Proceedings of the 3rd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2023), Part II
DOI: 10.54254/2755-2721/7/20230507

The application of bionics in optimizing ship resistance reduction

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Abstract. Since humans and nature have a shared destiny, harmony is the way for the two to get along. Learning from nature can lead to long-term and steady development for humans. Bionics is an emerging discipline that learns from nature modestly. The structure and products of the best organisms in species evolution work as a beacon for scientific and technological progress. In the field of ship fluid mechanics, the combination of bionics and ship and ocean engineering provides many simple and effective design schemes for the fluid performance optimization of ship materials and structures. This paper mainly summarizes and discusses the research and application status of bionics in the field of ship fluid drag reduction from four aspects, namely the imitation of biological shape, biological epidermal texture, biological function, and biological structure. Conclusions can be drawn that bionics can used to improve a ship's shape, structure, surface materials, and marine coatings to optimize ship fluid performance and effectively reduce ship drag.

Keywords: Bionics, Shipping, Anti-drag, Hydrodynamics.

1. Introduction

Ship resistance mainly includes friction resistance, wave resistance, viscosity resistance, and shape resistance, among which, friction resistance usually occupies the main part. Frictional resistance is generated by the tangential force between the ship's surface and the water. For example, for cargo ships, the friction resistance is about 65% of the overall resistance; for oil tankers, it can be about 80% of the total resistance. Therefore, how to effectively reduce resistance has always been the focus of the shipping industry. There are two main methods to reduce ship resistance: the first is to optimize the design of the ship's shape, for instance, using the spherical bow and wave plate design can reduce the wave resistance; the second is to change the property of the wet area of the hull, for example, the use of a hydrophobic coating, an increase of surfactant, and the application of gas can all used to reduce friction resistance [1].

After long-term natural selection, organisms have a beautiful and reasonable structure. Several basic biological materials, such as sugar, protein, minerals, and water, form a complex but accurate organic system and realize various biological functions [2]. For example, animal bones, skin, the mucosa of marine organisms, and shellfish shells are delicately structured and have excellent performance, far surpassing man-made materials and structures with similar functions. Bionics is to

DOI: 10.54254/2755-2721/7/20230507

take the excellent structure and characteristics of natural organisms as the research objects and apply the structural properties, energy conversion, and information process of organisms to technological innovation.

However, because organisms are complex and diverse, the environment they live in differs from each other, and ships also have various structures and functions, both the structural bionic theory and the application of structural bionic material engineering need in-depth research. This paper summarizes the research progress of the application of bionics in reducing ship resistance from four aspects: biological shape, biological epidermal texture, biological function, and biological structure. The author also analyzes the current situation of ship-bionics research and discusses its future development direction. This paper provides the research direction and method for future ship development in environmental protection and energy saving.

2. Bionics in ship resistance reduction

2.1. Resistance reduction design in imitation of the biological shape

Applying the shape of organisms in nature to the shape design of the hull is one of the applications of bionics. Water organisms have evolved a highly efficient swimming shape in the long years of living and reproduction, therefore, through the study of structural bionics, a better drag reduction effect of the ship shape can be designed. The Northwestern Polytechnical University of China built the world's first bionic underwater vehicle with an application ability (as shown in Figure 1). The vehicle completely imitates the shape of a manta ray. With sliding and flapping integrated mixed-propulsion ability, minimum fluid resistance can be achieved through hydrodynamic mechanism research. This bionic underwater vehicle can not only "glide" in water efficiently over a long distance but can also "flutter" with high kinetic energy. With a hard trunk and two soft wings, it is highly similar to a real manta ray both in shape and action. This kind of bionic underwater vehicle will play an important role in marine environmental protection in the future.

Figure 1. The bionic underwater vehicle imitating a manta ray (the picture originates from Northwestern Polytechnical University).

2.2. Resistance reduction design in imitation of the biological epidermal texture

Physical texture refers to the characteristics of the surface tissue structure that organisms have evolved to adapt to their living environment. Applying these surface textures to mechanical surfaces in a similar working environment can effectively improve the adaptability of machinery to the working environment, which is an imitation of biological epidermal texture [3].

Early researchers believed that friction is proportional to the roughness of the contact surface, and the way to reduce friction is to reduce the surface roughness coefficient of an object. However, with the pursuit of a high speed, the method of reducing the friction force by reducing the surface rough coefficient is no longer applicable. According to the hydrodynamic boundary layer theory, when the object is in a state of high-speed motion, the pressure and velocity distribution in the turbulent boundary layer on the object's surface will cause friction between the fluid and the contact surface. The smoother the surface, the greater the friction. So, people began to look for ways to reduce friction from those organisms swimming at high speeds in the ocean.

In the vast ocean, sharks are among the best of many different types of fish. They are highly streamlined, swimming-friendly, and covered with shield scales. Studies have found that in addition to providing strong protection to sharks, the shield scales can also increase their fluid power and allow them to swim faster. Under a magnification lens, these scales grow in the direction from head to tail, presenting dentate processes. Each scale has three to five radial ribs (as shown in Figure 2 (a) and (b)). Studies have shown that mimicking the shark epidermis structure plays a huge role in reducing friction [4]. An imitation of the shape features of the shark's shield scale is used for ship resistance reduction. The experiment shows that the resistance coefficient is reduced by 3.75% and the resistance of the container ship model is reduced by 3.89%, achieving a major breakthrough in resistance reduction. Scientists have also found that although sharks live at the bottom of the sea, they do not hang with any algae on their bodies and there are no other marine creatures found living on the surface of their bodies. Studies have found that, on shark's shield scales, there are many thorn bumps with irregular alignment, not as smooth as ordinary fish, which can make it difficult for plant spores to attach to the shark's surface. Thus, a bionic shark coating material called polydimethylsiloxane (PDMS) is invented by using plastic and rubber. There are many prismatic thorn bumps on the surface of the material (as shown in Figure 2 (c)), which will expand and shrink with the current change, making constantly peristalsis on the surface of the ship. The coating material does not affect the ship's speed and can prevent seaweed and other seabed organisms from sticking to the bottom of the ship. This material has reduced the settlement rate of algae and other spores on the ship's bottom by 85%, with an obvious effect [5].

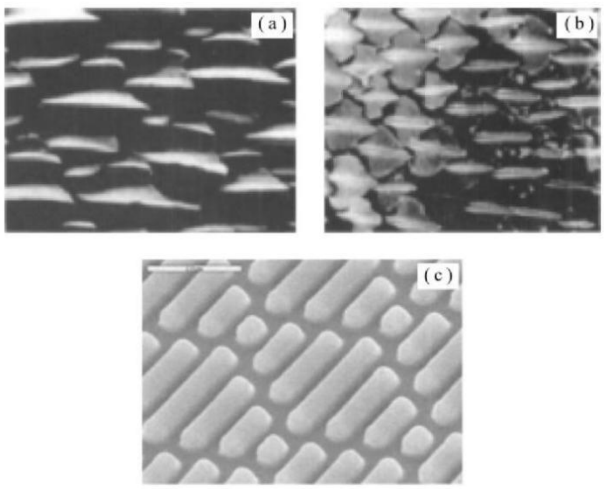

Figure 2. Microstructure and biomimetic material of the shark epidermis PDMS (the picture originates from antifouling potential of lubricious, micro-engineered, PDMS elastomers against zoospores of the green fouling alga Ulva (*Enteromorpha*)).

Due to the streamlined shape of the body and its special epidermal structure, the dolphin travels in the sea at a much higher speed than its usual swimming speed. The outer skin (as shown in Figure 3) is covered with a smooth corneous membrane and the dermis below the skin is covered with papillae filled with blood and body fluid. These papillae can help dolphins withstand a large amount of pressure when they swim at high speeds [6]. Gray et al. found that dolphins can swim at a high speed thanks to the "adaptive surface" of their elastic skin. When the dolphin's surface skin rubs rapidly against the seawater, the epidermis changes correspondingly from a smooth surface to an irregular and

DOI: 10.54254/2755-2721/7/20230507

non-smooth surface, which leads to a change in the nature of the surrounding flow field of the dolphin during swimming. The surrounding flow field is transformed from turbulence into a laminar flow. This phenomenon is called "adaptivity" [7]. Since dolphin skin changes with their swimming speed, scientists developed a bionic underwater robot by imitating the "adaptivity" of the dolphin's pitted surface skin changing with its swimming speed. Through a comparative experiment between the bionic robot with a pitted surface and one with a smooth surface, it is found that the bionic robot with a pitted surface has a significant resistance reduction effect and its speed is also increased by 5% [8].

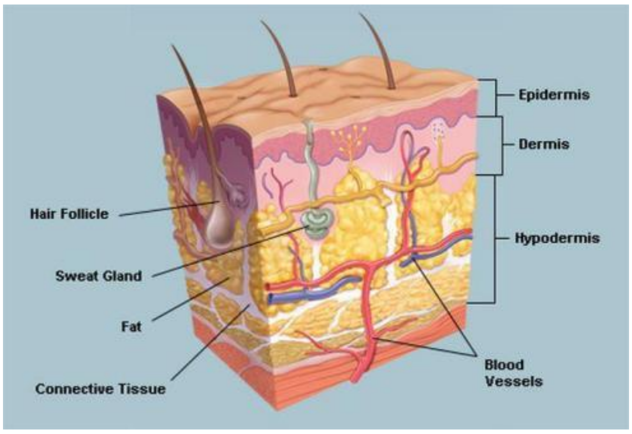

Figure 3. The structure of dolphin epidermis (the picture originates from the Internet).

Figure 4. The surface of the hull underwater attached by shells and mollusks (the picture originates from the Internet).

In addition to the shark texture and dolphin texture mentioned above, other efficient biomimetic non-smooth textures also include puffer spines. These creatures in nature optimize their surface tissue structure to adapt to the living environment and this kind of structure optimization is utilized and imitated to improve the surface design of the hull so that the ship can adapt to the water environment like aquatic organisms. Compared with morphological imitation, texture imitation pays more attention to surface materials and special structural attributes, which not only needs enough scientific and technological support but also needs careful observation of nature with more ideas being put forward.

2.3. Resistance reduction design in imitation of biological function

During more than 2,000 years of development, the material of the hull of the ship changed from wood covered by lead plates at the bottom to iron in the early 18th century. Since then, anti-pollution coatings such as copper, arsenic, mercury, and other oxides appeared and were widely used to prevent the ship from being polluted. There are a wide variety of organisms attached to the surface of ships when sailing in the ocean. The organism-attached parts are mainly those underwater parts, waterline areas, propellers, and seawater pipes. Usually, there are mainly algae and barnacles in the waterline part and shells and mollusks in the boat's bottom part. The attachment speed is fast. Figure 4 shows the surface of the hull underwater. This situation has greatly increased the resistance of ships, so in the 20th century, with the demand for high-speed ships, resistance reduction coating materials in imitation of the biological function started to come into the sight of scientists.

2.3.1. Study on the structure of large marine organisms. As for ships, epidermal microbial attachments can increase their resistance and reduce their swimming speed. Studies have found that organisms in nature have their own unique anti-fouling mechanisms, including chemical anti-fouling (active molecules, biological enzymes) and physical anti-fouling (microstructure, surface function, etc.) [9]. Many large marine organisms do not have microorganisms attached to them. Sharks, for example, have shield scales in the same direction, compact and orderly, ensuring a smooth surface and preventing microbial attachment; besides, the shark skin can secrete mucus, thus forming a hydrophilic surface to make it difficult for organisms to attach and can effectively reduce the friction resistance with the seawater. For the anti-fouling resistance reduction problem, according to the marine plankton attachment law and bionics principle, Xu Guoqing put forward a solution of "bionic dolphin skin and anti-fouling composite group epidermis", that is, choosing hydrophobic high-performance acrylic polymer material for coating substrate and using the method of mutual penetration network to form the coating with a hydrophilic-hydrophobic material microphase separation epidermal structure by combining with hydrophilic natural non-toxic polymer persimmon tannin antibacterial water absorption resin. The resistance reduction effect is significant [10].

2.3.2. Study on the extractive of freshwater and land plants. Eight bacteria were purified from the marine biofilm by 725 Research Institute of China Shipbuilding Industry. Results showed that the 725-4 strain can effectively inhibit the attachment of algae, various invertebrate larvae, and the formation of mussel filopodia [11]. Diterpenoids derived from corals as well as loop-opening steroid compounds showed significant effects on parasitism in young barnacle larvae. Moreover, halofuranone compounds with high-efficiency resistance to barnacle larval parasitism can be isolated from red algae; green algae contains terpenoids which can prevent pollution against bacteria and microalgae; the phenol compounds contained in fan algae also play a positive role in preventing the growth of bacteria [12]. Sponges in the ocean can also metabolize many unique decontamination products [13]. Two sponges, *Aplysina fulva* and *Callyspongia crassa*, found on the Saudi coast, both metabolize the metabolite with good growth inhibition for marine bacteria [14]. In addition, researchers at the University of Bonn in Germany have discovered the secret of the "superhydrophobic" of *Salvinia natans*, which has many clumps of radioactive micro-hairs on its surface with a very hydrophilic tip. After entering the water, the plant is able to lock the water molecules to the hairy tip, effectively protecting the air layer from the tip to the leaf surface. Researchers believe that imitating the surface structure of *Salvinia natans* to make a new coating will have broad application prospects. By forming an air film on the surface of the hull through a special coating, the energy consumption caused by the friction between the ship and the water can be reduced by 10%, with an excellent resistance reduction effect. In addition to looking for coatings to control pollution from marine life in the same environment, many anti-fouling extractives have also been found in land plants, such as capsaicin and paeonol, which have a similar anti-fouling function [15].

2.3.3. Study on the shell of shellfish. Xie Guotao of Wuhan University of Technology took five kinds of shells with different surface micro-structures, including *Dosinorbis japonica*, *Gafrarium pectinatum*, *Chlamys nobilis*, *Cyclina sinensis*, and *Lioconcha castrensis*, as bionic objects [16]. Polydimethylsiloxane (PDMS) is used as the material for male die and Epoxy resin E44 and polyurethane'PU glue are used as the material for female die. Thus, a biomimetic surface with the micro-structure of the shell surface can be made by applying the method of biological replication molding. Using three-dimensional surface contour measurement equipment and the biorthogonal wavelet transform method, six parameters are compared, namely the surface average roughness Sa, the mean square root Sq, the surface steep degree Stdi, the surface ten-point uneven value Sz, the valley peak distance Sy, and the surface texture index Stdi. By analyzing the advantages and disadvantages of the two materials, the research lays a foundation for the study of the anti-fouling method based on shell surface microstructure.

However, so far, domestic research on the shell structure is mainly focused on the internal microstructure of the shell and the resulting material properties, as well as the surface wear resistance of the shell-based bionic prism geometry. The research on the marine stain biological attachment properties of the shell still has great room for development. Therefore, the relationship between shell surface morphology and the attachment degree of marine defacing organisms as well as the attachment mechanism of shell resistance to marine defacing organisms are proposed to be studied in the future, thus establishing the biomimetic inhibition technology based on surface morphology and anti-attachment mechanism. The specific research method is shown in Figure 5 [17].

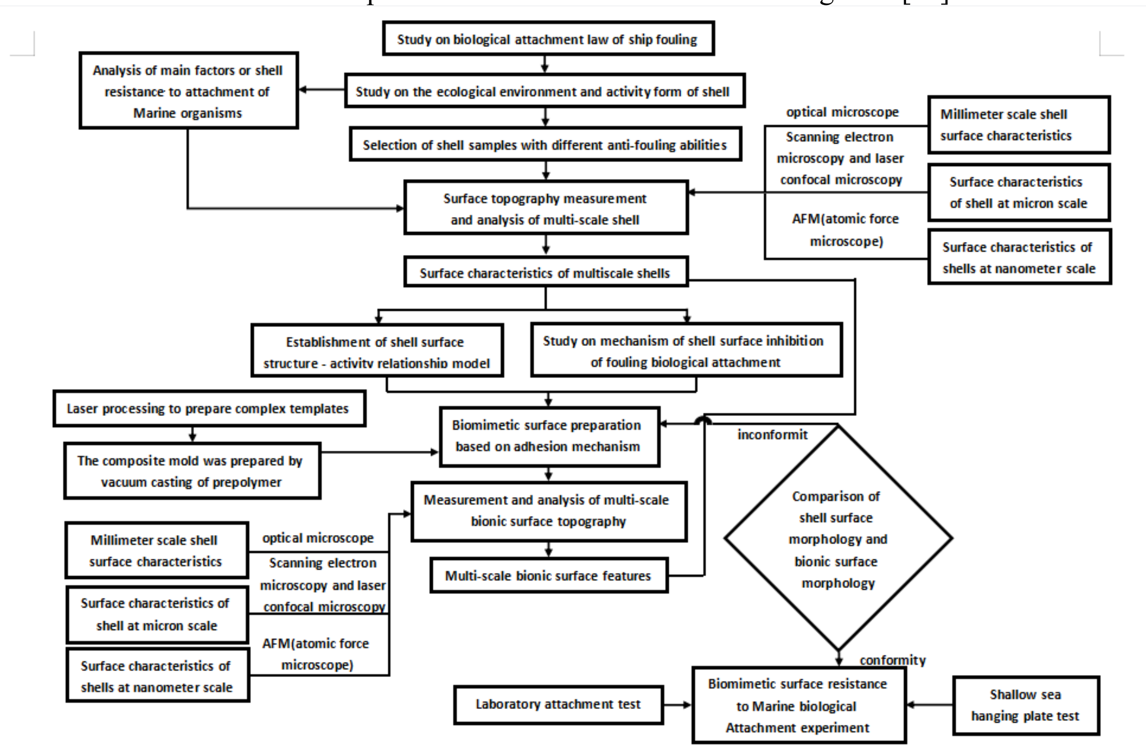

Figure 5. The research method of the biomimetic inhibition technology based on surface morphology and anti-attachment mechanism.

2.4. Resistance reduction design in imitation of biological structure

To reduce the resistance of submarine navigation in the water, the biological structures of swordfish and humpback whales are used to design a bionic submarine to reduce water resistance. The front part of the submarine imitates the sword-like upper jaw of swordfish, the rear of the submarine imitates the tail of swordfish, and there are stabilizing fins both on the left and right sides of the middle of the submarine imitating the fins of humpback whales, which can maintain the balance of the submarine and significantly reduce its swing and vibration combined with the shock mitigation system installed on the submarine. This submarine combining a variety of bionic structures effectively reduces water resistance and improves the submarine's ability to adapt to underwater navigation. At present, flying fish is a major research direction of ship bionics, which involves the transformation of two kinds of fluid media. Flying fish can jump out of the water at a high speed and slide tens of meters in the air. The high power and low resistance of flying fish are the exploration directions of bionics in ship resistance reduction.

3. Significance of bionics application in ship resistance reduction

With the rapid development of biological sciences, bionics has produced various combinations with disciplines in other fields. Bionics pursues learning from nature, finds inspiration from nature, and puts those inspirations into practice. In the design of ships, many creatures of nature provide solutions for the optimization of ships. From the appearance, the imitation of creatures makes ships look elegant and streamlined. Functionally, diverse and complex biological structures also provide a reference for ships to adapt to the ocean. With the concept of green ship proposed, effective energy saving is needed while increasing the ship’s speed and reducing pollutant emissions. Advanced technology is the premise of green ship design and manufacturing. The application of bionics in the field of ship design

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can provide many new inspirations for ship design. Therefore, the research and development of bionics are still yet to be studied and discussed more, and the significance of bionics in the field of ship design should be paid attention to from many different perspectives.

4. Conclusion

This paper studies the application of bionics in resistance reduction of the ship mainly from the aspects of biological shape, biological epidermal texture, biological function, and biological structure. In conclusion, bionics can be used to improve the shape, structure, materials, and coatings of a ship, thus optimizing the fluid performance of ships to effectively reduce ship resistance. Bionics is a trend in the development of ship design. It can not only help speed a ship but also reduce the emission and the loss of fuel oil, thus protecting environment and saving energy. Apart from ship resistance reduction, bionics can also be used in ship shock absorption, pollution prevention, and even in military, industrial, construction, and other fields. Bionics is the intersection of many disciplines, such as biological science, materials science, medicine, chemistry, and engineering mechanics. Only by strengthening the multidisciplinary collaboration can in-depth research of bionics be enhanced, thereby promoting technological innovation.

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