Review on the ship drag reduction technology

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Abstract. The development of the theory of turbulence has made a breakthrough in the application of drag reduction technology on ships, which contributes to energy saving and environmental protection. When a ship is sailing, it has to overcome resistance. Total resistance includes frictional resistance, wave-making resistance, and viscous pressure resistance, in which frictional resistance acts as the main resistance for low-speed ships, and for high-speed ships, the main resistance is wave-making resistance. This paper reviews the ship drag reduction technology by giving a brief introduction to drag reduction methods using grooves, bulbous bows, bubbles, hydrofoils, wall vibration, and high-polymer additive respectively, as well as their principles.

Keywords: drag reduction, resistance, energy saving, ship.

1. Introduction

Compared with land transport, sea transport has the advantages of large volume, long distance, dense network, mature development, and relatively low cost. Therefore, ship transport is an important form of transport in the modern world. In the recent development process, because of the more and more obvious trend of globalization, the transactions between countries and regions are becoming more and more frequent, and the number of ships has also increased. However, in the process of transportation, ships will emit CO2 and other harmful substances, which will have a negative impact on the environment. The strong mobility as well as the unbounded, and trans-regional nature of ships in terms of carbon emissions also increase the difficulty of controlling ship emissions. And the drag reduction of ships can improve the carbon emissions of ships to a large extent, so as to alleviate the global greenhouse effect and other environmental problems.

First of all, resistance is the force required to push a ship through the water at a constant speed, i.e., with no acceleration. Resistance arises from a number of different physical processes. And in general terms, hydrodynamic resistance can be summarized as:

Total Resistance=Frictional Resistance+Viscous Pressure Resistance+Wave-making Resistance

So it is easy to understand that the core of ship drag reduction is to reduce these three terms of resistance, and all the methods listed below are based on this idea.

2. Grooves for drag reduction

This is actually a form of bionic drag reduction. NASA's research center in the 1970s [1] found that the tiny grooved surface downstream can effectively reduce the wall friction and has a certain scale of triangle groove as the best friction-reducing groove geometry. The use of the rib-grooved surface to reduce the hydrodynamic resistance not only breaks traditional ideas but also brings a new research direction for ship drag reduction. The idea that the smoother the surface, the less the resistance is questioned, and groove drag reduction has become a research focus in turbulent drag reduction technology. The technology originated from the bionics study on the skin of fish such as sharks [2]. After studying more than 40 kinds of sharks at different growth stages, Professor Reif found that, when sharks swim quickly, there are finely spaced scales on the skin, with rounded valleys between the scales, and the arrangement of scales is basically parallel to the direction of flow. Scales on shark skin can stabilize the boundary layer and reduce the resistance. Inspired by this, the wall friction resistance is reduced by the bionic non-smooth groove technology, and a good drag reduction effect can be achieved only by changing the surface shape, which is considered to be the most promising method in all kinds of drag reduction technologies. Progress has been made in the research on groove technology, the grooves in the drag reduction mechanism, the influencing factors of grooved surface drag reduction, and the industrial application of groove technology.

The microscopic flow field on the surface of the groove is different from the surface flow field in general, these special structures may be associated with the drag reduction effect. At the same time, researchers analyzed the principle of the groove surface turbulent drag reduction which leads to a variety of theories. One of the theories is "the second vortex group theory". Researchers think that the thickness of the bottom layer of viscous flow in contact with the bottom of the ship has an influence on the resistance of the ship, and the second vortex group is produced by the interaction of contra-rotating flow vortices with sharp peaks. The generation and development of "secondary vortices" weaken the strength of flowing vortices associated with low-velocity bands, inhibit the formation of low-velocity bands, and weaken the instability of low-velocity bands [3]. In other words, the process of low-velocity bands slowly lifting up and bursting is weakened, and the momentum exchange among fluid microclusters is reduced, thus achieving drag reduction.

3. Bulbous bows for drag reduction

Bulbous bow is a very common technique used on ships to reduce wave-making resistance. Around one hundred years ago, Froude explained the decrease in the drag of ships after the installation of torpedo tubes. He pointed out that this was due to the damping effect caused by the dulling of the bow by the torpedo tubes. Taylor was the first person to realize that a bulbous bow can be used to reduce wave-making resistance. In 1907, he fitted a bulbous bow to a battleship, which resulted in a higher speed with no change in power. In order to study the effectiveness of the bulbous bow, researchers conducted a large number of experiments and found that the bulbous bow could produce a 180-degree reversal wave, which could make the peaks and troughs of the waves formed by the hull and the bulbous separately meet and cancel each other, thus reducing the loss of energy, that is, reducing the wave-making resistance of the hull. Now there is a variable bulbous bow technology, which designs the bulbous bow with adjustable length. The water wave generated by the bulbous bow when the ship is sailing can be controlled by adjusting the length of the bulbous bow. The length of the bulbous bow can be adjusted at any time according to the ship's speed, so that the wave amplitude can be minimized at any speed after the superposition of the water wave generated by the bulbous bow and the water wave generated by the hull bow.

However, it should be noted that the disadvantage of the bulbous bow is that it increases the construction cost and affects the arrangement of mooring equipment. The purpose of the bulbous bow is to adjust the waves produced by the ship during sailing. However, after the implementation of deceleration sailing by various liner companies, the existence of the bulbous bow increases the ship running resistance due to the decreasing wave fluctuation amplitude. For example, the bulbous bow is easy to be damaged when leaving the dock and anchoring, which increases the cost of construction and affects the arrangement of mooring equipment. The effect of the bulbous bow is not ideal when the wind and waves are strong. The bulb itself is vulnerable to damage. Due to many factors, the design of bulbous bows of surface ships has not made any great breakthroughs in drag reduction for a long period. The complex outboard shape of the bulbous bow of large destroyers has a significant and

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intricate influence on drag reduction and energy saving. There are existing large destroyers using the bulbous bow as a sonar deflector, and this type of bulbous bow does not have the function of reducing drag and saving energy, but sometimes it will increase the drag [4].

4. Bubbles for drag reduction

As early as the late 19th century, Froude had proposed a method of reducing the resistance of boats by pumping air into the bottom of the boat to isolate the water from the hull. But due to limited theoretical research at that time, micro-bubble drag reduction technology was not applied to civilian ships until the 1960s. At present, the technology mainly focuses on the development of speedboats and catamarans. Compared with other high-speed ships (such as hydrofoils and hovercrafts), high-speed bubble ships have the advantages of simple structures, low costs, and easy maintenance. Besides, it is also convenient for high-speed bubble ships to leave the port [5].

In 1975, the Soviet scholars Migirenko [6], Dunischev [7], and Bogdevich [8] used a porous stainless steel flat plate to do the experiment. The micro-bubbles were introduced into the turbulent boundary layer to reduce the drag. The experimental results show that the diameter of the air vent and the volume concentration of the bubble have a great influence on the drag reduction rate. When the diameter of the air vent is 1-3 μm, the drag reduction rate is the highest. But when the diameter of the air vent is longer than 50 μm, the bubble drag reduction is almost ineffective. The ideal bubble diameter is 1-50 μm, and the bubble volume concentration reaches the maximum at the 1/10 boundary layer thickness from the wall. At this time, increasing the atmospheric flux will improve the drag reduction. When the airflow reaches saturation in the flow field, increasing the airflow has no effect on the drag reduction rate.

In the early 1980s, the United States researchers [9] conducted tests in a closed circulation water tunnel to verify the study of the Soviet Union. The maximum jet flow of the test was about 6 times of the previous test, and the test results were basically consistent. The local friction resistance could be reduced by 80%. The test results show that the drag reduction rate is obviously improved by keeping the inlet flow velocity unchanged and increasing the unit jet flow until the gas flow reaches saturation. The drag reduction effect decreases when the unit air jet flow remains unchanged and the inlet flow velocity increases. In the test process, it is found that the diameter of the air injection hole has no direct relationship with the drag reduction rate, and there is no difference between the drag reduction effect of the aperture of 0.5μm and 100μm under the same unit air injection flow and flow inlet speed.

In the 1990s, Hiroshima University in Japan carried out a micro-bubble drag reduction test. The results show that, with the increase of air injection volume, the model resistance increases correspondingly due to the increase of friction resistance and shape resistance. The resistance of the other model with the bubble covering decreases with the increase of the incoming flow velocity and the number of bubbles, and the bubble-blowing part has little effect on the wave-making resistance. As the model is covered by bubbles, bubbles tend to break away from the boundary layer under the influence of buoyancy, resulting in a low drag reduction rate.

Since the turbulent boundary layer of micro-bubbles and water is an extremely complex gas-liquid two-phase flow field, the drag reduction mechanism of micro-bubbles is still not very clear so far. In order to study this phenomenon in detail, the kinematic and dynamic characteristics of bubbles in water must be studied. A relatively shallow analysis of the principle of bubble drag reduction technology is that bubbles change the fluid around the ship and create the formation of a new flow circulation system as well as separate the hull surface from water, which eventually reduce the friction resistance [10].

At the same time, it is important to note that the bubble drag reduction method needs to inject gas into the bottom of the ship. This process requires energy consumption. From a practical point of view, if the drag reduction effect is not particularly obvious, the use of the bubble drag reduction method may increase the total energy consumption, which is not an economic choice. Another disadvantage is that the bubble is unstable, once the drag reduction bubble burst, greater resistance and noise will be produced, and if the bubble is too small, it can not achieve the drag reduction well, so attention is

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needed to the generation and elimination of bubbles. This is also the focus of the next research direction of bubble drag reduction.

5. Hydrofoils for drag reduction

If analyzed more meticulously, the drag of the ship contains not only the water part, but also the air part. For most ordinary ships, the proportion of the air resistance in the total resistance is very small. In other words, there is a need to reduce the volume of the underwater part of the hull to minimize the water part resistance. Water and air are both fluids, and the plane relies on its wings to move through the air at high speeds to gain the lift, allowing its huge fuselage to soar. Similarly, the wings of hydrofoils are installed under the hull. Hydrofoil ships moving forward at a high speed also get the lift. The heavy hull is above the water surface, and only the propeller and rudder are underwater. This is also the basic principle of hydrofoil resistance reduction [11].

Hydrofoil ships fly out of the water, so compared with gliders or high-speed catamarans with the same tonnage and speed, hydrofoil ships have only about half of the water resistance, namely with small power for higher speeds, which greatly improves the efficiency. The economic speed range of the hydrofoil is about 55-75 km/h, and the speed of the high-speed hydrofoil can reach 100 km/h (54 kn). Moreover, since the hull is separated from the surface of the water, though it is at high speeds, the wave is too small to cause damage to the bank, therefore, it is suitable for high-speed passenger transport operated in the inland river. A properly designed self-stabilizing hydrofoil system has a suitable motion response in wind and waves, and its pitch, roll, and heave motions are smaller than those of a coasting boat, catamaran, or hovercraft with the same size and speed.

Most of the hydrofoils in existence today are less than 1000 tons, and they mainly sail near the sea or in the inland river. The main disadvantage is that there are technical difficulties in building large hydrofoils at this stage, or increasing their speed further. The buoyancy provided by hydrofoils has a square relationship with the length, but the weight of the ship has a cubic relationship with the length, so it is difficult to make larger hydrofoil ships. That is why, at this stage, hydrofoils are mainly used for passenger transport rather than freight. In order to further improve the speed, problems of bubbles (cavitation) created by hydrofoils at a high speed also need to be solved. In addition, the higher fuel cost for hydrofoils using gas engines is also a commercial consideration.

6. Wall vibration for drag reduction

The traditional view is that the fluid flow can be worsened by the reaction of the vibration of the structure, so the vibration of such structures needs to be avoided. However, recent research results show that proper vibration of the structure can improve the flow state of the fluid and thus reduce the resistance. The theoretical analysis can be obtained by numerical analyses or software simulation, which will not be described in detail here.

With the increase of vibration intensity, flow field disturbance increases gradually. When the vibration intensity exceeds a certain value, the flow field cannot maintain stable flow into turbulence, and the flow resistance increases significantly.

At present, there is a large amount of research on vibration drag reduction, and there are two theories about its mechanism analysis: based on the first theory, it is believed that drag reduction is related to the vortex state on the vibrating wall in the periodic direction of wingspan, because this reduces the average velocity gradient at the viscous bottom, thus affecting the boundary layer. The streamer vortices in the near-wall area are also rearranged along the wingspan direction, thus weakening the wave intensity of streamer vortices in the transverse boundary layer. The second theory holds that there is a regeneration cycle phenomenon of quasi-flowing vortices in the turbulent boundary layer which maintains wall turbulence. Therefore, the quasi-flowing vortices are the main cause of the frictional force on the turbulent surface, and the wall vibration interferes with the regeneration cycle of the quasi-flowing vortices to achieve the purpose of drag reduction.

At present, the application of vibration drag reduction in ships is not very mature and its shortcomings are also very obvious: the noise is too large, the vibration frequency is not easy to control, and it can not be ignored that it will undoubtedly accelerate the fatigue of the hull.

7. High-polymer additive for drag reduction

In 1947, Toms observed the mechanical degradation of polymer flowing in a tube and found that if a small number of long-chain polymer additives were dissolved in Newton fluid, fluid movement resistance in the turbulent zone can be greatly reduced and slow down the occurrence of turbulence.

Polymer additives reduce drag by creating conditions from the inside boundary of the liquid. The common feature of long-chain polymer additives is that their rated molecular weights are up to millions of orders of magnitude. Scholars have done a lot of research on its drag reduction mechanism and come up with a variety of explanations from different angles. One explanation is that it can change the properties of the fluid. The high viscosity of the dilute polymer solution hinders the expansion of the vortex, reduces the burst frequency of turbulence, and makes the flow rate more stable. In other words, it changes the friction force between the fluid and the ship, and reduces the friction coefficient of the ship's surface [12].

However, the cost of polymer additives is huge. Although researchers have done a lot of experiments, little effect there is in reducing the cost. At the same time, the use of a large number of polymer additives will also have an impact on the river and sea environment, and long-term use will certainly bring environmental problems. Thus, the using standard of polymer additives needs to be strictly divided and planned.

8. Conclusion

This paper summarizes the common ship drag reduction technologies. They can mainly be divided into two types: the first one is to keep the ship displacement unchanged through a variety of technologies to change the nature of the fluid or change the distribution of the flow field, so as to reduce the resistance; the second is to reduce the displacement of ships through hydrodynamic methods by reducing the hull and water contact to reduce resistance. Several technical methods listed in this paper have their own advantages and disadvantages. Many scholars also try to make up for some shortcomings through the combination of several methods, such as the combination of the groove drag reduction method and the bubble drag reduction method, which can increase the stability of the bubble and further improve the drag reduction effect. At the same time, there is also a need to choose different drag reduction programs according to the use of the ship and different operating environments, so as to achieve the best balance between economy and efficiency. Finally, the drag reduction technology of ships plays a vital role in reducing energy consumption. In future, the emergence of more technologies can make ships more environmentally friendly.

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