Study on Marine Propeller Running in Bubbly Flow

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ABSTRACT

In recent years, air lubrication systems have been attracting attention as a method of reducing carbon dioxide emissions from ships. This method can reduce the frictional resistance through the injected air bubbles on ship bottom, and save energy for propulsion. An air lubrication system covers the ship hull with bubbles, if the air bubbles flow onto the propeller, a risk is that propeller efficiency will be loss and there will be an increase in the pressure fluctuations due to propeller cavitation.

The author has investigated the propeller performance in bubbly flow using model tests in order to apply air lubrication systems to ships. From the experimental results for a module carrier, the volume of air bubbles flowed into propeller was small and the increase of propeller pressure fluctuations was negligible. Furthermore, the author has reported the experimental results for several types of model propellers running in bubbly flow by changing the void fraction, the air bubbles effect on the propeller efficiency and the pressure fluctuations. At the normal condition (without air bubbles), in the case of less cavitation propeller, the pressure fluctuations of the propeller tend to be susceptible to the effects of air bubbles mixing was found.

Keywords

Air Lubrication System, Propeller, Cavitation, Air Bubble, Pressure Fluctuation

1 INTRODUCTION

The development of energy-saving ships has been greatly anticipated by the shipping industry as a countermeasure against the surging prices of raw materials, including oil, arising from the economic growth of developing countries, and environmental issues such CO_2 emission regulations for international shipping operations. The air lubrication method, which reduces the frictional resistance of the hull by using air bubbles, has been studied by a number of institutes because the method is expected to result in prominent energy-saving effects.

Kodama et al.(2000) performed tests using a flat-plate model ship with a total length of 50m and confirmed that the total resistance working on the model ship and the local frictional force working on the ship bottom were reduced by air bubbles. Verifications on actual ships have also been conducted; Kodama et al.(2008) demonstrated an energy-saving effect of about 5% in an actual ship test using a cement carrier in service.

Research on the use of computational fluid dynamics (CFD) to predict the effect of bubbly flow has also been conducted. Kawamura et al.(2009) simulated the flow around the cement carrier used by Kodama et al. for experiments, and evaluated the effects of changes in the ship posture and location of the bubble outlets on the resistance reduction ratio for the ship and the void fraction on the propeller disk area.

The Nagasaki Shipyard & Machinery Works of Mitsubishi Heavy Industries, Ltd., (MHI) completed YAMATAI, a module carrier belonging to the NYK-Hinode Line, Ltd., in April 2010 as shown in Figure 1. An air lubrication system(Mitsubishi Air Lubrication System; MALS) was installed on this newly built ship for the first time in the world on this occasion. The ship achieved an energy-saving effect of more than 10% at sea trials prior to delivery (Mizokami et al. 2010). While developing the MALS installed on the module carrier, air bubble predictions utilizing CFD technology were performed in addition to tests on model and actual ship. The tests on a model ship confirmed the flow of air bubbles along the bottom of ship and were used to evaluate the effect of the void fraction on the propeller disk area on the propeller characteristics and fluctuating pressure (Kawakita et al 2011). CFD was used with the

Figure 1 The world's first newly built ship with MALS

same ship to predict the distribution of the air bubbles void fraction on the hull surface, which is required to predict the reduction of the hull resistance, as well as the distribution of the void fraction on the propeller disk area, which affects the propeller performance (Kawabuchi et al 2011), (Kawakita 2012). This paper shows the propeller performance in bubbly flow using model tests in order to apply air lubrication system to the module carrier and other ships.

2 AIR BUBBLE BEHAVIOR AROUND SHIP HULL

The air bubble distribution around the hull surface is believed to an important parameter for reducing the resistance working on the hull, and must therefore be predicted accurately. In order to predict the amount of air bubbles flowed into the propeller, we estimated the distribution of void fraction at the propeller plane from the bubbly flow calculation around a ship hull using CFD (Kawakita 2012). Here, the void fraction is the ratio of air volume to the air-fluid mixture. The governing equations for bubbly flow calculation model are the mass and momentum conservation equations of the mixed fluid, the mass conservation equation of the void fraction and the momentum equation for the gas phase. In addition, the bubble flow model incorporates the drag reduction model by air bubbles. The air bubbles diameter of 1mm was used for calculations.

CFD calculations of straight running during still water were carried out for a module carrier. This ship was a twin-screw vessel characterized by its wide breadth and shallow draft. The outline of the module carrier that was actually used is shown in Table 1. The calculation results reported here are based on full scale using double model approximation without considering waves on a free surface and the suction effects of the propeller. All of the air bubbles were assumed to be of a uniform diameter and remain unchanged by the flow. No consideration was given to bonding of bubbles or division of a bubble into multiple bubbles.

Figure 2 shows the calculated void fraction distribution around the ship hull and Figure 3 shows the calculated void fraction distribution of the port side propeller position. The air blown from the air injector unit placed on the ship bottom becomes air bubbles, flows toward the stern along the bottom. The following trends were observed from this calculated results.

- Air bubbles flowed along the hull without escaping from the bottom of the ship.
- A smaller amount of air bubbles were distributed in the area near hull centerline.
- Air bubbles were concentrated in the area around skeg that covered the propeller shaft on the stern.
- Air bubbles were flowing in the vicinity of the bottom flowed into the propeller spread in the slope of the ship stern section.

The average void fraction of the propeller disk is expected about 0.1%.

Table 1 Outline of the module carrier

Length	162m
Breadth	38m
Depth	9.0m
Draft	4.5m/6.37m
Displacement	10,201t/19,818t
Propeller	CPP
Design Speed	13.25kt

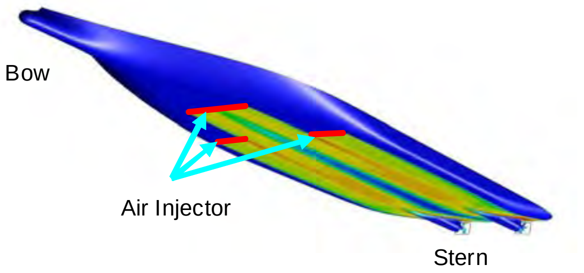

Figure 2 Void fraction distribution prediction on the ship bottom

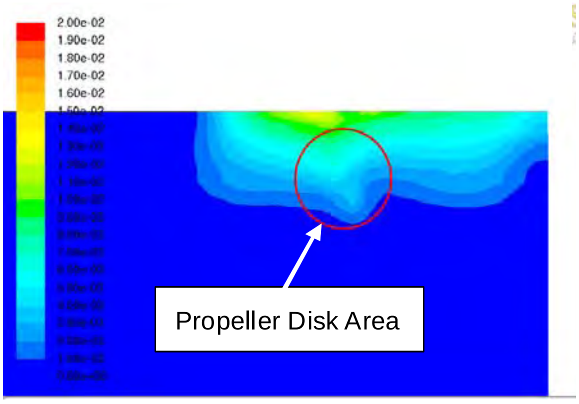

Figure 3 Void fraction distribution prediction on the propeller position (port side)

3 AIR BUBBLES IMPACT ON THE PROPELLER EFFICIENCY FOR THE MODULE CARRIER

3.1 Propeller Open Water Tests in Bubbly Flow

In order to investigate the effects of air bubbles have on the propeller hydrodynamic characteristics, propeller open water tests in bubbly flow were carried out in a towing tank. The experiments were done in Nagasaki Experimental Tank of Mitsubishi Heavy Industries. By measuring open water characteristics when air bubbles are flowing into the propeller center, we have investigated the effect of air bubbles have on the propeller thrust, torque and efficiency. The principal particulars of tested propeller are shown in Table 2 and the experimental arrangement is shown in Figure 4. The bubble injector was installed in 500mm front of the model propeller and the bubble generation nozzle was movable in the direction of water depth. The bubble generation nozzle was installed with 34 holes of 1mm in diameter on the side of the 38mm diameter pipe. The bubbles were released in the form of a circular diffusion to the propeller plane.

The normal propeller open tests fixed the number of propeller revolutions and changed the advanced speed, but the propeller open tests in this paper fixed the advanced speed and changed the number of propeller revolutions in order to keep the inflow situation of air bubbles to the propeller plane. This method was carried out for the diameter of the generated air bubbles was dependent on the advanced speed. The test conditions are shown in Table 3. The tests and analysis were carried out the following procedures.

1) After setting the bubble injector, the propeller open water characteristics (thrust coefficient: KT0, torque coefficient: KQ0, propeller efficiency: ep0) without air bubbles were measured.
2) The propeller open water characteristics (thrust coefficient: KT, torque coefficient: KQ, propeller efficiency: ep) in bubbly flow of several air volume were measured.
3) The propeller open water characteristics were compared with and without air bubbles relatively. Evaluation values were thrust ratio (KT/KT0), torque ratio (KQ/KQ0), and propeller efficiency ratio (ep/ep0).
4) The volume of air injected into the water was expressed in the void fraction α_1 in consideration of the air bubbles flowed into the propeller disk area.

$$\alpha_1 = \frac{Qa \times K}{Vm \times Am} \times 100 \qquad (\%)$$

Qa ; Air mass flow (m^3/sec),

K ; Flow rate of air bubbles into the propeller plane (Calculated from the pictures of underwater video camera),

Vm ; Flow velocity (m/s),

Am ; Propeller disc area (m^2)

Table 2 Principal particulars of tested propeller for module carrier

Diameter	250mm
Pitch Ratio	0.707
Boss Ratio	0.2579
Expanded Area Ratio	0.4761
Rake Angle	0deg.
Number of Blade	4

Table 3 Propeller open water test conditions

	m/s	rps
Slip	Velocity	Revolution
0.5	1.5m/s	17.0
0.45		15.4
0.4		14.1
0.35		13.1
0.3		12.1

3.2 Propeller Open Water Characteristics in Bubbly Flow

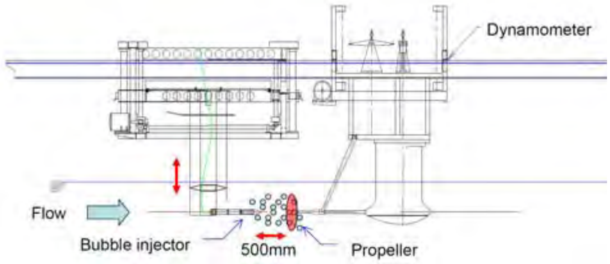

Figure 4 Layout of propeller open water test in bubbly flow

Fig.5 shows the results of comparing the propeller open water characteristics based on void fraction in bubbly flow near the operation point (Slip=0.3 and 0.4). When the void fraction(α_1) increased, thrust ratio (KT/KT0) and the torque ratio(KQ/KQ0) decreased. Because the drop of the thrust ratio was bigger than the torque ratio, the propeller efficiency ratio(ep/ep0) tend to decrease by the increase of the void fraction. The propeller open water characteristics in the bubbly flow are shown below.

- The thrust and torque decrease when the air bubbles flow onto the propeller. Therefore, when a lot of bubbles flow onto the propeller, adjustment of the number of propeller revolutions or the adjustment of the pitch angle of CPP may be necessary in actual ships.
- In the case of this module carrier, the propeller efficiency loss is less than 0.3% if the void fraction is less than 0.5%. The propeller efficiency loss is more than 1% if the void fraction is more than 1%.

Judging from the average void fraction distribution on the propeller disk obtained by calculated results in Chapter 2, the propeller efficiency of this module carrier remained nearly unchanged by the air bubbles. In fact, a decrease in propeller efficiency was not measured by full scale tests.

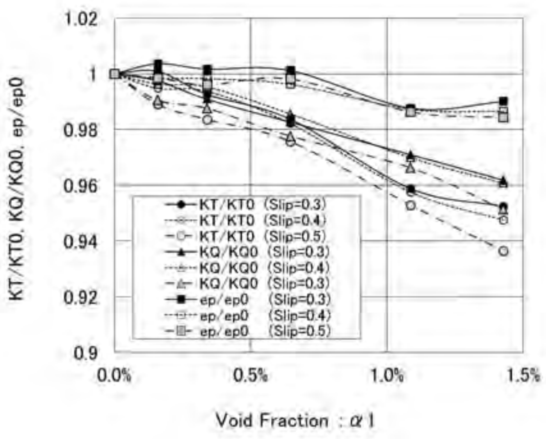

Figure 5 Relationship between the average void fraction on the propeller disk area and propeller open water characteristics (Slip=0.3 and 0.4)

4 AIR BUBBLES IMPACT ON THE PROPELLER PRESSURE FLUCTUATIONS

In order to investigate the effects of air bubbles have on the pressure fluctuations due to propeller cavitation, propeller cavitation tests in bubbly flow were carried out in a cavitation tunnel. Three kinds of propellers for the module carrier, tanker and container ship were used. The experiments were done in Nagasaki Experimental Tank of Mitsubishi Heavy Industries.

4.1 Pressure Fluctuation Measurement Tests in Bubbly Flow

From the CFD calculation results described in Chapter 2, since the sheet-like air bubbles might flow onto the propeller, the pressure fluctuation measurement tests were carried out in cavitation tunnel in the case that the sheet-like air bubbles flowed into the propeller. The test arrangement is shown in Figure 6. The flat plate which imitated the ship's bottom was installed above a propeller, and the pressure sensors were arranged in the flat plate surface. Wire mesh to simulate the ship wake was installed in front of the propeller. The nozzle of bubble injector was installed with 11 holes of 2mm in diameter at intervals of 12.5mm on the side of the 6mm diameter pipe. The photograph of the bubble injector and the wire mesh are shown in Figure 7. The air bubbles inflow positions to a propeller were set to three types of 'center' (50% propeller radial position), 'tip' (90% propeller radial position) and 'bottom' (between the propeller tip and the flat plate) as shown in Figure 8. The tests and analysis were carried out the following procedures.

1) The number of propeller revolutions was set to 25rps, the velocity and the pressure in the cavitation tunnel were set in the operation point without air bubbles.
2) In order to keep constant cavitation number σ_n at the time of an air injection into the tunnel, the pressure in the tunnel was constantly managed by the automatic pressure adjustment function of the cavitation tunnel. The air content was as a guideline of 60%.
3) Firstly, the pressure fluctuations without air bubbles $\Delta P0$ were measured. Then, the pressure fluctuations in bubbly flow of several air volume ΔP were measured.
4) Relative comparison of the pressure fluctuations with and without air bubbles were carried out. The evaluation values were pressure fluctuation ratio ΔP (1st ~ 3rd) / $\Delta P0$ (1st) on the basis of the pressure fluctuations of the first blade frequency without air bubbles.
5) The volume of air injected into the tunnel was expressed in the void fraction α_2 as follows.

$$\alpha_2 = \frac{Qa}{Vm \times Am} \times 100 \qquad (\%)$$

Qa ; Air mass flow (m^3/sec),

Vm ; Flow velocity (m/s),

Am ; Propeller disc area (m^2)

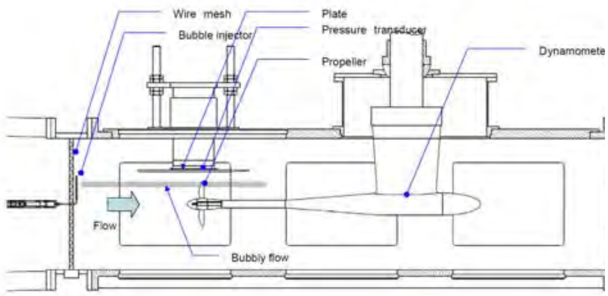

Figure 6 Layout of propeller pressure fluctuation measurements

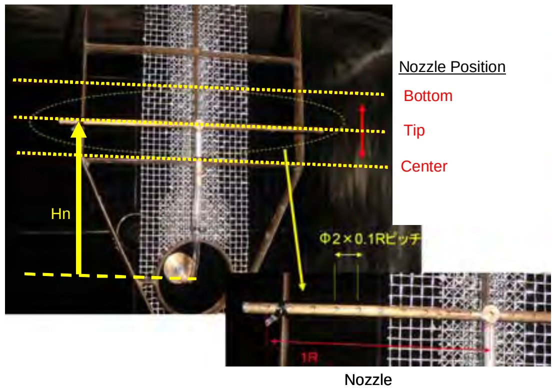

Figure 7 Wire mesh with bubble injector nozzle

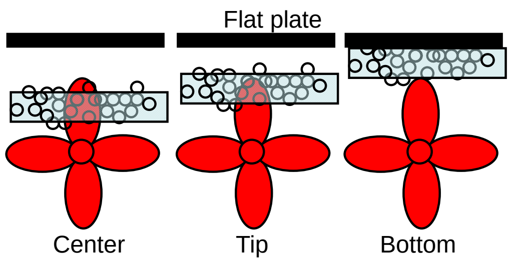

Figure 8 Bubble flow position

4.2 Propeller Pressure Fluctuation Characteristics in Bubbly Flow for a Module Carrier

The effects of propeller pressure fluctuations in the case that the sheet-like air bubbles flowed into the propeller were investigated for the propeller of the module carrier. The photographs of cavitation tests in the cases that the air bubbles inflow positions of 'center', 'tip' and 'bottom' are shown in Figure 9. When the void fraction α_2 increased, the air bubbles were captured in the tip vortex cavitation and tip vortex cavitation became thick. Figure 10 shows the comparison of the results of pressure fluctuation measurements when changing the void fraction α_2 in thrust coefficient KT=0.14 and the cavitation number σ_n=1.55. The numbers ①~⑭ in Figure 10 are compatible with the number of test conditions listed in Figure 9.

In this test results, it was found that the pressure fluctuation ratio of the first blade frequency was increased most when the α_2=0.23% without depending on the air bubbles inflow position and it increased about 2~2.5 times than the case without air bubbles(α_2=0%) The pressure fluctuation of the higher-order blade frequency tended to decrease due to the increase of the void fraction.

The pressure fluctuation ratio of the first-order blade frequency was extremely increased in the case of α_2=0.23% at the center air bubble inflow position 'Center'. Judging from the situation of ④ in Figure 9, it is thought that this phenomenon occurred because the cavitation volume on the propeller blades increased for

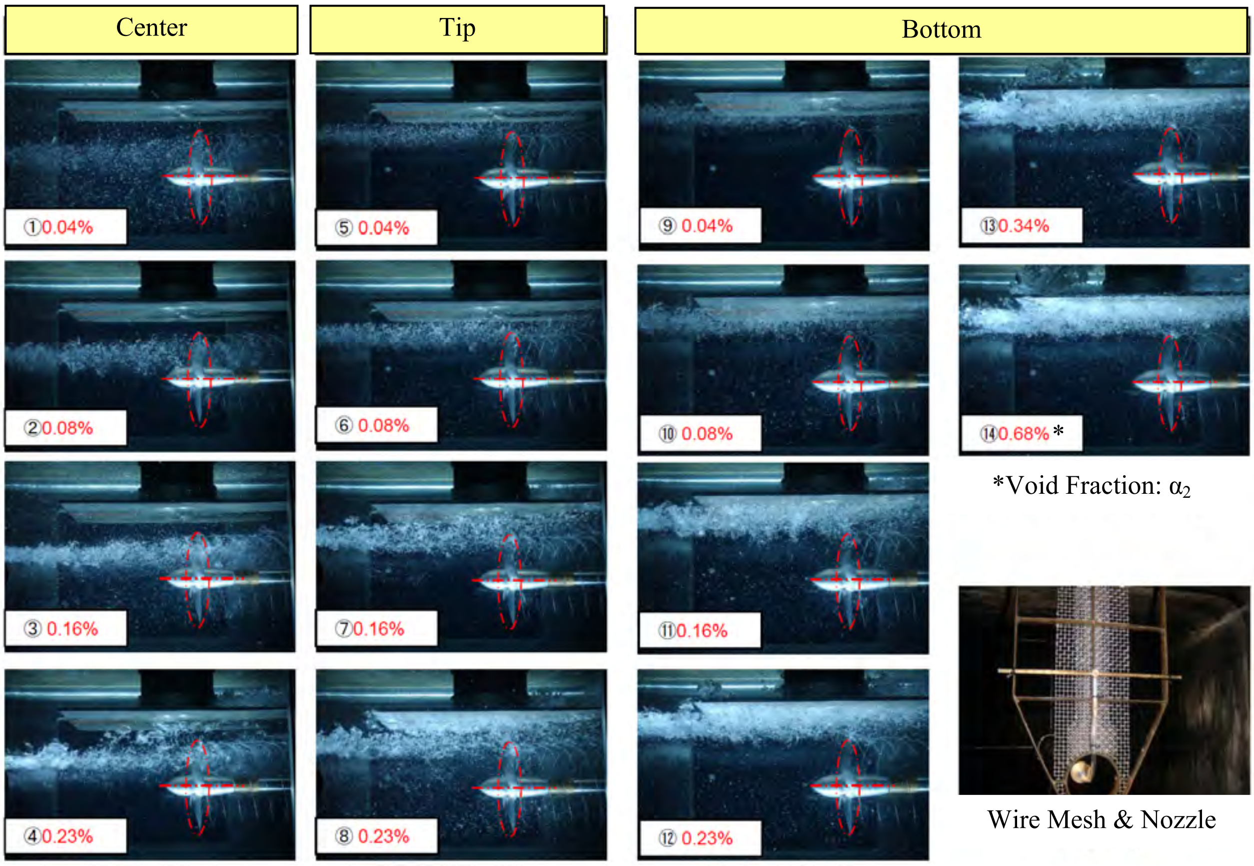

Figure 9 Photographs of cavitation tests in bubbly flow (Slip=0.4)

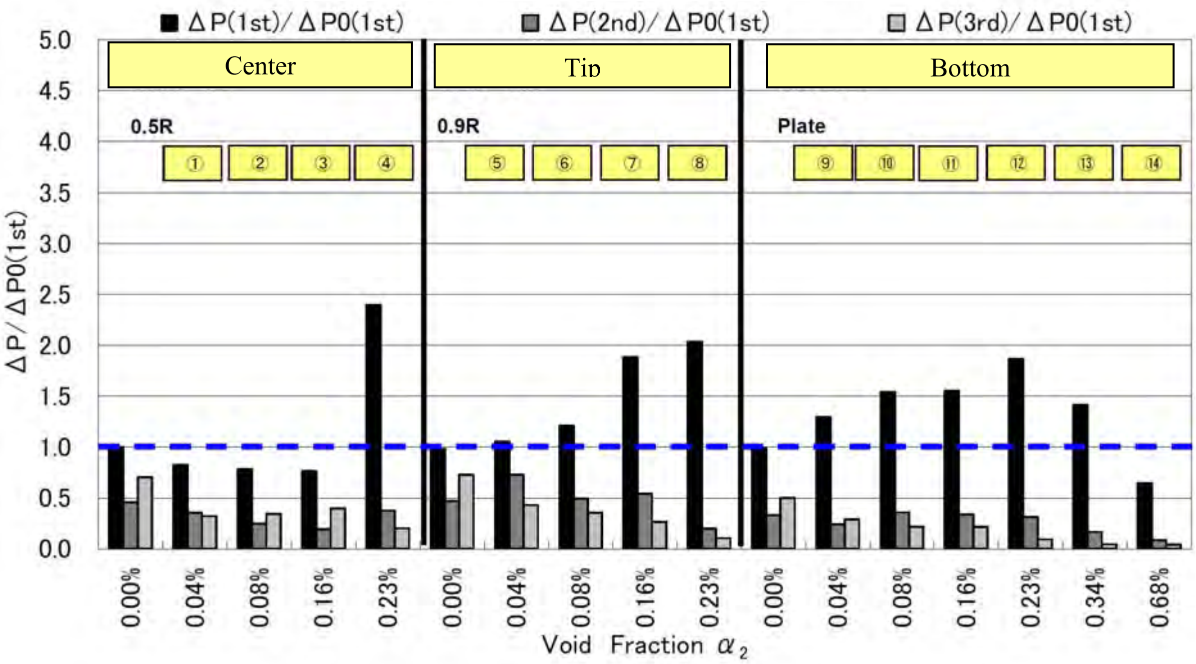

Figure 10 Results of propeller pressure fluctuation measurements in bubbly flow (KT=0.14, σ_n=1.55)

the increasing of the amount of air bubbles which flows into the blade tip part.

The phenomenon that the pressure fluctuations increased when air bubbles flowed into the tip of the propeller ('Tip') showed the same tendency as the experimental results of Hinatsu et al (2009).

If the air bubbles inflow position is 'bottom', the pressure fluctuation ratio decreases with increasing the void fraction α_2 as the peak of α_2=0.23%. When the void fraction α_2=0.68%, the pressure fluctuation ratio becomes less than 1, the propeller pressure fluctuations decrease by air bubbles. This phenomenon is regarded as the cushion effect with air bubbles.

The characteristics of the propeller pressure fluctuations in the bubbly flow are shown below.

- When the air bubbles flowing near the blade tip, the pressure fluctuation of the first blade frequency tend to increase gradually and the higher-order blade frequency tend to decrease gradually.
- In the case of this module carrier, the increment of pressure fluctuations was a peak at the void fluctuation α_2=0.23%, the pressure fluctuation of the first blade frequency was increased about 2~2.5 times. On the other hand, the pressure fluctuations of high order blade frequency more than second order was not increased.
- In addition, if air bubbles flowed between the propeller and the flat bottom, when the void fraction was more than 0.68%, there was a possibility that the pressure fluctuation was reduced by the cushion effect.

Judging from the average void fraction of the propeller disk obtained by calculated results in Chapter 2 was about 0.1%, the pressure fluctuations of this module carrier remained nearly unchanged by the air bubbles. In fact, the increase of pressure fluctuations measured by full scale tests was not observed in MALS working conditions.

4.3 Propeller Pressure Fluctuation Characteristics in Bubbly Flow for other propellers

In order to investigate the effects of air bubbles have on the pressure fluctuations due to the differences of propeller shape and operating conditions, propeller cavitation tests in bubbly flow were carried out in a cavitation tunnel for two kinds of propellers for tanker and container ship. The model propeller A is a 5 bladed propeller for tanker and its principal particulars are shown in Table 4. The model propeller B is a 6 bladed propeller for container ship and its principal particulars are shown in Table 5. The experimental method is the same as the method described in section 4.2. The air bubbles inflow position was set only 'tip' in the cavitation tests.

In case of propeller A, an example picture of cavitation test is shown in Figure 11 and the comparison of the pressure fluctuation ratio of the first blade frequency when changing the void fraction α_2 and the cavitation number σ_n in the thrust coefficient KT=0.18 are shown in Figure 12. When the cavitation number was low, the pressure fluctuations were observed the tendency to rise rapidly at the low void fraction. There was relatively small amount of cavitation which occurred on propeller A

Table 4 Principal particulars of model propeller A

Diameter	220mm
Pitch Ratio	0.656
Boss Ratio	0.16
Expanded Area Ratio	0.474
Skew Angle	18deg.
Number of Blade	5

Table 5 Principal particulars of model propeller B

Diameter	250mm
Pitch Ratio	1.016
Boss Ratio	0.19
Expanded Area Ratio	0.789
Skew Angle	25deg.
Number of Blade	6

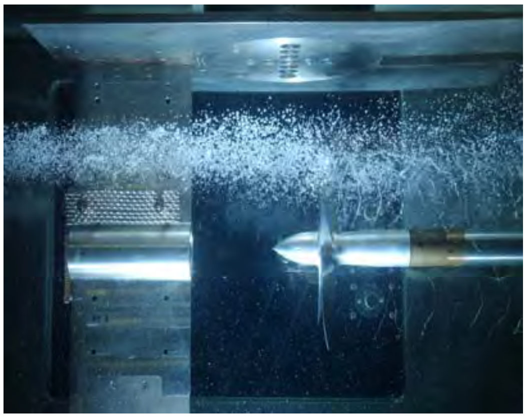

Figure 11 Photograph of cavitation test in bubbly flow (Propeller A)

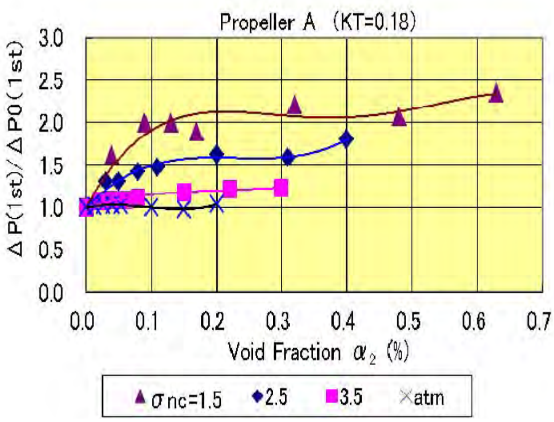

Figure 12 Results of propeller pressure fluctuation ratios in bubbly flow (Propeller A, KT=0.18)

without air bubbles.

In case of propeller B, an example picture of cavitation test is shown in Figure 13. The comparison of the pressure fluctuation ratio of the first blade frequency when changing the void fraction α_2 and the cavitation number σ_n in the thrust coefficient KT=0.17 are shown in Figure 14. When the void fraction was low, the pressure fluctuations of propeller B were not observed the tendency to rise rapidly in comparison of the pressure fluctuations of propeller A. There was relatively large amount of cavitation which occurred on propeller B without air bubbles.

Judging from the results for propeller A and propeller B, the characteristics of the propeller pressure fluctuations in the bubbly flow are shown below.

- At the normal condition (without air bubbles), in the case of less cavitation propeller, the pressure fluctuations of the propeller tend to be susceptible to the effects of air bubbles mixing.
- If the average void fraction in the propeller disk become more than 0.2%, there was a possibility that the propeller pressure fluctuation of the first blade frequency was doubled or more in comparison with the case without air bubbles.

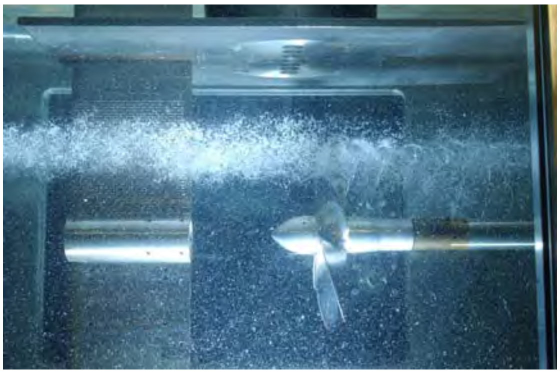

Figure 13 Photograph of cavitation test in bubbly flow (Propeller B)

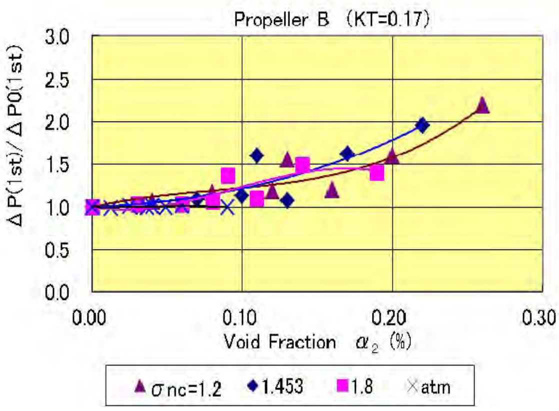

Figure 14 Results of propeller pressure fluctuation ratios in bubbly flow (Propeller B)

5 Conclusion

The hydrodynamic performance of a propeller running in bubbly flow was investigated by model tests mainly as a necessary consideration item for application to various types of ships with the air lubrication system that reduces the frictional resistance of the hull by using air bubbles. As survey results for the module carrier which was a twin-screw vessel characterized by its wide breadth and shallow draft, it was found that the amount of air bubbles flowing into the propeller was small, the decrease of propeller efficiency and the increase of propeller pressure fluctuations were negligible as well as the full scale test results. Furthermore, from the experimental results for two kinds of other propellers running in bubbly flow by changing the void fraction, at the normal condition (without air bubbles), in the case of less cavitation propeller, it was found that the pressure fluctuations of the propeller tend to be susceptible to the effects of air bubbles mixing in the flow.

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