analysis, a two-dimensional numerical simulation model was established using finite element simulation software, the COMSOL Multiphysics, as shown in Figure 2(a). At the top part of the composite skin, the block is fluid area (material is water, density is 1000 kg/m^3, and sound speed is 1440 m/s); the composite skin layer with the V-shaped groove is polyurethane (density 928 Kg/m^3, Young's modulus 0.001 GPa, Poisson ratio 0.40); and the honeycomb structure is aluminum alloy (density 2180 Kg/m^3, Young's modulus 68.9 GPa, Poisson ratio 0.33). The integration of forces is set at the interface between the fluid and solid domains, as shown in Figure 3. The left and right sides are set as continuous boundaries, and the fluid's motion is set to flow in from the left and out from the right. Fixed constraints are set on both sides of the solid domain. An auxiliary scan is set with a list of liquid flow velocity values of (0.1 1 2 3 4 5 6 7 8 9 10 20 30 40 50 60 70 80 90 100), with a unit of m/s.

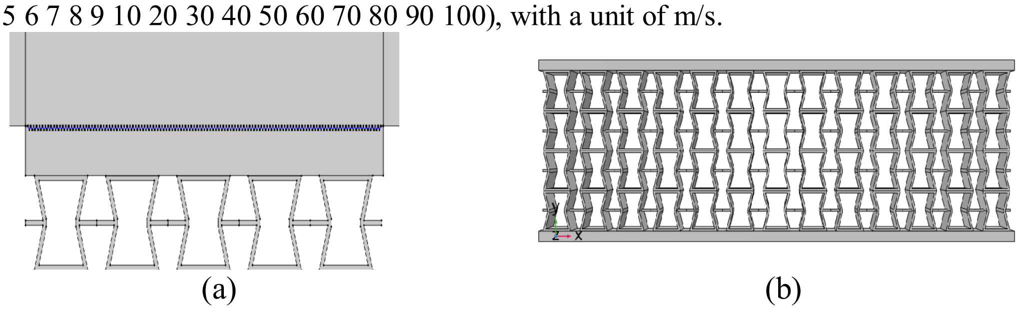


Figure 2. Simulation model for flow and pressure resistance analysis of mechanical metamaterial composite skins.

During the analysis of pressure resistance characteristics, as shown in Figure 2(b), a three-dimensional model is directly used for simulation analysis. The material parameters, boundary conditions, and constraints are consistent with the abovementioned two-dimensional model. The boundary load is set on the upper surface of the model, with only the load in the y-axis direction set to 1 N/m². Adding a steady-state and linear buckling study to the research allows for analyzing the model's maximum and minimum stresses and critical load factors.

3. Results and discussion

3.1 Flow resistance analysis

To verify the drag reduction effect of composite skin, we analyzed several models, including a: surface with both grooves and honeycomb structure, b: surface without grooves and honeycomb structure, c: surface without grooves but with honeycomb structure, and d: surface with grooves but without honeycomb structure. The variations of resistance on the different skin surfaces with flow velocity in turbulent environments are shown in Figure 3. It can be seen that, compared with smooth skin, skins with only surface grooves have a significant decrease in flow resistance at high speeds. At the same time, skin with only negative Poisson's ratio metamaterial supports also slightly decreases flow resistance in the same case. It is worth noting that the flow resistance at low speeds significantly increases after introducing the surface groove structures. However, when the surface groove structures are combined with the concave honeycomb structures, the flow resistance at low and high speeds is further reduced. This means that although the groove structure reduces the flow resistance at high speeds, it adversely affects the control of structural vibration due to the pressure pulsation under low-speed working conditions. However, due to the negative Poisson's ratio and elastic wave bandgap effect of the concave honeycomb metamaterials, the effects of the pulse pressure on the skin at low speeds can be significantly suppressed, further enhancing the drag reduction effect of the skins. The combined effect of these two structures is particularly evident under low-speed conditions.

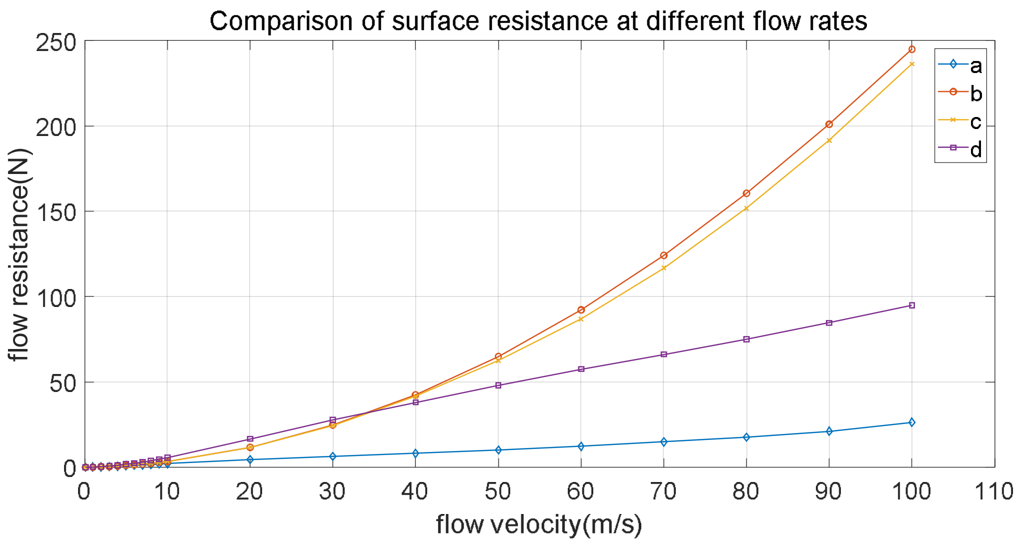


Figure 3. The resistance curves of different comparative models under different flow velocities. a: surface with both grooves and honeycomb structure; b: surface without grooves and honeycomb structure; c: surface without grooves but with honeycomb structure; d: surface with grooves without honeycomb structure.

Figure 4 shows the variation of flow resistance with the number of concave honeycomb layers. It can be seen that the flow resistance decreases with the increase of honeycomb layers. However, after the number of honeycomb layers reaches 4, the drag reduction performance of the skins will not be significantly improved. This means that the negative Poisson's ratio characteristic of the concave honeycomb structures can already be demonstrated when the number of layers reaches 4. Therefore, a four-layer structure is an optimized choice to provide good drag-reduction performance for the skin without significantly increasing its thickness. In addition, the analysis of different structural parameters shows that as long as the Poisson ratio is less than 0, the flow resistance is greatly reduced compared with the simple v-type groove structure.

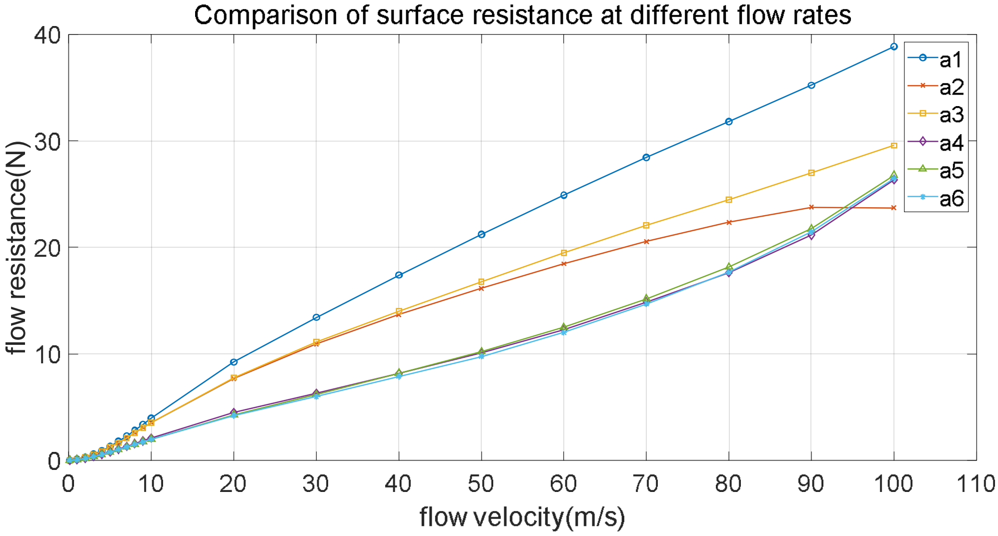
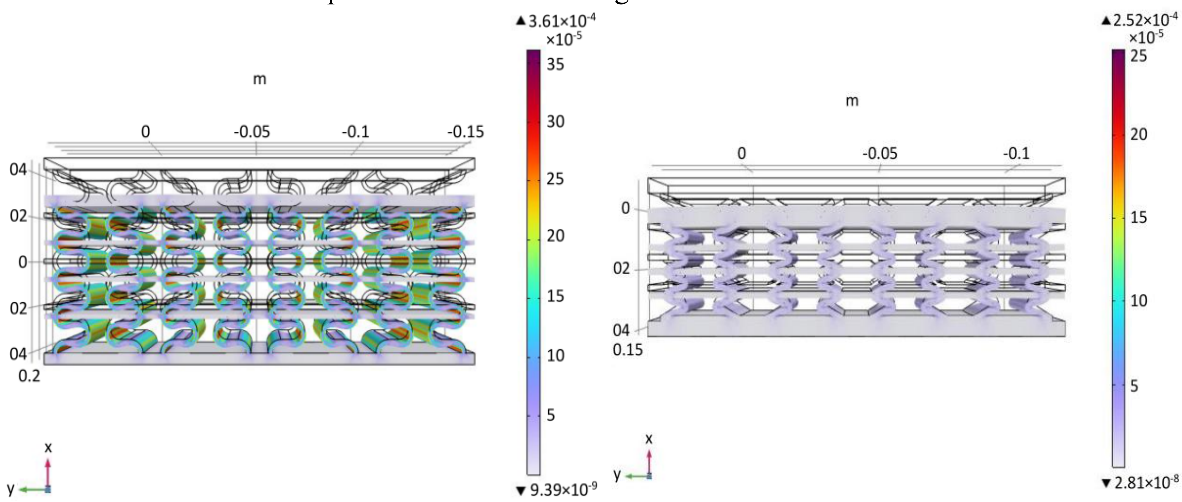
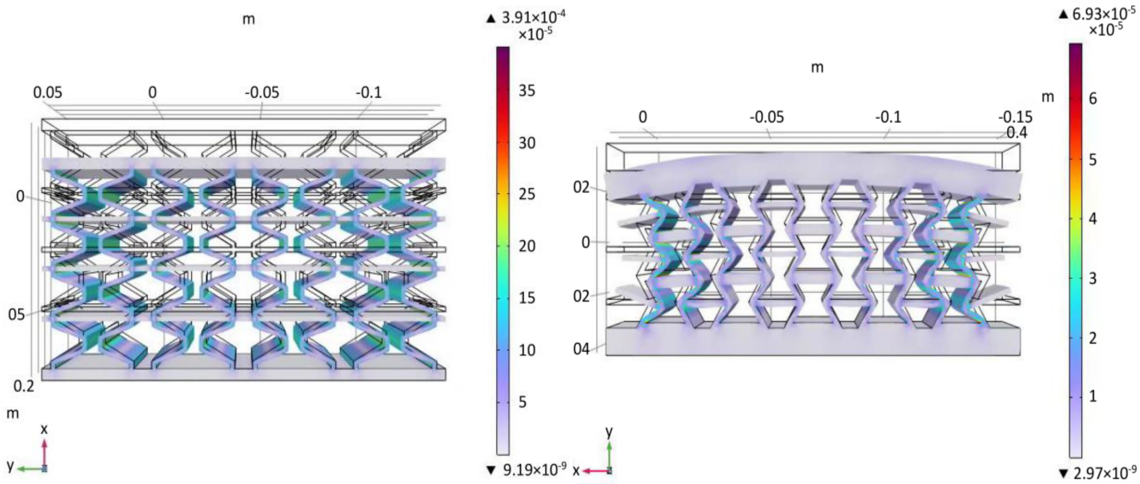


Figure 4. The resistance curves of composite skins with different layers of honeycomb structures under different flow rates, where a1-a6 represent composite skin with 1-6 layers of honeycomb structures, respectively.

3.2 Water pressure resistance analysis
The deformation and stress distribution of composite skins with four different configurations, including U-shaped honeycomb, V-shaped honeycomb, zigzag honeycomb, and honeycomb sandwich panel, under certain hydrostatic pressure, were studied using Finite element simulation. The stress distributions under the same pressure are shown in Figure 5.



(a) (b)



(c) (d)

Figure 5. Stress and deformation of composite skin of different configurations subjected to unit load; (a) U-shaped honeycomb; (b) V-shaped honeycomb; (c) zigzag honeycomb; (d) honeycomb sandwich panel.

Compared to U-shaped and zigzag elements, the stress concentration of the metamaterials with V-shaped elements significantly decreases during deformation, as shown in Figures 5(a)-5(c). The U-shaped configuration of the ribs makes it easier for the metamaterials to undergo large deformation under positive pressure, which makes it suitable for impact resistance but not conducive to the design of withstanding high static water pressure. The V-shaped configuration also has the same characteristics. Therefore, metamaterials with V-shaped elements can better utilize the anti-deformation characteristics of negative Poisson's ratio structures and withstand greater external forces. It is worth noting that honeycomb sandwich panels have much smaller maximum stress values, as shown in Figure 5(d). The panels connecting multiple units simultaneously can couple the deformation effects of multiple units and generate a uniform effect. It results in a more uniform stress distribution of the overall structure and reduces stress concentration in the structure. Therefore, the pressure that can be endured increases. Furthermore, the critical loads and maximum stresses of various structures were calculated, as shown in Table 1. It is consistent with the results in Figure 5, proving the validity of the above analysis

Table 1. Composite skin stress states of different configurations.

	U-shape honeycomb	V-shape honeycomb	Zigzag honeycomb	Honeycomb sandwich panel
Critical load	2.0068E6	2.1287E7	1.9271E6	1.9393E7
maximum stress	3.61*10^(-4)	2.25*10^(-4)	3.91*10^(-4)	6.93*10^(-5)

4. Conclusion

In summary, based on the drag reduction technology of flexible skin and mechanical metamaterials theory, a composite functional skin is proposed, which consists of the V-groove drag reduction surface on top and negative Poisson's ratio metamaterials on the bottom. Mechanical analysis models were established using the COMSOL software, and the drag reduction and water pressure resistance characteristics were analyzed. The results show that the proposed structure has a better drag reduction effect than simple elastic skin with V-grooves during high-speed and low-speed navigation, and stronger pressure resistance can be achieved simultaneously. By comparing different drag reduction models, the drag reduction characteristics of the composite skin are analyzed, and optimized metamaterials cell configuration is obtained. The results provide new ideas for the design of thin-layer multifunctional integrated underwater skins for UUV. Since the flow resistance of underwater skins is

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affected by many factors, and these influence laws are complex and even contain many nonlinear effects, further experimental research and demonstration of metamaterial composite skin are needed to promote its practical application in engineering. This will facilitate a deep understanding of its behavioral patterns and ensure its reliability and effectiveness in practical applications. Due to the complexity of underwater equipment research, most depend on experience. In the future, different materials and different cellular structures can be tried for further in-depth exploration.

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