Effects of Air Injections on the Resistance Reduction of a Semi-Planing Hull

Gyeong-Hwan Kim*, Hyochul Kim*, Seung-Hee Lee†

Abstract

The effects of the air on the reductions in resistance when supplied under the bottom of a semi-planing ship with a step are investigated in the present study. A 1.275 m long FRP model is constructed and the pressure and viscous tangential stresses over the planing surface of the hull with and without air supply are measured through measuring holes carefully selected at the towing tank of Seoul National University. Locations of holes most suitable for air injection are surveyed in front of the planing surface of the model with careful examinations of the limiting streamlines and pressure distributions measured without air supply. At those locations, found to be just front of the step, air has been supplied into a wake region to form an air filled cavity of fixed type. Flow rates and pressure of the supplied air as well as the local pressure and shear stress distributions on the hull surface are measured to understand the physics involved as well as to determine the conditions most effective in resistance reduction at the design speed.

It has been found that total resistance of the stepped semi-planing hull can be considerably reduced if an air cavity generated by an adequate air injection at the bottom of the hull near the step. After the cavity optimized at the given speed, air bubbles also have been generated right behind the point where dividing streamlines re-attach to further reduce the frictional resistance but found to be not so effective as the air cavity in resistance reductions.

1 Introduction

Until recently, frictional resistance due to a fluid viscosity has not been paid so much attention as the other components of a ship resistance since it is believed that the viscosity is a nature and friction between hull surface and water is unavoidable. Most efforts have been given to the reductions in wave or form resistance which can be achieved by refining hull shapes.

The efforts to reduce wave resistance yield great accomplishments and further reductions seems almost impossible. Increasing demands for ships with high speed and efficiency, however, require more reductions in ship resistance and recently many researchers begin focusing on reductions in frictional resistance. Reductions in frictional resistance can be achieved

---

*Member,RIMSE, Seoul National University
†Member, Inha University

by either reducing the wetted surface area, or by altering flow characteristics or the effective viscosity itself. For the purpose, various studies including injecting polymer[1] or electro-analyzed microbubbles[2] of low viscosity in the boundary layer or employing local appendages such as Riblet[3] and LEBU[4] have been performed. Unfortunately, most of the methods found to be impractical since they may cause pollution, consume extra power or are effective only under special conditions. The idea of supplying air instead of polymer or microbubbles between hull surface and water to reduce the frictional resistance is attractive since it can overcome such shortcomings.

Theoretically, reductions in resistance due to air supply can be explained in two ways, microbubbles in the boundary layer effectively reduce viscosity or fixed air cavity attached on the hull surface effectively reduce wetted surface area and hence frictional resistance itself. It has been reported that almost 80 % of the frictional resistance of a flat plate is reduced when microbubbles are injected under the plate. But it is not known how large the extra power spent for bubble injection was[5], It has been also reported that almost 30 % of the total resistance of a pusher barge is reduced with air cavity generated under the hull surface. In this case only 2 % of the engine power is needed for the air blower[6]. These results indicate reductions in resistance of full size ships are possible in practical sense and physical phenomena involved should be more thoroughly investigated. Prior to the present work, a basic study on the effects of air injection on the resistance of a full cargo ship with a bulbous bow has been performed by one of the present authors. Flow fields around the hull and resistance components have been measured and it has been shown that air supply is effective for resistance reduction[7].

In the present research, a practical hull form is selected with the background stated above and influences of air supply on the reductions in resistance are studied. A semi-planing ship with a stepped bottom between station 6 and 4 has been selected. It is a combination of a conventional hull forms with U-shape rounded sections in the front and a planing type hull with a chine behind the step. Pressure and frictional resistances on the planing surface behind the step, with and without air injection, have been measured and the influence of air supply on reductions in the resistance of the ship has been investigated.

2 Model Tests

2.1 Model

It is found from the results of the full slow ship with a bulbous bow[7] that the influence of air supply becomes more effective as the air flow rate under the bottom and the ship speed increase. The planing hull selected in the present study has almost identical cross sectional shapes aft. Hence, the streamlines near the bottom of the hull show little changes along the main flow direction and coincide with it approximately. If the hull is planing, the major component of the total resistance will be a frictional one and reductions in the resistance become more probable with air supply. If the supplied air in forms of microbubbles flows through the boundary layer underneath the bottom, the effective viscosity of the mixed fluid drops considerably and so does the frictional resistance. And in this case, the more reduction will be achieved if the smaller the sizes of the bubbles become. In the other hand, if the supplied

Table 1: Principal Dimensions of the Model

Particulars	Symbol	Model I	Model II
Scale Ratio	λ	1/20	1/20
Length Between Perpendiculars	LBP (m)	1.275	1.275
Breadth moulded	B (m)	0.250	0.250
Draft moulded, mean	T_M (m)	0.0567	0.0575
Displacement	∇ (m^3)	0.00703	0.00715
Wetted Surface Area, bare hull	S (m^2)	0.2783	0.2918
Block Coefficient	C_B	0.387	0.390
Longi. Center of Buoyancy	LCB (m)	-1.369	-0.128

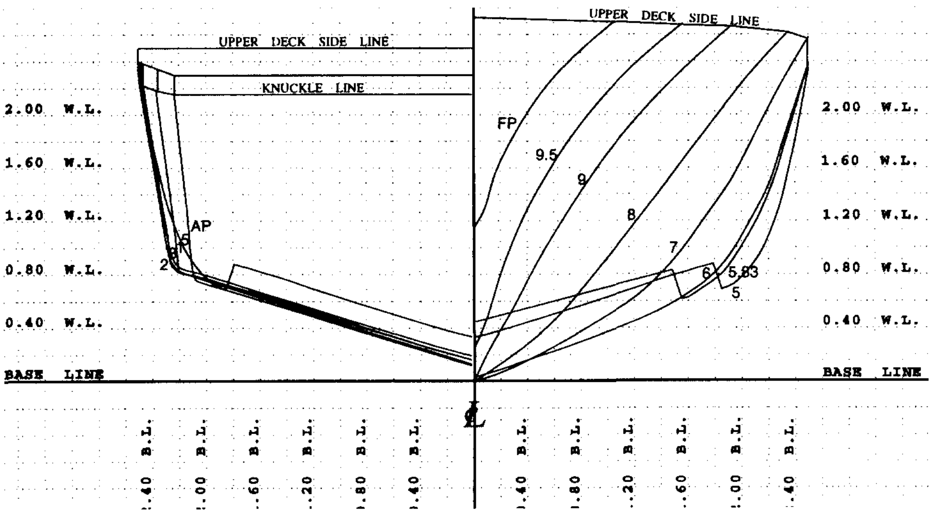

Figure 1: Body Plan of the Semi-Planing Ship with a Step

air forms a cavity which is attached to the hull surface, the more reduction is expected with larger area of attached cavity. A hull form with a step is better than flat ones in obtaining larger cavity since a fixed cavity easily forms inside the separated wake behind the step.

The body plan of the selected hull form is shown in Figure 1. The barrier strip with triangular sections are employed between the station 4 and 6, where transition of the hull form from a rounded to a chine section occurs to reduce the supplied air leaking from the bottom of the model. The principal dimensions of the ship are given in Table 1.

The model of the selected hull is made of FRP. The length of the model is $1.275m$ and stations are marked on the surface where water and buttock lines are drawn every $1cm$ for conveniences of observations. Tagori type turbulent stimulation studs are installed along the station 9.5 with a $10mm$ spacing.

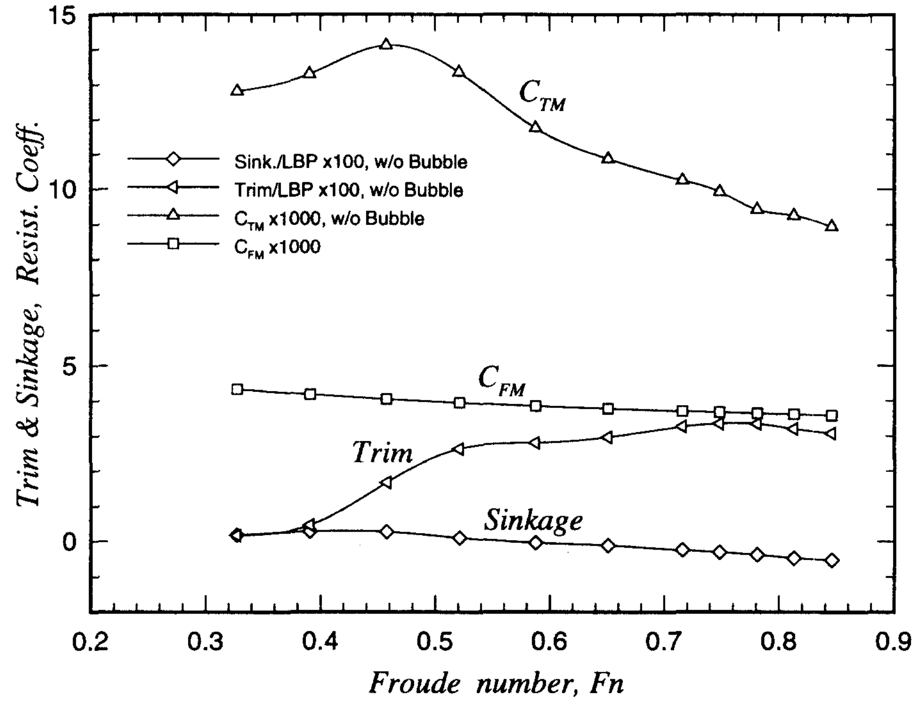

Figure 2: Resistance and Hull Attitude of the Model without Air Supply

2.2 Resistance and Hull Attitude

The design speed of the selected ship is 22 knots and the resistance of the model are measured in the range of 1.16 $\sim$ $2.99m/s$ which corresponds to the ship speed of 10 $\sim$ 26 knots. The results are shown in Figure 2. The model experiences a change in the trim condition at $F_n = 0.3$ which rapidly grows with speed after then. The maximum value of the total resistance coefficient C_T occurs where the rate of the change of the trim becomes maximum. After the point, C_T decreases with increasing speed and eventually the model starts planing at $F_n = 0.55$. Near the design speed, $F_n = 0.71$, the trim and sinkage reach almost constant values and the attitudes of the hull become stable.

2.3 Limiting Streamlines and Measuring Holes

Paint tests are performed to trace limiting streamlines at the model speed of $2.5m/s$ which corresponds to the ship speed of 21.73 knots. The limiting streamlines are shown in Figure 3, among them 13 limiting lines representing typical of flow characteristics near the hull surface are chosen with even spacings approximately. Pressure and shear stress along the streamlines are measured to find resistance components acting on the planing surface. Preston tube arranged too to close each other will experience interferences and may cause inaccurate measurements. Hence, 6 of the streamlines out of the 13 selected are moved to the opposite side to distribute measuring points evenly on the whole bottom.

The priority is given to the measuring of pressure resistance acting on the planing surface.

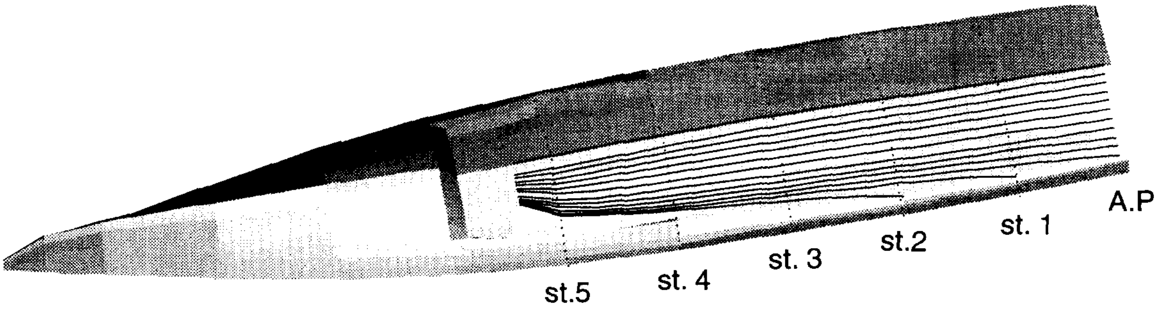

Figure 3: Limiting Streamlines at the Bottom without Air Supply

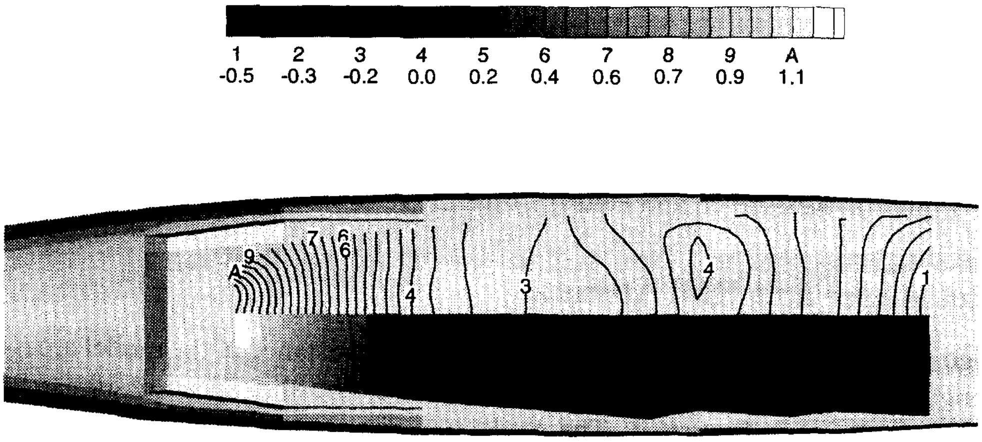

Figure 4: Pressure Distribution on the Bottom of the Model without Air Supply.

Thus, pressure holes are arranged along the limiting streamlines already marked on the surface and pressure distributions are measured with manometers. The distributions measured are useful in determining the locations of the air holes to minimize the power necessary for air supplying as well as the pressure resistance itself. Sixteen measuring points along the each limiting streamlines are selected between station $\frac{1}{3}$ to $5\frac{1}{3}$ with $\frac{1}{3}$ station spacings. It totals up 190 measuring points where Preston tubes and manometers are installed following[8].

The diameter of the measuring hole is $3.0mm$ where copper tubes are inserted vertically to the surface to measure the pressure. The measured pressure distribution is shown in Figure 4. Later, Preston tubes are installed at the same holes and pressure components are measured in the direction from aft to fore. The results analyzed with Patel's formula[8] are shown in Figure 5.

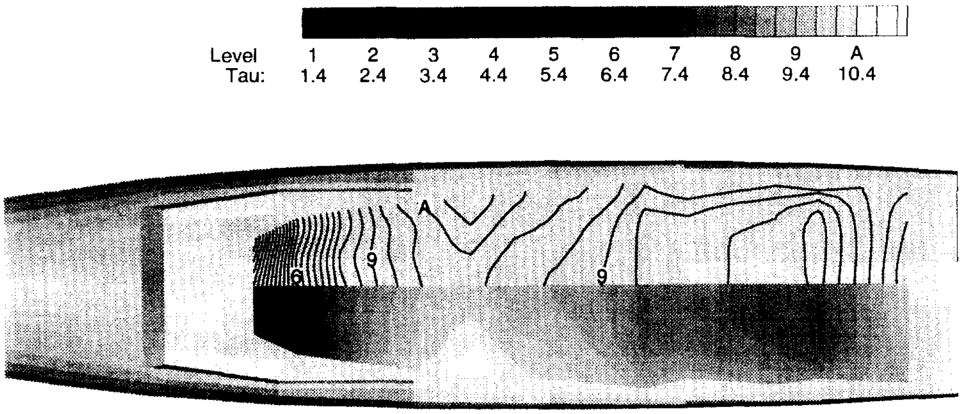

Figure 5: Local Shear Stress Distribution on the Bottom of the Model without Air Supply.

3 Effects of Air on Resistance Reduction

3.1 Air Cavity

Measurements shows a profound pressure concentration in the region between station $\frac{1}{3}$ and $5\frac{1}{3}$ and a pressure drop right front of the station 6. Limiting streamlines shown in Figure 6 indicate formation of vortical flow at the step, including bilge vortices along the air barrier strip installed along the chines at both side of the bottom.

It is a well known fact that at the surface discontinuous or with an extreme curvature separations will occur and which produce a vortical flow downstream, a wake. A fixed cavity will be easily formed inside the wake with injection of a gas and hence effectively reduces the wetted surface area and thus the frictional resistance. It is perceivable that air may be supplied into the wake to be efficient and to effectively reduce the friction. To confirm the fact, along the keel line several locations for air holes are preselected and flow variations on the bottom of the model due to the changes of the location of air supply are recorded by a video camera and a mirror underwater. One of the photographs is shown in Figure 6 where formation of an air cavity is apparent. It is found that air should be supplied into the wake region to form a cavity, the best location for the air supplying is just before the step and once air cavity forms the total resistance measured decreases as expected. There exists an optimum rate for supplying air and increase of air above it does not develop the cavity further, extra amount of air just escapes the cavity through the cores of bilge vortices.

For the various values of air pressure, the total resistance is measured and the optimum rate of air supply has been decided to be the one which yields the minimum total resistance. The shape of the cavity for the case is shown in Figure 7. At the optimum rate of air supply, the total resistances of the model are measured for a range of speeds as shown in Figure 8. It shows that air cavity reduces total resistance indeed and the effects become more dominant as the model speed increases.

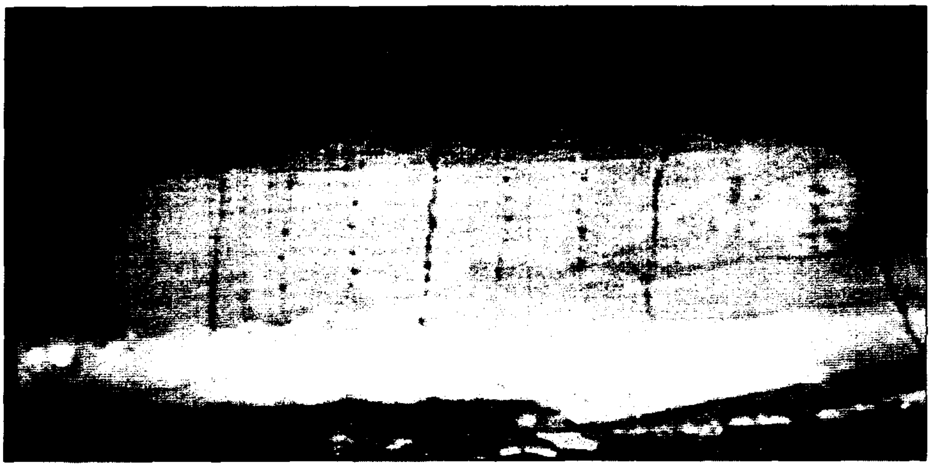

Figure 6: An Air Cavity Formed behind the Step by Air Injection.

Figure 7: The Air Cavity Optimum for the Design Speed

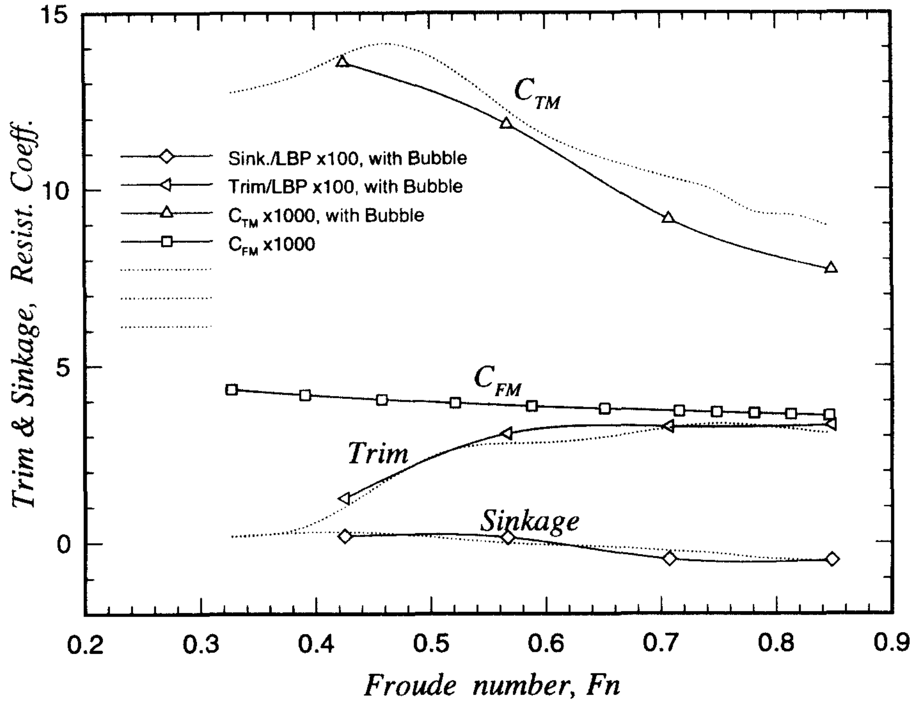

Figure 8: Resistance and Hull Attitude of the Model with Air Cavity.

3.2 Micro Air Bubbles

A paint test performed with the optimum air supply shows limiting streamlines as in Figure 9. The figure indicates that some of the streamlines pass underneath the cavity re-attaches on the bottom, some re-enter the cavity, and the rest just pass by to the stern. Friction due to the shear flow representable by the re-attached streamlines would not be negligible but air suppled in this region is of no use since air does not form a cavity, it was simply swept away.

The effects of the air bubbles on the drag reduction have been reported by many researchers [8,9,10,11]. For example, Tokunaga[5] reported supplying air bubbles into the boundary layer of a flat plate through holes of $0.5\mu m$ diameters on a porous surface reduce almost 80 % of the frictional resistance. However, the results cannot be directly applied to a full scale ship since then the similarity relations for air bubbles require Weber number being identical and the diameter of the air bubbles supplied to the bottom of the ship should decreased to $\frac{1}{\lambda}$ of the model where λ is a scale ratio between the ship and the model. It seems impractical to find porous material satisfying such criteria and, even if found, it may engulfs excessive power to generate air bubbles through. Hence, for application to the full scale, the sizes of the air bubbles for model tests should be fairly larger than the one given above. In the present research, the diameter of the holes for air supply has been decided to be $0.4mm$.

Air holes are arranged parallel to the streamlines at $\frac{1}{3}$ station spacing behind the re-attaching point since C_P is relatively small there and may require less power for air supplying. Figure 10 shows the results when air bubbles are supplied through the holes near the re-attaching point in addition to the air cavity already formed behind the step. The results indicate the

Figure 9: Limiting Streamlines at the Bottom with Air Cavity

effect of air bubbles for drag reduction is not so profound as the air cavity. The rate of air supply and air pressures are $25l/min$ & $0.12MPa$ for air cavity and $20l/min$ & $0.1MPa$ for air bubbles at the model speed of $2.5m/s$.

The model tests for the ship show that the air cavity reduces resistance considerably. The formation of a cavity depends on the shape and speed of the model, but insensitive to either the hole locations or the amount of the air supplied into. Hence, the hull form itself should be modified if an air cavity forms and being maintained more easily. It necessitate relations between the hull shapes and flow fields around as well as the physical nature of a cavity formation being more carefully studied before to get more reductions in resistance. The effects of the micro air bubbles should also be investigated not at the model speed but in the real ship conditions. Otherwise, the requirement of dynamical similitude for air bubbles may result in prohibitively small bubble sizes.

3.3 Resistance Components

The transient records for resistances and attitude of the model before and after air injection are shown in Figure *11*.

The resistance of the model during acceleration will be greater than that with a constant speed. Once the model reaches a constant speed, the resistance and attitude of the model also attain stable values. The trend is carefully watched through a monitor and the air is supplied right after the steady state is reached. Measurements show that it takes about 3 seconds before the resistance and hull attitude re-stabilized at the speed of $2.5m/s$ to show considerable changes in the measured values.

The reductions in resistance may come from the changes both in the resistance components due to the air and in the effective hull shape due to the attitude changes. To confirm the idea, local pressure and shear stress distributions on the planing surface are measured. The locations for measurements are a sub-set of those in the experiment without air supply. Fig-

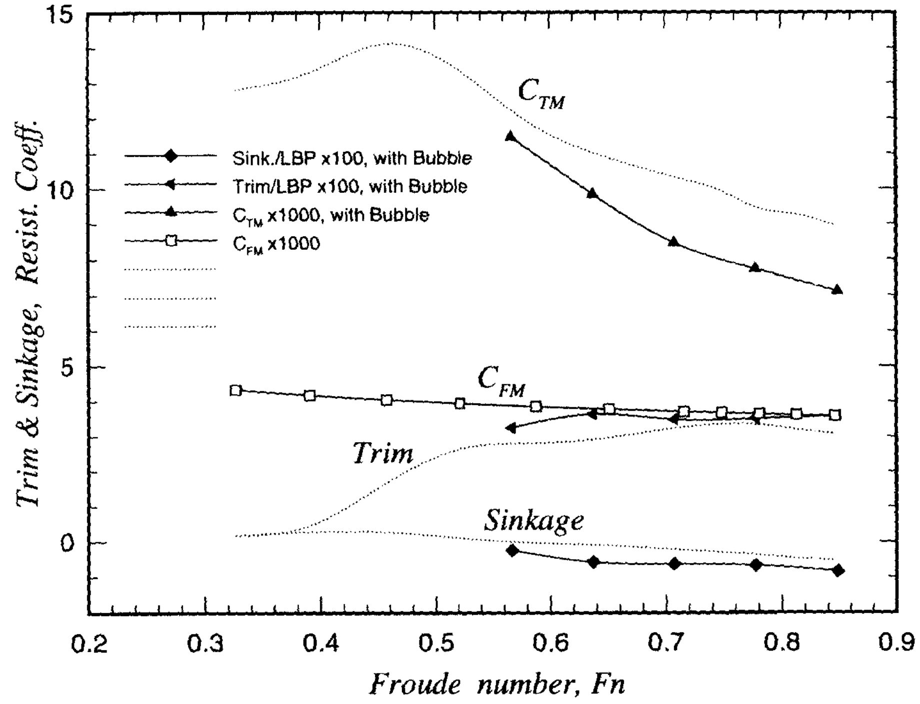

Figure 10: Resistance and Hull Attitude of the Model with Air Bubbles.

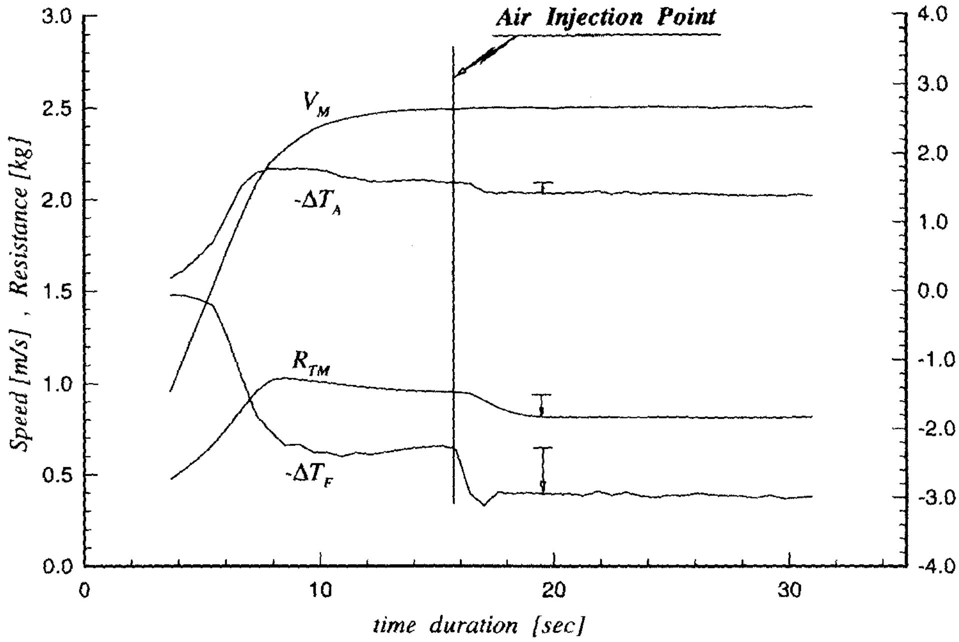

Figure 11: Transient Record of Resistance and Attitude before and After Air Injection

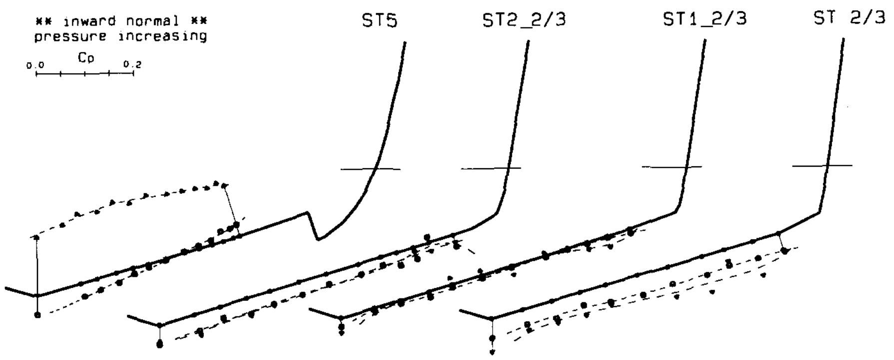

Figure 12: Changes in Local Pressure due to Air Supply.

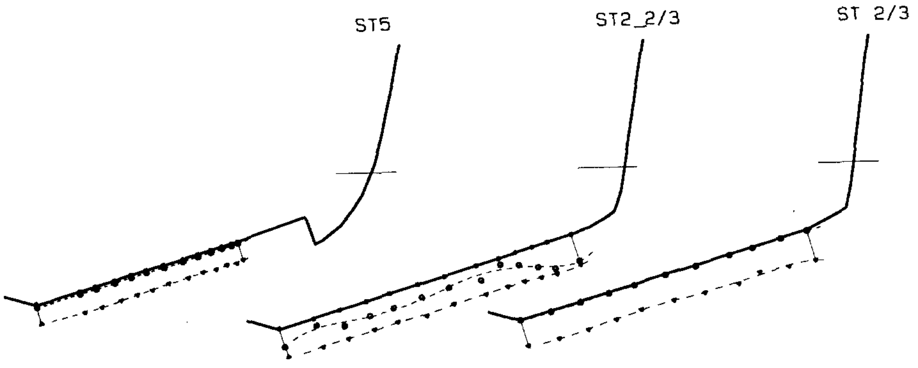

Figure 13: Changes in Local Shear Stress due to Air Supply.

ure 12 and 13 compares the measured pressure and the shear stress, respectively, with those for measurements without air supply along the stations behind the step. Figure 12 shows an apparent pressure drop inside the air cavity near the step. The drop contributes to the reduction in pressure resistance since the longitudinal slope is relatively large in the region. Pressure drops are also found on the planing surface, however, longitudinal slope there is not large enough to cause noticeable changes in the resistance. Figure 13 confirms that shear stress vanishes inside the cavity. Decreases in shear stress are also evident on the planing surface near both the air holes (station $2\frac{2}{3}$) and the stern (station $\frac{1}{3}$) where considerable downward longitudinal slope exists. In the region between the two where the longitudinal slope is upward, no apparent changes in the shear stress are found. To conclude, the reductions in resistance mostly come from the air cavity and thus thorough study to investigate flow characteristics involved are necessary. The changes in the attitude and the increase in the surface pressure due to the air can also contribute to the reductions in resistance and have to be investigated in detail.

4 Conclusions

Air has been supplied underneath a model of a semi-planing ship with a step at the bottom. It is shown that almost 21% of the total resistance of the model can be reduced. The flow characteristics around the hull has been carefully studied and causes for the reductions are sought.

The conclusion of the present experimental study are as follow:

- At a given speed, an optimum air cavity attached on the hull surface can be formed near the step by an adequate air supply. The air cavity is very effective for reducing both the pressure and the viscous resistance.
- The shapes of an air cavity depends on the local configurations of the hull and the resulting flow fields there. The effects of the cavity on the resistance reduction increase as the model speed increases. The increase in the rate of the air supply does not show any significance.
- The air bubbles generated on the planing surface is also effective for resistance reductions. The effects are not as large as the air cavity and seem sensitive to the flow characteristics caused by local hull configurations such as the longitudinal slope of the surface.
- More reductions in the resistance of a ship may be anticipated with refinements of the hull shape. The leakage of supplied air through the bilge vortices should be minimized with proper choice of the air barrier strip and bottom inclinations.

Acknowledgement

The work reported in the present paper has been supported partly by the KOSEF under grant 971-1011-063-2.

References

[1] McCarthy, Flat-Plate Frictional-Drag Reduction with Polymer Injection, JSR, June 1970.

[2] McCormick, M.E., Bhattacharrya, R., Drag Reduction of a Submersible Hull by Electrolysis, Naval Engineers J., V.85, pp.11-16,1973.

[3] Reed, J. C., Using Grooved Surfaces to Improve the Efficiency of Air Injection Drag Reduction Methods in Hydrodynamic Flows, JSR, V.38, No.2, pp.133-135, 1994.

[4] Shirose Y., Computation of the Turbulent Frictional Drag Reduction by LEBU, Transactions of WJSNA, V.75, pp.21-34, 1989.

[5] Tokunaga K., Reduction of Frictional Resistance of a Flat Plate by Microbubbles, Transactions of WJSNA, V.73, pp.79-82, 1987.

[6] Ivanov, A.N., Kalyuzhny, V.G., Pavlenko, A.N., Problem of Hydrodynamic Resistance Reduction by Artificial Gas Cavities on the Vessel's Hull, Krylov Institute of Tech,

[7] Lim, K., Kim, H., On the Variation of Resistance Components due to Air Bubble Blowing on Bulb Surface, Transaction of SNAK, V.33, No.1, pp54-64, Feb. 1996.

[8] Madavan, N.K., et al., Numerical Investigation into the Mechanisms of Microbubble Drag Reduction, J. Fluids Eng. ASME, V.107, pp.370-377., 1985.

[9] Madavan, N.K., Deutsch, S., Merkle, C.L., Reduction of Turbulent Skin Friction by Microbubbles, Physics of Fluids, V.27 no.2, pp.356-363, 1984.

[10] Merkle, C.L., Deutsch, S., Cimbala, J., Microbubble Drag Reduction, Proc. 16th Sympo. on Naval Hydrodynamics, pp.199-215, 1987.

[11] Doi, Y., Mori, K., Hotta, T., Frictional Drag Reduction by Microbubbles, J. of SNAJ V.170, pp.55-63, 1991.

[12] Preston J. H., The Determination of Turbulent Skin Friction by Means of Pitot Tube", J. of the Royal Aeronautical Society, V.58, pp.109-121, Feb. 1954.