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Resistance Reduction of a High Speed Small Boat by Air Lubrication

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Abstract

The resistance reduction by an air lubrication effect of a large air cavity covering the hull bottom surface and the similarity relations involved have been investigated with a series of towing tank tests of three geometrically similar models. The test results of geometrically similar models have indicated that a large air cavity was formed beneath the bottom having a backward-facing step by artificially supplying air is effective for resistance reduction. The areas of air cavity and the required flow rates of air are directly related to the effective wetted surface area. The traditional extrapolation methods seem to be applicable to the estimation of the resistance in the tested range if corrections are made to account the changes in the frictional resistance caused by the changes in the effective wetted surface area. To investigate the effectiveness of air lubrication in improving the resistance performance of a practical ship, a small test boat having a backward-facing step under its bottom has been manufactured and speed trials in a river have been performed. Air has been supplied artificially into the downstream region of the bottom step to form a large air cavity covering the bottom surface. The results have confirmed the practical applicability of air lubrication for the resistance reduction of a small high-speed boat.

Keywords: air lubrication, air cavity, frictional resistance, resistance reduction, bottom step, geometrically similar models, test boat, speed trial

1 Introduction

Fluid viscosity is one of the major components contributing to frictional drag, which cause considerable energy loss to ships as well as other fluid machineries. The very first idea for the improvement in the energy efficiency would be the reduction of fluid viscosity itself. However, the influence of fluid viscosity to frictional drag will be insignificant at the high Reynolds numbers typical of real ships if comparing to the other contributors such as Reynolds stress, etc. Therefore, the development of the methods to reduce frictional drag includes the consideration of turbulence structures and may become extremely complicated. Nevertheless, efficient ways for frictional drag reduction has been continuously sought and a large number of techniques capable of practical application have been reported in recent years(Bushnell and Hefner 1990). However, attempts to reduce frictional resistance have been seldom made in the field of naval architecture probably due to the great successes in the reduction of wave resistance achieved in the last few decades and since frictional resistance cannot be easily isolated from the complicated resistance components. However, growing needs for reducing operation costs and environmental impacts necessitate the increase in ship speeds or considerable energy savings. The recent accomplishment and improved understanding on the phenomena involved in frictional drag and the nature of turbulence structures encourages researches on the reduction in frictional resistance within the ship hydrodynamics communities(ITTC 2002).

Among various techniques for the reduction in frictional resistance, the so-called air lubrication technique may be the most practical one for displacement ships since it is cost effective and environmentally safe. Concepts of air-lubricated ships were introduced from the early 19th century. From the 1960's, air lubrication techniques have been employed to the practical ships, mostly in Russia and great energy savings have been reported(Butuzov 1997).

In the present work, effects of a large air cavity beneath the hull bottom surface on the resistance have been studied experimentally with three geometrically similar models equipped with a unit for air supply. In the first stage, the roles of key parameters, such as step heights and flow rates of air at various advancing speeds of the models have been examined. And then, scaling laws governing cavity areas and flow rates of air have been sought and the extrapolation procedure of total resistance has been studied. Finally, the practical applicability of air lubrication to a test boat has been investigated.

2 Air lubrication

In the applications of air lubrication techniques for the reduction in ship resistance, air is supplied usually onto the bottom surface of a ship to effectively form an air cavity covering the hull surface as large as possible. The air cavity covering the hull surface may reduce the effective wetted surface area and hence the frictional resistance. If it is the case, the resistance of the displacement ships can be reduced effectively without significant changes in hull attitudes that occurred in air-supported vehicles such as ACV or SES(Bushnell and Hefner 1990, Butuzov 1997).

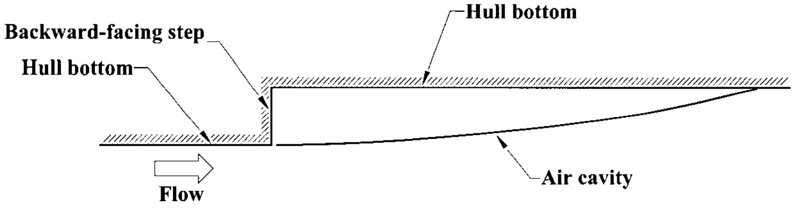


Figure 1: Schematic drawing of an air cavity formed under a hull bottom having a backward-facing step

The basic idea behind air lubrication techniques is very simple. However, practical applications will not be always realizable because it needs the formation of stable and large air cavities enough to achieve the meaningful reduction in ship resistance. A large air cavity can be more efficiently generated under the hull bottom if the air is supplied into the downstream of a backward-facing step as shown in Figure 1. The wake formed in the downstream of the step provides a region of spatially fixed circulating flow and if air is supplied in this region, water is displaced gradually by air and eventually a relatively large air cavity of nearly steady state can be formed(Knapp et al. 1970). When the area of the hull surface covered by the air cavity is large and stable enough, the significant reduction in the effective wetted surface area and the frictional resistance can be achieved. It has been reported that the reduction in the total resistance with air lubrication reaches up to about 20% in model experiments with a careful arrangement of backward-facing steps and an appropriate supply of air(Kim et al. 1997, Jang et al. 1999).

3 Resistance reduction of geometrically similar model ships

3.1 Geometrically similar model ships

Three geometrically similar model ships have been manufactured to investigate the effects of air lubrication on resistance reduction. Shells of the model ships are made of transparent plastic and scales are marked on the hull bottom to observe the shapes of the air cavities beneath the hull easily. As shown in Figure 2, the fore parts of the model ships have a simple shape consisting of developable surfaces and the after parts have a prismatic body shape. Two parts are manufactured separately to allow easy adjustment of step heights.

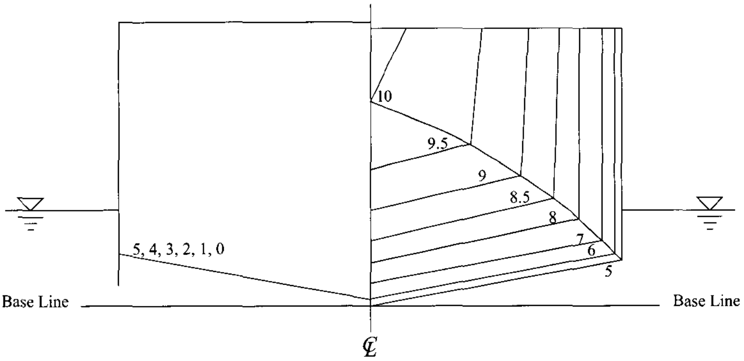


Figure 2: Body plan of geometrically similar model ships

Table 1: Principal particulars of geometrically similar model ships

Model Name		L	M	S
Scale Ratio, λ		1	1.33	2
Lwl	(m)	1.8	1.35	0.9
Breadth, B	(m)	0.4	0.3	0.2
Draft, T	(m)	0.0756	0.0567	0.0378
Step Height, h	(mm)	5	3.75	2.5
Deadrise, α	(°)	10		

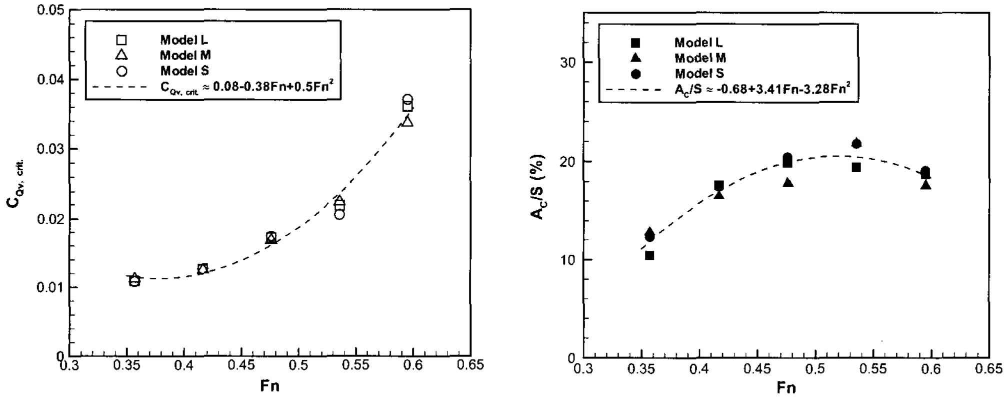
Longitudinal strips are attached along the bilge of the after hull at both sides to prevent air leakage and to minimize any three-dimensional effects occurring in the downstream of the step (Jang and Kim 1999). The three model ships are named as "L", "M" and "S" representing large, medium and small, respectively and the principal particulars are shown in Table 1.

3.2 Air cavity and scaling law

From the previous experience (Jang et al. 1999), it is known that the area of an air cavity formed in the downstream of a step usually increases with the increase in the flow rate of air but do not above a certain flow rate of air, i.e., the critical flow rate of air. This artificial air cavity is maintained by the balance of supplied air and leaked air due to entrainment process. However, when the supplied air is in excess of leaked air too much, this balance is maintained by the pinching-off phenomenon (Knapp et al. 1970) where large air mass is detached periodically downstream end of the air cavity and the area of air cavity covering the hull surface has little change. The amount of resistance reduction also ceases to increase at the critical flow rate of air. So, the increase in flow rate of air beyond the limit is useless. The critical flow rates of air for each geometrically similar model ship have been measured over the Froude number range of $Fn \cong 0.35\sim0.6$. The flow rate of air(Q_{Air}) is made non-dimensional with the towing velocity (V_M), the breadth (B) and the step height(h) of a model ship as shown in Equation (1)(Sato et al. 1997) and the results are summarized in Figure 3.

$$C_{QV} = \frac{Q_{Air}}{V_M \cdot B \cdot h} \tag{1}$$

The area of air cavity(A_c) at the critical flow rate of air has been measured and also is shown in Figure 3 in the non-dimensional form of the ratio A_c/S where S is the wetted surface area. Figure 3 shows that scale effects are not dominant and critical flow rate coefficients of air(C_{QV}, crit) and non-dimensional areas of the air cavities(A_c/S) have almost identical values for all three models at a given Froude number.



(a) Critical flow rate coefficients of air (b) Non-dimensional areas of air cavities

Figure 3: Critical flow rate coefficients of air and non-dimensional areas of air cavities dependent on Froude number

The shapes of air cavities have been recorded by a video camera installed above the model ship. In Figure 4, the observed shapes of air cavities formed beneath the bottoms of each model ship at the Froude number of 0.595 are shown when air is supplied at their critical flow rate. The length scales are made non-dimensional by the step heights of each model ship in Figure 4. As shown in Figure 4, the shapes of the air cavities are almost similar except the region near the stern where the air cavities are unstable and hard to measure the shapes exactly. Therefore, it is concluded that the Froude number scaling rules the phenomena, and viscosity and surface tension can be neglected at the critical flow rate of air.

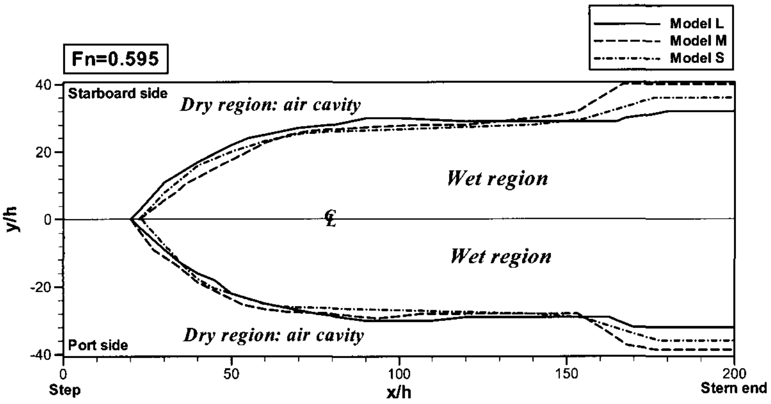


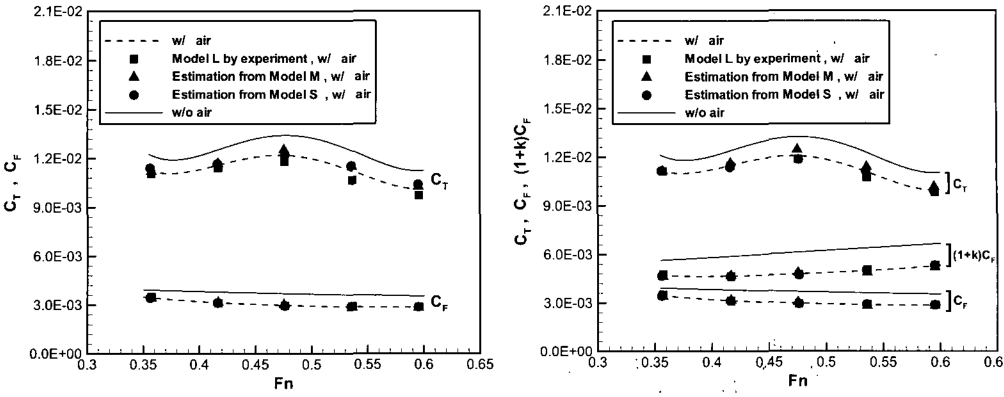
Figure 4: Air cavity shapes formed in the downstream of the bottom step at $F_n = 0.595$

3.3 Resistance estimation of larger geosim models from smaller ones

In two-dimensional approaches, the resistance of a real ship can be estimated from the values obtained in model tests with the Froude's similarity law and a model-ship correlation line. If the air cavity covering the hull surface is geometrically similar and hence the reduction in the wetted surface area is, the total resistance coefficient(C_T) can be estimated by the two-dimensional method shown in Equation (2) in which C_F is the frictional resistance coefficient and C_R is the residuary resistance coefficient. In three-dimensional method, the resistance of a real ship may be estimated with Equation (3) in which k is the form factor. However, it is difficult to adopt the Prohaska's method to define a form factor in this case since the effective hull form may be different due to the air cavity with the changing Froude number. The difficulty can be partly overcome if the Telfer's approach is used since form factors are defined at each Froude number(Tanaka 1991).

$$C_T = \frac{S - A_C}{S} C_F + C_R \tag{2}$$

$$C_T = \frac{S - A_C}{S} (1 + k) C_F + C_R \tag{3}$$



(a) Estimation by 2-D method (b) Estimation by 3-D method

Figure 5: Resistance coefficients of model "L" estimated form the test results of model "M", "S"

Based on the above discussions, the applicability of the two estimation methods has been examined by predicting the resistance of different models. For the purpose, the resistance of the largest model "L" is predicted from the results obtained for the medium and small size model "M" and "S", respectively by using the Equation (2) and (3). The ITTC 1957 line has been used as the model-ship correlation line. The results are shown in Figure 5 where the resistance of model "L" without supplying air is also presented for comparison. It is seen that approximately 10% of the total resistance of the model "L" is reduced and both the two and three-dimensional estimation methods give reasonably good estimation. The results of the three-dimensional analysis indicate that a considerable amount of the resistance reduction comes from the form resistance components. It is possible that the air cavity is playing a certain role in smoothing the flow behind the step but more careful study to identify the cause involved and to accommodate the estimation in the effect of the wetted surface area changes through the resistance prediction procedure will be necessary.

4 Application to a test boat

4.1 Particulars of the test boat

A small test boat equipped with an outboard engine is built of FRP(Fiberglass Reinforced Plastics) to examine the practical applicability of an air lubrication technique. The hull form of the test boat has been derived from an existing racing boat(Yokoo and Takahashi 1960) with slight modification as shown in the body plan of Figure 6. A step is placed at the bottom of the boat, starting near the mid-ship section, and air has been supplied through the array of holes tapped on the hull bottom in the downstream of the step. Wedge-shaped barriers also have been attached to the both sides to prevent the air leakage.

The principal particulars of the test boat are given in Table 2, in which Length over all and the Breadth of the test boat is shown to be 3.16 m and 1.089 m, respectively. The maximum output of the outboard engine is 15 hp.

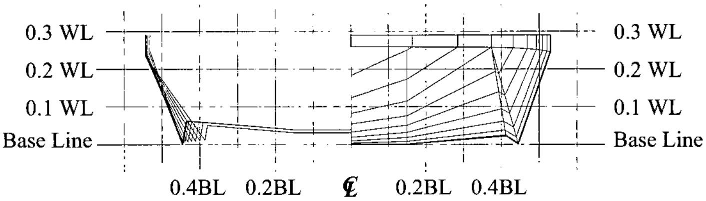


Figure 6: Body plan of the test boat for an application of the air lubrication

Table 2: Principal particulars of the test boat

Item		Test boat
Loa	(m)	3.16
Breadth, B	(m)	1.08
Step height, h	(mm)	39
Deadrise, α	(deg.)	5
Hull weight	(kgf)	57.5
Max. engine output	(hp)	15

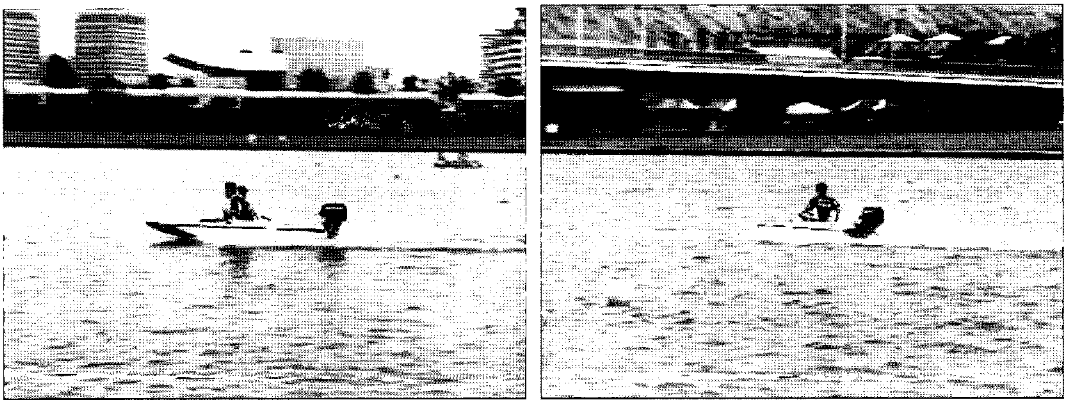


Figure 7: Speed trials of the test boat in a river

4.2 Speed trials of the test boat

A series of speed trials has been performed in a river and the boat speed changes by supplying air have been investigated. Figure 7 shows pictures of the speed trials. An air tank for scuba diving has been used as a source of compressed air since the loading capacity of the test boat was not sufficient enough to hold the heavier equipments and since no power source was available onboard. The amount of air stored in the air tank is about 1700 liter in the standard condition. Air can be supplied at the flow rate of 300 liter/min maximum. If a significant resistance reduction by air lubrication effect occurs, the speed of the test boat will increase. Therefore, the effects of air lubrication on resistance reduction can be estimated by the changes in the speed of the test boat.

It was assumed that the same opening of the engine throttle valve could ensure the same propulsion power in the speed trials.

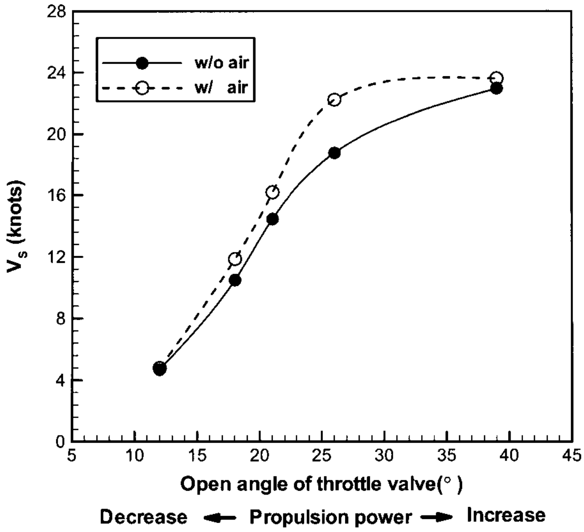


Figure 8: The result of the speed trials

The result of the speed trials are shown in Figure 8. The abscissa indicates the open angle of the throttle valve and the ordinate does the boat speed with and without air supply, respectively. As shown in Figure 8, the maximum increase in the boat speed by air supply is about 17%. This indicates that an air lubrication technique can be utilized as a useful tool for the improvement in the resistance performance of a high speed boat. The insensitivity near the maximum open angle of the throttle valve may arise from the unstable hull attitude at the speed.

5 Conclusions

Three geometrically similar models are made to investigate the scaling law governing air lubrication effects. Air is supplied in the downstream of the step placed on the bottom of each model ship and relations between flow rates of air, the shapes and areas of air cavities as well as resistance reduction are observed.

It is found that there exist critical flow rates of air for each Froude number. The critical flow rate coefficients of air and non-dimensional cavity area at critical flow rate depend on the Froude number and scale effects are not dominant. If air is supplied at the flow rate above this critical value, the shapes of air cavities generated on each geometrically similar model ship are also similar. If it is assumed that the wetted surface area decreases as much as the air cavity area, traditional estimation methods of resistance may also be applied.

A test boat of 3.16m long has been constructed to examine the practical applicability of an air lubrication technique through speed trials. In the speed trials, the propulsion power of the outboard engine has been assumed to be the same at the same open angle of the throttle valve. The maximum increase in the boat speed by artificial air supply was about 17%. It is concluded that there exists fairly good possibility that an air lubrication technique applied to high-speed boats with a backward-facing step on the bottom can be an effective means for the improvement in resistance performance.

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