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The Effect of Fouling on an Increase in Skin Frictional Drag on a Ship's Hull and the Reduction Techniques

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Abstract

A ship's hull is typically covered by fouling even though it is protectd by anti-fouling systems and this results in an increase in skin frictional drag, higher fuel consumption and eventually an extra operational cost. In this paper, the approaches to cope with ship's hull fouling in the past such as anti-fouling ship-building materials and anti-fouling paints are provided with their limitations. Furthermore, the effects of fouling on an increase in skin frictional drag are presented in both terms of ship performance and an operating cost. It is found that, in the study of the Arleigh Burke-class destroyer, even the presence of small calcareous fouling or weed could generate an increase of 31% in shaft power and the operation cost of dealing with a fouling issue could be as high as US$ 2.4 million per ship per year. Three noticeable techniques of skin frictional drag reduction, namely air layer, outer-layer vetical blades and polymer additives, are introduced with the basic concepts. It is observed that the fully-continuous air layer could reduce more than 80% in the local frictional drag.

1. Introduction

Marine Structures, even those with the protection of anti-fouling (AF) systems, are regularly colonized by fouling organisms leading to an increase in skin frictional drag. This increase causes the performance loss of marine vessels, decreased speed at maintaining effective power or added power at keeping desired speed. Consequently, an economic penalty due to higher fuel consumption for typical marine vehicles, scheduling problems due to delays for cargo ships and strategy issues due to undesirable speed for naval vessels are arisen.

In order to solve the increase of skin frictional drag caused by fouling, the use of different materials for ship hulls instead of steel or iron was introduced. Between 1862 and 1904, to prevent corrosion and fouling, steel or iron was replaced by wood as a ship building materials [1]. Copoer coating was then applied to wooden hulls to protect them for destruction. As a by-product, copper kept the hulls from fouling at port. The efficiency of copper as an anti-fouling material directed to attempts to clad steel or iron with copper for a hull material. However, accelerated corrosion was found for such a combined material. The influences of fouling in this period were clearly illustrated by a quotation from one of Instituion of Naval Architects (INA) in London [2]. He says “of some protective and anti-fouling compositions in use by the Navy, it is no exaggeration to say that, as far as speed is concerned, one half of our fleet would be useless before one year had elapsed, from the accumulation of rust, weed and shell.”

Anti-fouling painting was considered to be an effective approach to keep ship hulls from fouling. The first record of anti-fouling paints was in a British Patent of William Beale, in 1625. Until 1895, there were more than 300 anti-fouling paints registered. It was observed that most of them were quite ineffective. One of exotic anti-fouling paints was the paint with a mixture of fish scales and red lead. Holzapfel [3] conducted serveral experiments on ‘vanishes’ anti-fouling compositions. It was found that the combination of copper and mercury was very effective. However, this composition was “capable of being gradually dissolved in sea water,” The practical proof of this problem was the inter-docking periods of 2-2.5 of the ships with ‘vanishes’ anti-fouling coating. Therefore, the application of ‘vanishes’ anti-fouling composition was gone down for the next 70 years.

The usage of self-polishing copolymers (SPCs) including tributyl tin (TBT) as a biocide was proposed to demolish fouling on ship hulls. This ‘self-polishing’ paint, for practical use, could ensure a foul-free hull for up to 5 years. However, while the paint itself become smoother, it contributed more roughness to the ship hulls as a result of surface damages. Nevertheless, the success of tributyl tin as a biocide was not last due to environment concerns. Therefore, tributyl tin is now banned for marine applications in some regulations.

Although these techniques presents the potential to resolve a fouling issue for marine vessels, they show some limitations and restrictions. As a result, these techniques become impractical and the fouling issue still remains. Eventually, skin frictional drag reduction techniques in addition to anti-fouling systems are introduced to compomise the increase in skin friction drag due to fouling. The most noticeable techniques for the reduction of skin frictional drag, mentioned in the ITTC (International Towing Tank Conference) quality system manual for resistance and propulsion test and perforamnce prediction with skin frictional drag techniques, are the air lubrication, the outer-layer vertical blades and the polymer additives.

In this paper, how fouling generates an increase in skin frictional drag is explained. The quantities of skin-frictional drag increases as a result of the presence of slime and shell are then given. In addition, the economic impact of an increase in skin frictional drag is discussed. Finally the most noticeable techniques for skin frictioanl drag reduction are introduced.

2. Skin Frictional Drag

For marine vessels, skin frictioan drag completely arises as a result of the viscosity of the flow moving along a ship hull. Skin frictional drag on some hull types can present as much as 90% of the total drag even though the hull is out of fouling [4]. Therefore, an increase in skin frictional drag, even with a small amount, can play an important role in the total resistance of a ship hull.

2.1 Effect of Fouling on Skin Frictional Drag

The effect of fouling on skin frictional drag can be observed in the mean velocity profile. In other words, fouling causes a loss in momentum in the inner region where the local mean velocity is a function of only wall shear stress, fluid density, kinematic viscosity and distance from the wall. This region is characterized by a downward shift in the log-law. This shift is called the roughness function, $\Delta U^+$and calculated as Equation 1.

$$\Delta U^+ = A\log[y^+] + B \qquad (1)$$

where A is the log-law slope which is equal to 5.62 [5], B is the log-law intercept which is equal to 5.0 [5] and y^+ is defined as Equation 2.

$$y^+ = \frac{yu_\tau}{\nu} \qquad (2)$$

where y is the distance from the wall, u_t is the friction velocity and ν is kinematic viscosity of the fluid.

The roughness function as Equation 1 generates an addition of skin frictional drag which results in the performance loss of marine vessels.

2.2 Effects of Slime and Shell on Skin Frictional Drag

Ship's hull fouling can be categorized into 2 groups: slime and shell. The effects of both categories are presented as follows.

2.2.1 Slime

A slime layer forms rapidly and contributes to the beginning of fouling growth. For the hulls with only the presence of slime, frictioinal resistance could be increased by 8-14% [6]. Bohlander [7] conducted a set of full-scale trails on a frigate with an organotin and cuprous oxide anti-fouling coating. The results indicated that the total propulsvie power was added by 8-18% due to a mature slime film.

2.2.2 Shell

From the classic pontoon tests of Kempf [8], the maimum drag increase emerged as 75% of the wetted surface area was covered by shell fouling. However, even shell foulgin overspead only 5% of the wetted surface, the drag increase was found to be 66% of the maximum.

2.3 Economic Impact of an Increase in Skin Friction Drag

As an increase of skin frictional drag occurs because of fouling, it is important for ship operators to make a decision between the unscheduled dry-docking and recoating costs on the one hand, and the continuing extra fuel cost penalty, in-service, on the other.

Milne and Hails [9] presented the results of global study on the savings due to anti-fouling coating. The savings were determined in for categories: fuel cost savings due to the decreased frictional resistance, savings due to expanded inter-docking periods, savings due to consequential reduced dry dock costs and indirect savings, for instance, savings due to the lower requirement to transport bunkers to refuel ports. The annual savings in the four groups in US$ were 720, 409, 800 and 1,080, respsectively. This yielded a grand total annual saving, for the world fleet, of approximately US$ 3,000 million.

The British Navy established an allowance of a 0.25-0.50% per day increase in frictional drag and therefore 35-50% increase in fuel consumption was predicted for a naval ship with 6-month operation [10]. Alberte *et al.*

[11] mentioned that increased drag due to hull fouling wasted the US Navy US$ 75-100 million in fuel penalty.

In the consideration of hull cleaning cost, there are two types of hull cleanings: full cleaning and interim cleaning, according to Naval Ships' Technical Manual 2006. A full cleaning refers to removal of fouling form the whole underwater hull, propellers, shafts, struts and rudders, while fouling form propellers, shafts, struts and rudder is removed in an interim cleaning. For the US Navy, it is found that the average frequency of full hull cleaning was 0.21 per year, whereas teh average frequency of interim cleaning was 2.4 per year. In 2009, the estimated cost of a full cleaning was US$ 26,808 and that of an interim cleaning was US$ 18,735.

Schultz *et al.* [3] investigated the economic impact of biofouling on the Arleigh Burke-class destroyer (DDG-51), a twin-screw ship powered by four General Electric LM2500 gas-turbine engines. It is found that an increase of 31% in shaft power was generated by small calcareous fouling or weed at a speed of 15 knots. However, as the speed was increased to be 30 knots, the increase was reduced to be 20% for the same fouling. Increases in shaft power was associated with increases in fuel consumpton which became the major determinant of an extra operating cost. It is noted that the hull with such a fouling caused an increase of 20.4% in fuel consumption in comparison with the hydraulically-smooth hull. This is equal to an extra cost of roughly US$ 2.4 million per ship per year.

3. Skin Frictional Drag Reduction Techniques

As mentioned before, anti-fouling paints with biocides are very useful for the prevention of fouling on ship hulls. However, some marine regulations currently prohibit the use of biocides in anti-fouling paints. This leads to a greater presence of fouling on the hull resulting in an increase in skin frictional drag. As it is difficult to remove the increase in skin frictional drag, a number of alternative techniques are introduced to reduce skin frictional drag instead.

3.1 Frictional Drag Reduction with Air Layer

Jang *et al.* [12] investigated the reduction of frictional resistance with air layer on the hull bottom of a ship. As air is injected into the boundary layer of the wetted area, a flow consists of both air bubbles and water. If the amount of injected air increases, air bubbles start to form patches covering the surface. The patches with the co-existence of air bubbles can called a transitonal air layer as shown in Fig. 1. It is observed that the frictional drag on the surface with the coverage of a continuous air layer can be decreased successfully if the reduction of wetted surface occurs. This is because the friction with water possibly change into that with air [13]. The decrease in the lcoal frictional drag on the surface with a transitional air layer can be obtained from 20% to 80%.

Fig. 1 transitional air layer [14]

If the quantity of injected air is increased further, the air layer on the weted surface become fully continuous as illustrated in Fig. 2. This fully-continuous air layer can offer the reduction of more than 80% in the local frictional drag [15,16].

Fig. 2 fully-continuous air layer [14]

3.2 Outer-layer vertical blades

An *et al.* [17] conducted the experiment on the application of outer-layer vertical blades to a real ship model of KVLCC. The arrays of outer-layer vertical blades are installed at the side bottom and flat bottom of the model. The characteristics and the installation system of the blades are demonstrated in Fig. 3. It is found that the outer-layer vertical blades can yield the resistance reduction of 2.15 – 2.76%.

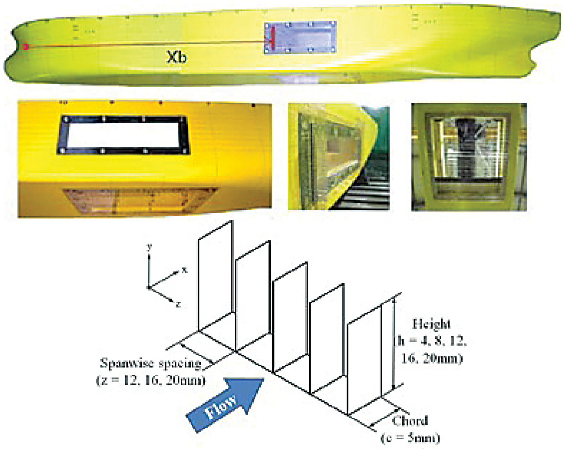

Fig. 3 geometry parameter of outer-layer vertical blades and installation system of the blades [17]

3.3 Polymer additives

PolyEhyleneOxide (PEO) is well recorded as an effective drag reduction additive. This additive is generally mixed with SPC in anti-fouling paints. From the direct force-balance measurement at high-speed circulating water channel, more skin frictional reduction with a maximum of 33% can be given by using anti-fouling with PEO [18]. Nonetheless, in a towing tank test, an additional decrease in skin frictional drag due to an inclusion of polymer additives is about 10%.

4. Summary

Fouling has a great influence on an increase in skin frictional drag of a ship hull. The applications of anti-fouling systems are proposed but most of them come with limitations and restrictions. Consequently, fouling is still a primary source of such an increase. This paper presents three techniques of skin frictional drag reduction as the approaches to compensate the increase. Among of these techniques, air layer on the hull bottom seems to offer the highest reduction rate. However, this techniques requires additional power for air injection. Therefore, the compromise between skin frictional drag reduction and power increse is essential to be considered.

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