EFFECT OF AIR LUBRICATION METHOD ON FRICTIONAL RESISTANCE REDUCTION OF SHIP

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Abstract

Air lubrication method is a method in that air bubble is introduced into the turbulent boundary layer developing downstream along the solid surface in water flow. Effect of air lubrication on reducing frictional resistance is proved from the experiment results. Obtained results show that maximum total resistance reduction can be reduced 11% in ballast condition and 6% in full load condition with the assumption that thrust deduction is constant for with and without bubble injection. Effect of air bubble in reducing frictional resistance persists for the whole bottom area. Reduction rate of shear stress under the bottom of ship seems to be larger up stream and smaller toward the side of the ship. The mean propeller inflow velocity is increased for with air lubrication from no air condition due to the viscous resistance reduction. Estimation of wake fraction or advance speed of propeller based on viscous resistance reduction when bubble was injected is also considered.

Keywords: Air lubrication, Energy saving, Frictional resistance reduction

Introduction

Requirement of energy saving due to the limitation of natural resource and high expense of fuel consumption is necessary in ship transportation. Extensive researches aiming to reduce drag of ship have been carried out. Successful results obtained from wave making resistance reduction by optimizing ship hull forms have played very importance role in energy saving for the last few decades. Nowadays numerous investigations are concentrated on reducing frictional resistance which is about 70% of total resistance of low speed ship. Methods of frictional drag reduction such as polymer method, surfactant method, etc. are employed widely. In these methods, air lubrication is emerging as a promising method because of its applicability to the real ship with high expected result of friction reduction. This method is also friendly with environment.

In air lubrication method, bubbles are injected into the turbulent boundary layer under the bottom of the ship. Due to the effect of bubble, frictional resistance is reduced. Air lubrication was first mentioned in the research of McComick and Bhattacharyya in 1973. Successive researches of many authors have been carried out after that. Madavan et al. (1984) obtained impressive result with more than 80% of skin friction reduction. Watanabe et al. (1998) carried out experiment to investigate the skin friction reduction by air bubble of very long slender model ship with flat bottom. They used two models of 20 m and 40 m long with 0.6 m in width. These models were tested in the towing tank with test speed of 7 m/s. Experiment result showed that total resistance reduction was about 14%.

Practical application of air lubrication method to the real ship has been investigated by a series of the real ship experiments for the last few years. The first real ship experiment was done in 2002 using the training ship Sein-maru. Energy saving of 2% was obtained in this experiment. The second real ship experiment was carried out three years after that, in 2005, using the cement carrier Pacific Seagull. Maximum total resistance reduction in this experiment was small, only about 1%. However, based on these obtained results, the effect of bubble on frictional resistance reduction of ship was proved.

From the results and accumulation of experience obtained from the two previous experiments, the real ship experiment using the same ship, Pacific Seagull, was carried out in 2008. The real ship experiment was conducted by the cooperative research project with National Maritime Research Institute Japan (NMRI), Hokkaido University, Osaka University and Azuma shipping company. New Energy and Industrial Technology Development Organization (NEDO) sponsored for this project.

Preliminary Experiment

In order to develop the equipment for real ship experiment, preliminary experiments using very long slender model ship were conducted at NMRI's towing tank in 2006. The model ship is 50 m long, 1m wide with flat bottom. The draft is 0.05 m. End plates with 5 cm high and about 50 m long were attached along the side end on both port side and starboard side of the model to prevent the dissipation of bubbles out of the bottom model. Figure 1 shows the overview of long slender model ship in the 400 m towing tank. As shown in the figure, the model was towed by the carriage. The velocity used in the tests was 7 m/s. This speed is the same as the ship speed in real ship experiment which would be carried out in 2008. In the preliminary experiments, bubbles were injected at positions of 3 m, 10 m and 26 m downstream from the bow end of the model. Result of resistance reduction was shown by Dr. Kodama (Kodama et al. 2007). From his results, resistance reduction was decreased with the increasing of air flow rate. Maximum resistance reduction of about 30% was obtained at air injection rate 3.918 m^3 /min.

Figure 1. 50m model test at NMRI

The new type shear stress sensor for real ship experiment was verified by measuring shear stress of 50 m length model and comparing with results of other sensors of NMRI.

This shear stress sensor was designed and produced by Toda's laboratory for real ship experiment with air bubble in the SR 239 project of the Shipbuilding Research Association of Japan. The sensor was developed in order to gain more knowledge about the air bubble resistance reduction mechanism by measuring local shear stress at various locations on the ship surface during the experiment. Since the shear stress sensor would be used for existing ship, the mounting method was required no hole drilled on the ship surface when installing the equipment. Small dimensions and accuracy in measurement were also required. This new type shear stress sensor was designed to fulfill all of these requirements. Detailed information and structure of this sensor are shown in Toda, et al (2005). The picture of this sensor is shown on Figure 2.

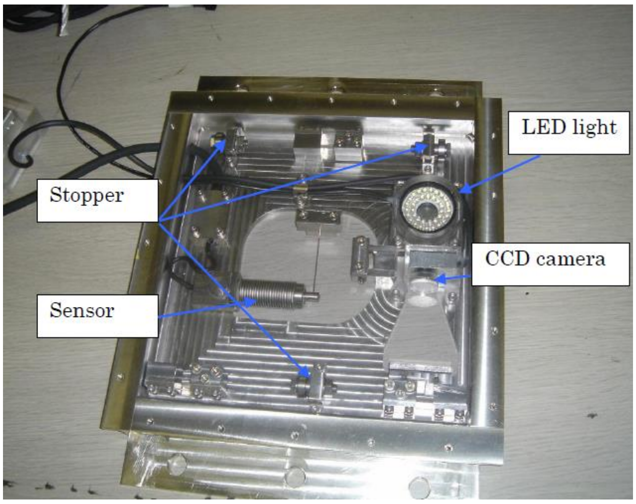

Figure 2. New type shear stress sensor

In the experiment, the new type sensor was mounted at 27.4m downstream from the bow end. Figure 3 and 4 show the comparison of the results obtained from the new type sensor and NMRI's sensors which were located right after and before the sensor of new type, concretely at 25.5 m and 29.5 m downstream from the bow end. In these figures, result of the new type shear stress sensor is depicted by continuous curve. Qa is the air injection rate. y is the measured location in horizontal direction done by NMRI. Here, y= 0 is the middle point of bottom area. As shown in these figures, when air injection rate is less than $3m^3$/min obtained result from this shear stress sensor and NMRIs' shear stress sensors agree quite well to each other. When air injection rate was larger than $3m^3$/min, bubble clustered at the bottom of model. The model heeled slightly. Air bubbles were forced to move toward one side of the model and concentrate at the gap between end plate and fairing plate due to the buoyancy. The fairing plate mentioned here was used to reduce the height difference between the sensor surface and the surrounding surface. That why the result obtained from the new type sensor is different with the result obtained from NMRIs' sensors which were installed flush with the bottom surface of model. However, a good agreement of the results with air injection rate less than $3m^3$/min means that the new type sensor is reliable to use at the same speed of the real ship experiment.

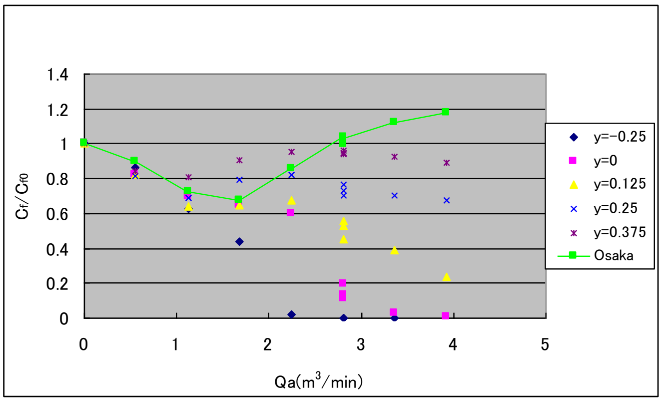

Figure 3. Comparison of the results of new type sensor and NMRIs' sensor at 25.5m downstream

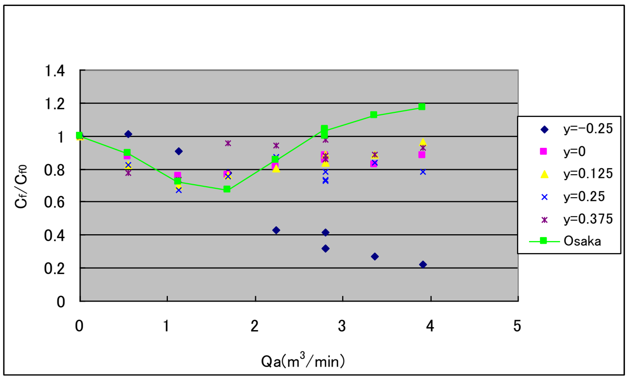

Figure 4. Comparison of the results of new type sensor and NMRIs' sensor at 29.5m downstream

Real Ship Experiment

Experimental Equipment

The real ship experiment was carried out in 2008 by using the cement carrier Pacific Seagull. This ship has a box shape hull and long, wide flat bottom. Cruising speed is 12.4 knot. The principal dimensions of Pacific Seagull ship are shown in Table 1.

Table 1. Principal Dimensions of Pacific Seagull

Length over all	126.6 m
Length between perpendiculars	120.0 m
Breadth	21.4 m
Depth	9.9 m
Draft	7.0 m
Draft (ballast) in experiment	4.0 m (trim by stern 1.5 m)
Speed (service)	12.4 kt

The general arrangement of equipment is shown in Figure 5. In this experiment, the ship was equipped with blowers, cameras, ultrasonic velocity profiler thrust and torque gauge on the propeller shaft, shear stress sensors on the hull surface and etc. Air was supplied from 5 sets of blowers which were installed on the main deck. Maximum bubble generation was about 110 m^3/min. Strain gauges were attached on the shaft directly following the method of Hylarides to measure thrust and torque acting on the propeller shaft during the experiment. In order to measure shear stress, three sensors were installed under the bottom of the ship. Two were on the starboard and one was on the port side. The position of these sensors was 50m downstream from the bubble injection position. The installation work can be seen in Figure 6.

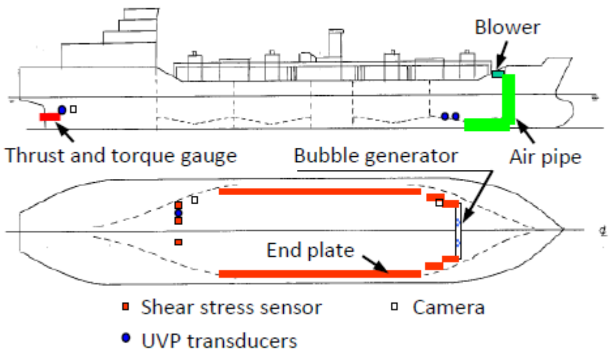

Figure 5. General arrangement of equipment

Figure 6. Strain gauges were attaching on propeller shaft

Experiment Results

Experiment with air lubrication was carried out for both ballast and full load condition. During the experiment, number of active blowers was altered to adjust amount of air injected under the bottom of ship.

Figure 7 shows an example of thrust and torque reduction when 5 blowers were active. The abscissa is the time of experiment. The ordinate is the value of thrust (N) and torque (N.m). In this figure, value of thrust and torque are depicted by brown curve and orange curve, respectively. Due to the effect of bubble, torque and thrust are decreased with the assumption that value of thrust deduction is constant with and without bubble. Similar time delay can be observed due to the distance between the injection point and propeller.

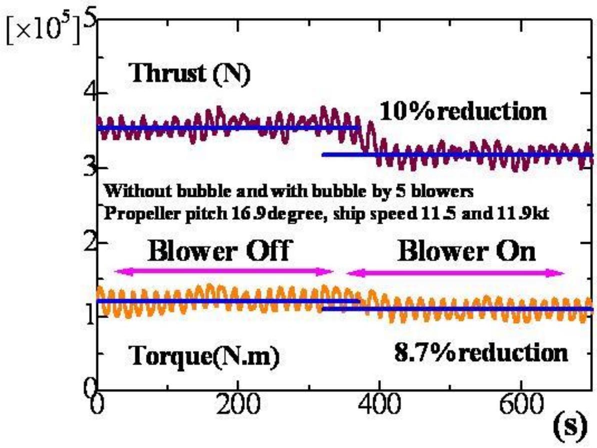

Figure 7. Example of raw time history of thrust and torque with and without bubble

The power delivered to the propeller P_D is calculated by the following equation:

$$P_D=2\pi Qn \quad (1)$$

Where, Q: propeller torque;

n: rate of revolution

In the real ship experiment, number of revolution was fixed, so the torque reduction means the power reduction. It means that the fuel consumption would be decreased by this reduction.

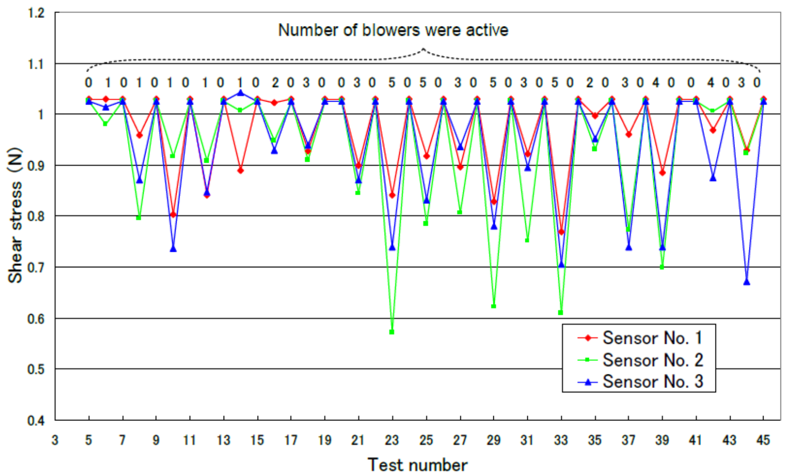

Figure 8. Result of shear stress in ballast condition

Figure 8 shows the result of shear stress reduction. In this figure, the horizontal axis is the number of test in the experiment. The vertical axis is the value of shear stress. Maximum shear stress reduction of sensor No.2 as well as of all sensors is 44.3%. This result is obtained when 5 blowers were active. Maximum local shear stress reduction for sensor No. 1 and sensor No. 3 is 25.3% and 34.46%, respectively. The distribution of shear stress reduction can also be referred from this figure. It looks like that shear stress reduction is decreased toward the side end of the ship.

Madavan et al. (1985) assumed that the effective bubbles in reducing drag will persist for as much as 60-70 boundary layer thicknesses downstream of the injection region. In the real ship experiment, shear stress sensors were installed at the location of 50 m downstream from the injection position. Clear reduction collected from the experiment results of all three sensors proves that the effect of bubbles remains whole bottom area and the larger reduction seems to be obtained in the upstream region. This result can be referred to the result obtained from the 50 m model experiment in NMRI (Kodama et al. 2007).

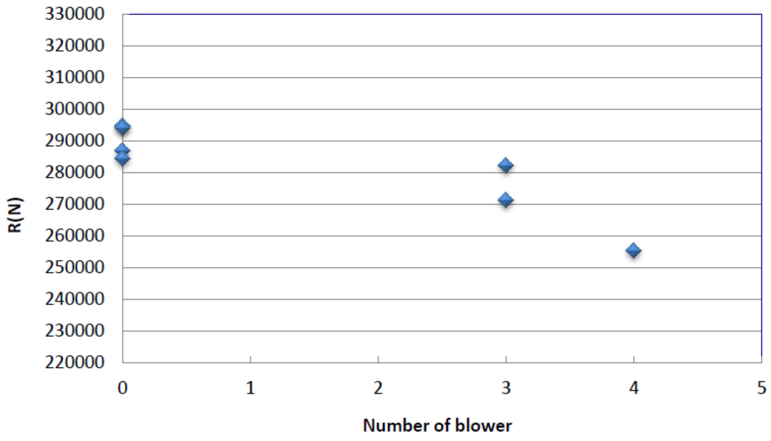

Figure 9. Example of total resistance in ballast condition at pitch angle of 17 degrees

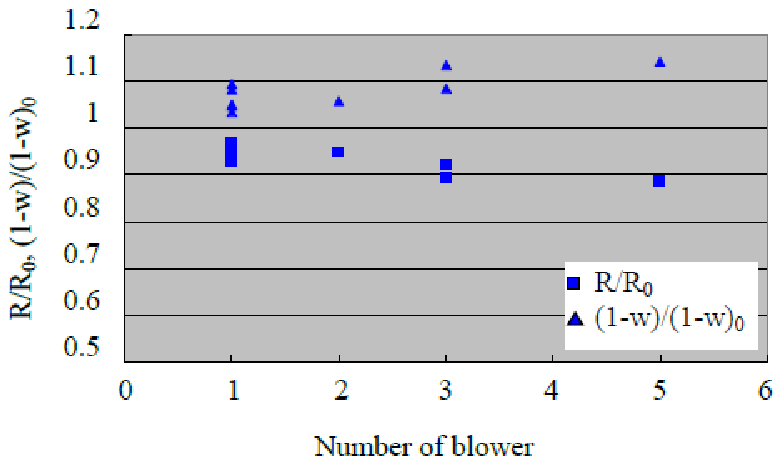

Figure 10. Analyzed ratio of R and 1-w between with and without bubble for ballast condition, pitch angle 16.9 degrees

Figure 9 shows an example of total resistance at pitch angle of 17 degrees. In this figure, the horizontal axis is the number of blowers. Number “0” means no bubble injection. The vertical axis is the value of total resistance R. As shown in the figure, the decreasing rate of total resistance corresponds to the increasing of air flow rate.

In Figure 10, the horizontal axis is the ratio of total resistance and effective wake fraction between with and without bubble. The subscript “0” means without bubble. The vertical axis is the number of blowers. The ratio of R/R_0, $(1\text{-w})/(1\text{-w})_0$ are depicted by square dot and triangle dot, respectively. From the result, when number of blower is increased, the ratio of R/R_0 is decreased or in other words the more resistance reduction can be obtained. Maximum total resistance reduction of the ship is about 11% in ballast condition and about 6% in full load condition.

Speed of advance of propeller is also considered in the experiment results. As shown in Figure 10, ratio of effective wake fraction increases when increasing air flow rate. It means the mean flow in the propeller plane increases due to the skin friction reduction.

Estimation of 1-w

Total resistance consists of 30% wave making resistance and 70% viscous resistance based on full scale prediction from model experiment. The ship which was used in real ship experiment has large bottom area and this area is nearly 50% of wetted surface area in ballast condition. The effect of bubble was only observed at the bottom of ship. It means that 11% total resistance reduction obtained in experiment is the reduction in viscous resistance of bottom part. From the above analysis, if we consider only bottom area of ship, the viscous resistance reduction of covered area by bubbles will be 35%.

Table 2 shows the results of wake fraction. In real ship experiment, measuring results showed that thrust and torque were decreased when bubbles were injected. Assuming that the change of density and details of flow field can be neglected, thrust coefficient and torque coefficient will be decreased. According to the propeller diagram, when thrust coefficient and torque coefficient are decreased, the advance coefficient of propeller J will be shifted to the right. That means J will be increased. Definition of J is expressed as follow:

$$J = \frac{V_A}{nD} \quad (2)$$

Where, n: rate of revolution of propeller

D: propeller diameter

V_A: advance speed of propeller

From the above definition, when J is increased, speed of advance of propeller V_A will be increased because the rate of revolution of propeller n is kept the same before and after bubble injection. Based on the fact that large difference in velocity of ship between with and without bubble injection was not observed during the experiment, the increasing rate of V_A will be equal with the increasing rate of (1-w). The result shows that in case of bubble injection the value of (1-w) is increased by 0.065 when it is compared with the without bubbles case. Hence, speed of advance of propeller will be increased by 0.065.

Table 2. Values of 1-w, 1-t and Total Resistance Rate When 5 Blowers were Active

	Without bubble	With bubble
Total resistance ratio	1	0.89
Viscous resistance ratio of bottom area	1	0.65
1-w	0.573	0.638
1-t (assumed constant from model experiment)	0.81	0.81

The viscous wake is estimated from international towing tank conference (ITTC) procedure like in the equation below:

$$w_v = w - w_p \quad (3)$$

Where, w_v: viscous wake component

w_p: inviscid wake component

From equation 3, we have:

$$w_v = w - (t + 0.04) \quad (4)$$

Where, 0.04 is to take account of rudder effect

t is thrust deduction

Substitute w, t from Table 2 to Equation 4 we have: $w_v = 0.197$

When bubble was injected, frictional resistance is decreased. Assuming that the ration of w_v for with and without bubble injection is proportional to viscous resistance reduction at bottom area, predicted w_v for with bubble condition is:

$$w_v = 0.197 \times 0.65 = 0.128$$

Consequently, 1-w for with bubble can be calculated as follow

$$1 - w = 1 - (w_v + t + 0.04)$$
$$= 1 - (0.128 + 0.19 + 0.04) = 0.642$$

This value is a little bit higher than the measured value showed on Table 2 (0.638), but the increase of mean velocity can be explained by the decreasing of resistance in bottom area with the considering that the density change and details of the flow field are ignore.

Conclusions

The effect of bubbles in reducing frictional resistance or ship resistance is clearly proved by real ship experiment result. Shear stress reduction seems to be increased upstream and decreased toward the side of the ship. Total frictional resistance reduction is 11% and 6% in case of ballast and full load condition, respectively.

Supply power is decreased from the fact that torque reduction and only slightly change in velocity of ship is observed. The mean velocity at propeller plane is increased due to the viscous resistance reduction from the thrust measurement results. Estimation method of mean velocity at propeller plane with bubble is also considered.

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