Flow Visualization and analysis by PIV Measurement System using Micro-bubbles as Tracer in Ship Model Basin
- Measurement in Still Water and Regular Waves-

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Abstract To measure and analyze the flow around ship model, use of micro-babbles as tracer is proposed here. The system has two high speed cameras for stereo photography with continuous laser light sheet. Using continuous laser light sheet flow around ship can be observed directly.
To make validation of the present system flow analysis of uniform flow and regular waves in ship model basins is carried out. From the comparison between flow velocity analyzed by the present system and that measured by current meter in different three ship model basins, it is found that the correlation factors of the basins are over 0.99 for flow velocity of ship advance direction. In regular waves the trajectory of the wave motion is compared to small amplitude wave theory and analyzed value. From the comparison it is found that the agreement is well for different wave frequencies.
Continuously, flow measurement using a ship model of large tanker has performed in still water and in regular head waves. From the analysis it is found that the difference of the flow vector between still water and regular head waves can be evaluated qualitatively. Thereafter to understand the flow around propeller the tank tests in self propelling condition of the ship model are performed. From the comparison between the tests with propeller and without propeller, the effect of propeller suction is revealed.
From the various comparisons the effectiveness of the PIV system using micro-bubbles to obtain flow information around ship is confirmed.
Keywords: PIV, Micro-bubbles, Resistance Test, Self-Propulsion Test

1 Introduction

In order to reduce Greenhouse Gas emission from ships, energy efficiency is important for ship design and ship operation. To improve ship energy efficiency in seaways, flow visualization around propeller in waves is a key for increase propulsive performance.

To measure the flow around ship model, PIV measurement system has been installed in some ship model basins and the measured results have been published eg.[1], [2], [3], [4], [5]. Commonly the PIV system in ship model basin is composed of synchronous stroboscopic laser light sheet (LLS) with camera and tracer of silver coated hollow glass spheres or nylon particle. However use of the tracer may affect operation of wave makers since the tracers can not be collected from the ship model basin. Tank test of self propelling the ship model requires high accuracy in measurement of thrust and torque, thus the discharge of the tracers has a risk for less accuracy.

To solve the problem, use of micro-babbles as tracer is proposed for flow visualization and analysis around ship. Present system is superior to PIV system using tracer of solid type since the collection of the micro bubble tracer is free. The system has two high speed cameras for stereo photography with continuous LLS. Using continuous LLS flow around ship can be observed directly.

To make validation of the present system flow analysis of uniform flow and regular waves in ship model basins is carried out. From the comparison between flow velocity analyzed by the present system and that measured by current meter in different three ship model basins, it is found that the correlation factors of the basins are over 0.99 for flow velocity of ship advance direction. In regular waves the trajectory of the wave motion is compared to small amplitude wave theory and analyzed value. From the comparison it is found that the agreement is well for different wave frequencies.

To improve ship energy efficiency in seaways flow around propeller in waves is important to understand the behavior. Therefore flow measurement using a ship model of large tanker, which length is 4.2m has performed in still water and in regular head waves. From the analysis it is found that the difference of the flow vector between still water and regular head waves can be evaluated qualitatively. Thereafter to understand the flow around propeller the tank tests in self-propulsion condition of the ship model are performed. From the comparison between the tests with propeller and without propeller, the effect of propeller suction is revealed.

This paper reports experimental techniques using present system and acquired data. From the various comparisons the effectiveness of the PIV system using micro-bubbles to obtain flow information around ship is confirmed.

2 Micro-bubble generator and Characteristics of Generated Bubbles

As a generation method of the micro bubble, there are (1) Gas-liquid mixture shear method, (2) Cavitation method, (3) Pressurized dissolution method, (4) Fine pores method, etc.

Micro bubble generator used in this study is combined Gas-liquid mixture shear method and Cavitation method.

In this micro bubble generation device, a first, air and water mixed by pump.

This mixing water is further mixed in the cylindrical mixer with multiple protrusions in the inside, and micro bubble is generated [6].

First of all, basic property of the micro bubble was examined.

Measurement of the diameter of the micro bubble illuminated the transparent beaker which satisfied the micro bubble water by the laser sheet light, and it expanded by the microscope and was photographed.

Image resolution of the microscope is 720 × 480pixel, the photographing range is 6.5 × 4.3mm, and the resolution is 9.1μm/pixel.

The diameter of the bubbles, the bubbles from the number of pixels of the image is calculated by assumption of the true sphere.

The measuring result of bubble diameter is shown in Fig.1.

Diameter of bubble from the figure are distributed between the 10 μm to 60 μm and average diameters is 31 μm.

The rising speed of the micro bubble in which such bubble diameter is small is slow. And, the micro bubble is shrink and is disappeared with rise.

By repelling, because the micro bubble is being charged negatively, bubble does not combine [7].

The result of investigation of basic property of the micro bubble was expected as a tracer of future PIV measurement.

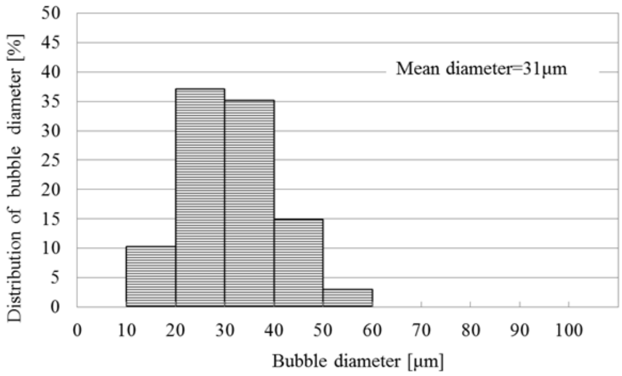


Fig. 1 Distribution of bubble diameter

3 PIV measurement system

The configuration of the PIV measurement system using micro-bubbles which is developed for the ship model basin is shown in Fig.2. The system has a discharge part of micro bubbles in front of LLS, a continuous LLS to illuminate the flowing bubbles and two high-speed cameras to take stereo images of the flow.

The detailed arrangement of the PIV system using the present measurement is shown in Fig. 3. The system is prepared for the flow measurement around a model ship, so that a traverse device for moving the measuring section in the width direction of the ship (*y*-axis). The high-speed camera used in the PIV system is able to take a VGA size image at 200 frames per second and the minimum illuminance is 10 lux (at F-number 1.4). A lens having a focal length is 12 mm and F-number 1.2 is used for the measurement. The image taken by the high-speed cameras has a size of 250mm × 190mm and the resolution is approximately 0.4mm per pixel. A continuous wave laser of green light (wave length is 532nm) of 4W output is used for the light source of laser optical system. Using two mirrors the laser light is directed in the water and is diffused in a fan shape by a cylindrical lens. Finally, the laser light sheet illuminates the object upward through a mirror.

The thickness of the LLS of the present system is about 1mm, therefore, if the movement of the micro bubbles to the outside of the LLS plane is large, the tracer will be lost from the continuous images. In such case the analysis by PIV is impossible. It is known if the amount of movement to the outside of LLS plane is less than 1/4 of the thickness of LLS, the measurement does not affect the accuracy of the analysis. [8] Regarding to the present system, up to 0.050m/s for outside of LLS plane can be analyzed with the high-speed camera of the 200 fps and LLS thickness of 1mm.

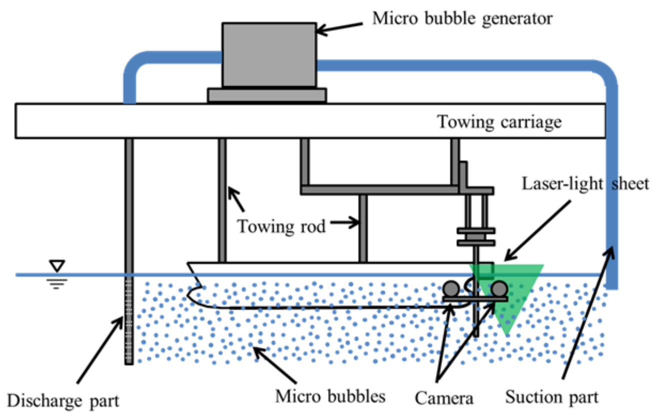


Fig. 2 Side view of the system configuration

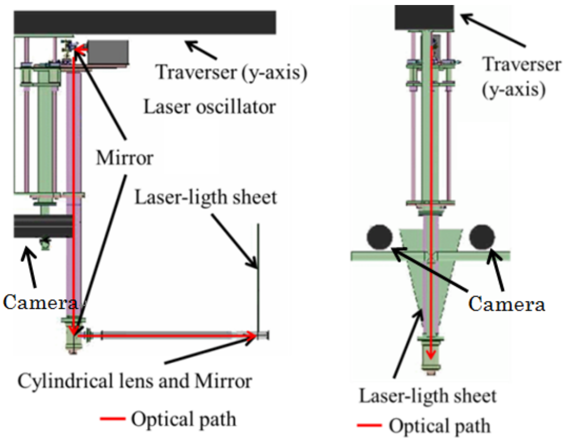


Fig. 3 PIV system, front view(Left) and side view(Right)

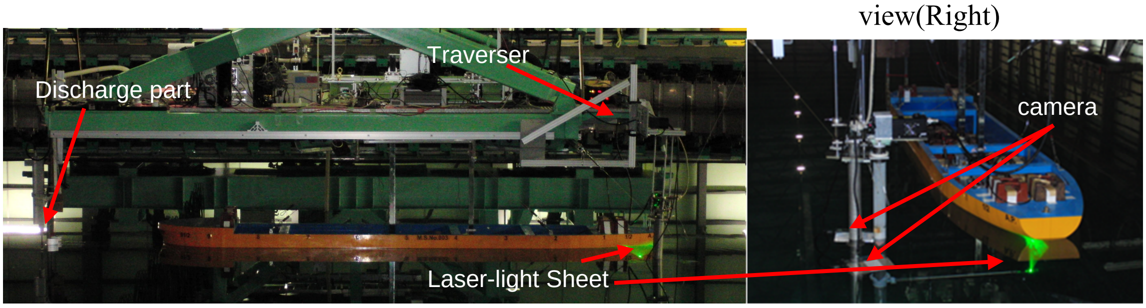


Fig. 4 Setup of the PIV measurement

4 Verification test

In order to validate the present system, flow measurement in uniform flows and in regular waves are carried out at three ship model basins in National Maritime Research Institute. The basins used are Wave tank (50m in length, 8m in breadth and 4.5m in depth), Actual Sea Model Basin (80m in length, 40m in breadth and 4.5m in depth) and 150m Towing Tank (150m in length, 7.5m in breadth and 3.5m in depth). Right-handed coordinate system is used here, where *x*-axis is the main flow direction, *y*-axis is the vertically above direction and *z*-axis is the port direction.

The measurement results of the uniform flow are shown from Fig. 5 to Fig. 7 and Table 1.

Fig. 5 shows the time histories of the analyzed flow velocity of *x*-axis; *U*, *y*-axis; *V* and *z*-axis; *W* at 150m Towing Tank, respectively. Comparing with *U*, *V* and *W*, it is observed that the variation of *W* is larger than *U* and *V*. *W* is the velocity of outside of LLS plane, so that it has large variation in contrast with *U* and *V*. In Fig.5 the average value ($\overline{U}$, $\overline{V}$ and $\overline{W}$) and variance (S_U^2, S_V^2 and S_W^2) are shown altogether.

Then the probability density functions (PDF) which are obtained by the data of Fig. 5 are shown in Fig.6.

From the figure PDF is approximated by normal distribution, although *V* and *W* have a slight bias.

The correlation between the average velocity of the main flow direction analyzed by PIV ($\overline{U}$) and measured velocity through the water ($\overline{U_w}$) is shown in Fig.7. This figure shows that the uniform velocity analyzed by PIV which are carried out at the different ship model basins has a well correlated with measured velocity and as well as well agreed with the mean line; a solid line in Fig.7. The correlation coefficient (*R*) is over 0.99 in any cases. This confirms the present PIV system has a high accuracy as a measurement device.

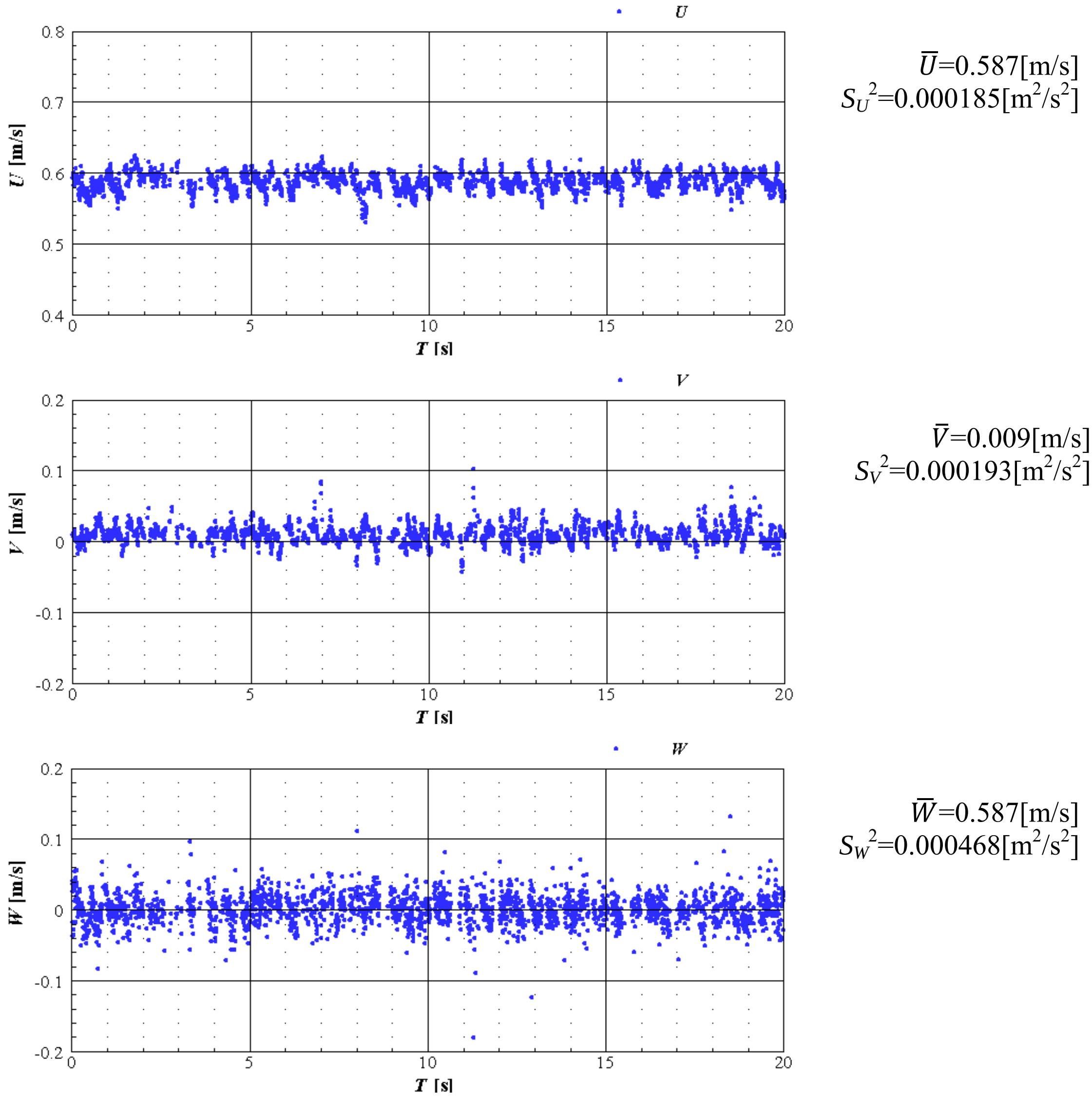


Fig. 5 Time series of measurement velocity *U*(top), *V*(middle), *W*(bottom) at 150m towing tank

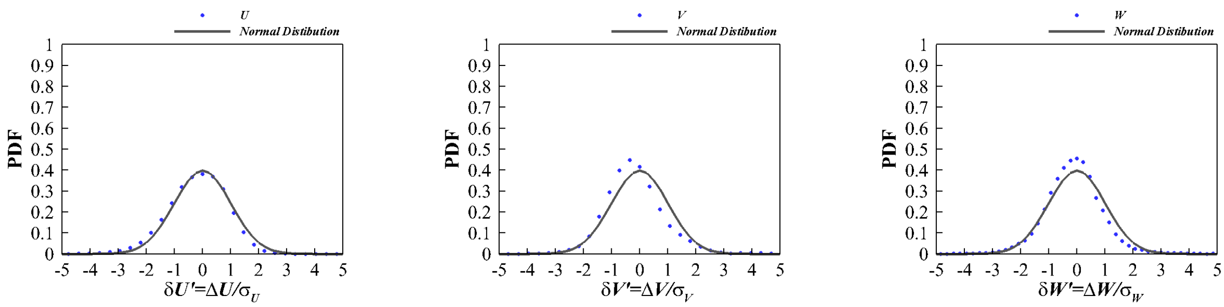


Fig. 6 Probability density distribution *U*(left), *V*(middle), *W*(right)

Following to the validation by uniform flow, flow analysis in regular waves has carried out. Fig.8 shows the results of wave height; H_w=0.050m and wave period; *T*=2s of regular waves in Wave Tank. (a), (b) and

(c) show the result at different depth of *y*=-0.187m, *y*=-0.224m and *y*=-0.261m, respectively, where *y*=0 is water surface. In Fig.8 a solid line shows the theoretical value by small amplitude wave theory and dots show analyzed by PIV. From the figure *U* and *V* at *y*=-0.224m and *y*=-0.261m both value have well agreed, however, *U* at *y*=-0.187m has a slight bias. It is observed that *U* at *y*=-0.187m is shifted to the speed-increasing side. This considered that this is caused by the discharging the micro bubbles into the water. The bias of the *U* observed at shallow and the discharge part of the micro bubbles is located near water surface. Thus if the discharging velocity of the micro bubbles are larger than the flow velocity to be measured it is necessary to minimize the discharging velocity.

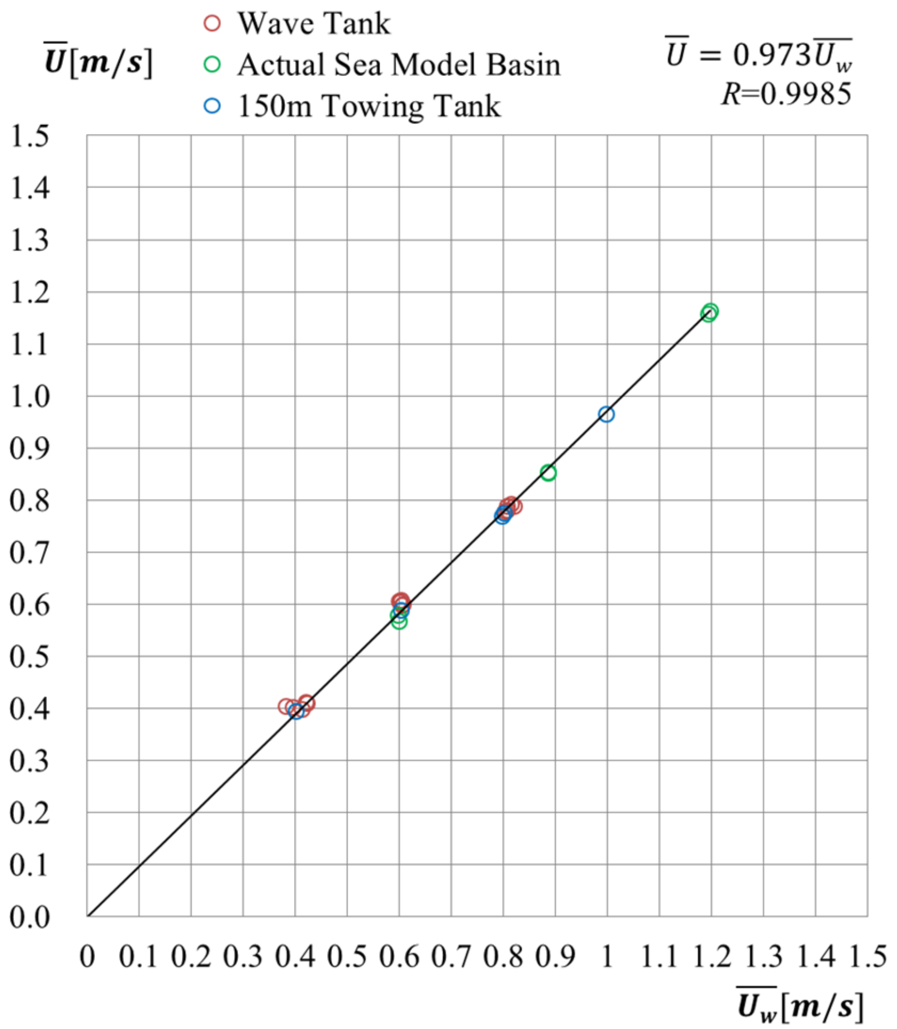
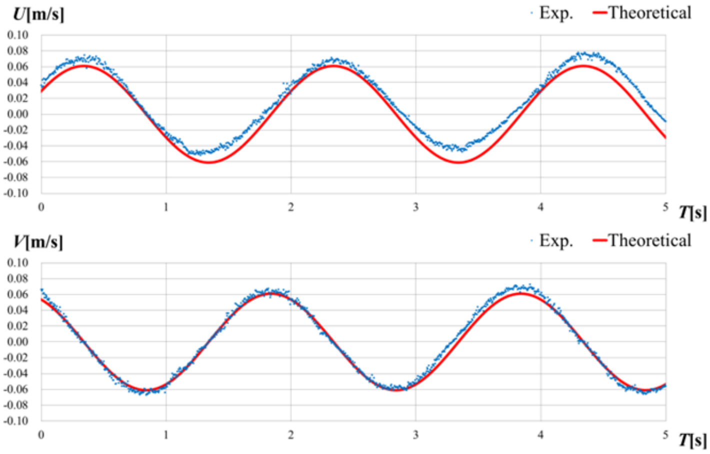


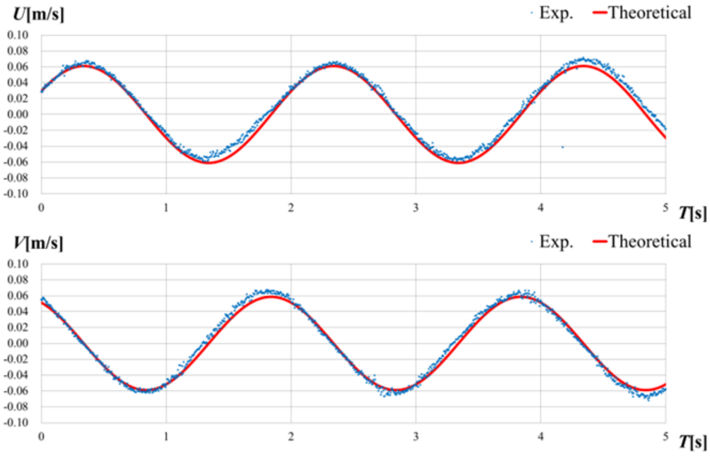
Fig. 7 Comparison ($\overline{U}$) between of PIV and water current meter ($\overline{U_w}$)

Table 1 Slope (a) coefficient and correlation coefficient

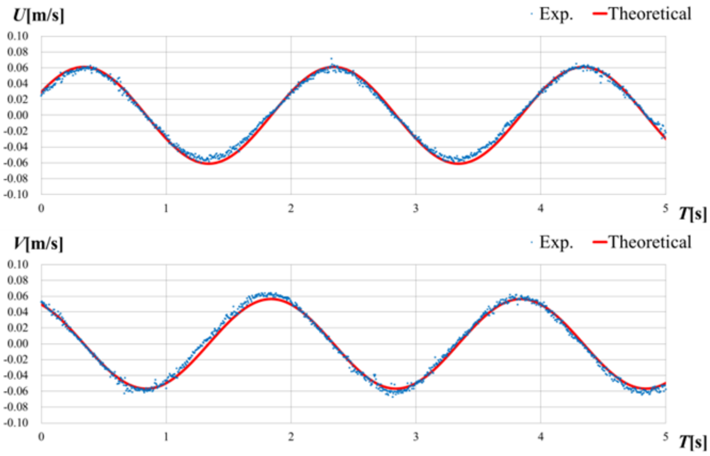
$\overline{U} = a\overline{U_w}$	a	R
Wave Tank	0.981	0.9967
Actual Sea Model Basin	0.965	0.9996
150m Towing Tank	0.968	0.9999
ALL	0.973	0.9985



(a) y=-0.187m, U(top), V(bottom)



(b) y=-0.224m, U(top), V(bottom)



(c) y=-0.261m, U(top), V(bottom)

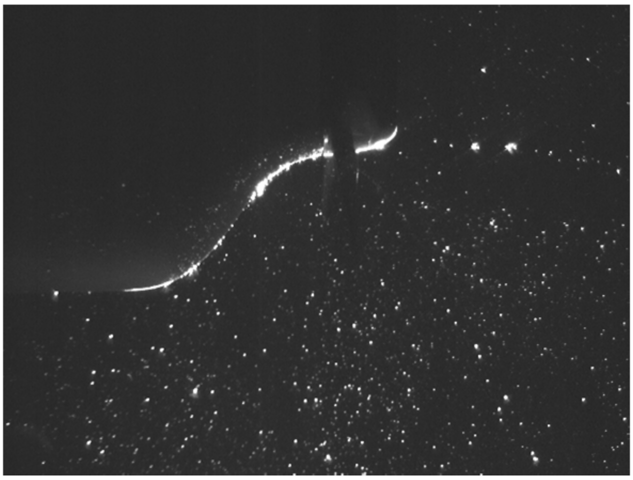
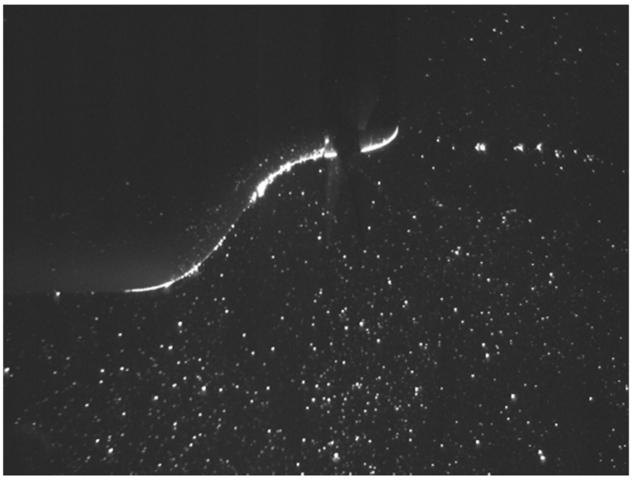
Fig. 8 Time series of measurement velocity(Hw=0.050m, T=2s)

5 Flow field measurement around a ship model

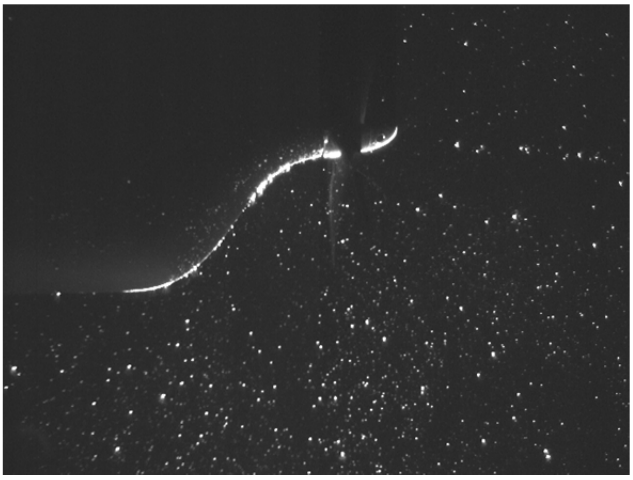
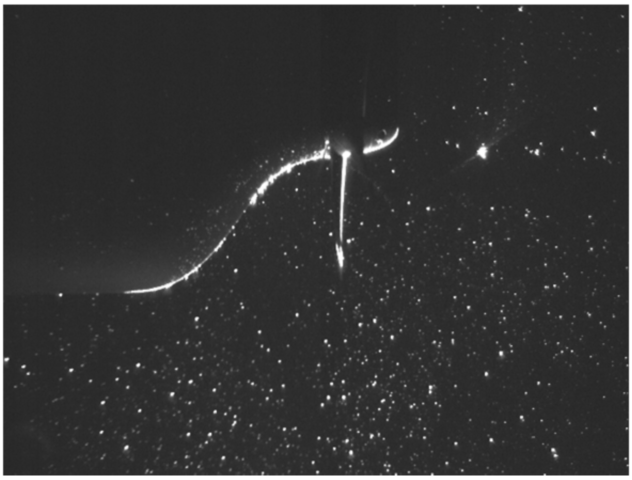
The flow measurement around a model ship is carried out in 150m Towing Tank. The principal dimensions of the model ship of VLCC (Very Large Crude oil Carrier) is shown in Table 2. Ship speed of the model (U_m) is 0.6 m/s (F_n = 0.094) which corresponds to 10.3knot in full scale ship. Measured sections are selected as center line (C.L.) and 0.7R, R is radius of a propeller; R=60mm of model scale. Right-handed coordinate system is used, where origin of x-axis and y-axix is aft perpendicular (A.P.) and water surface, respectively. In this section, speed is normalized by towing speed (U_m). An example of the measured image in self-propulsion test in waves (wave length-ship length ratio, λ/L, is 1.1) is shown in Fig. 9.

Table 2 Principal dimensions of VLCC

Item	Model	Ship
ship length L [m]	4.160	324.00
ship breadth B [m]	0.7704	60.00
ship draught d_m [m]	0.2632	20.50
Condition	Full load	

$T=\Delta t\times 1$ $T=\Delta t\times 2$

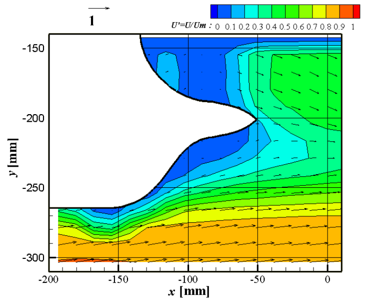
$T=\Delta t\times 3$ $T=\Delta t\times 4$

Fig. 9 Visualization(Self-Propulsion Test λ/L=1.1) Δt=1/200fps

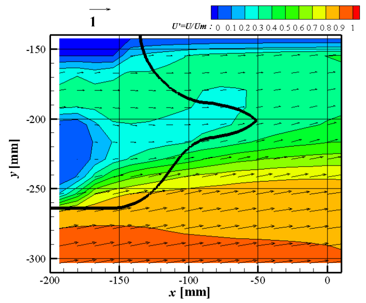
5.1 Ship flow in still water condition

Tank test to measure the ship flow around the propeller is carried out in both resistance test and self-propulsion test in still water condition. The results of analysis by PIV in a resistance test is shown in Fig.10 with ship profile. (a) and (b) show the result of C.L. and 0.7R section, respectively. Fig.10 and the following figures are drawn the averaged value in space-fixed coordinate system. Form the figure it is observed down flow upper and rear of the stern tube in C.L.. Please note, since the LLS illuminates from under the model ship to upward, it is not possible to measure the just upper part of the stern tube.

The results of the self propulsion test is shown in Fig. 11. From Fig.11, it is found that upward velocity at the forward of the propeller is increased compare with the same condition in resistance test. The phenomena of accelerated flow by the propeller rotation is measured and analyze. Unfortunately it is not possible to measure the part of strong three dimensionality flow at this time, since the frame rate of the camera is slow and not enough. Therefore, the flow at rear of the propeller (-50mm $\leq x$ and -230mm $\leq y$ of C.L.) will not measure accurately.

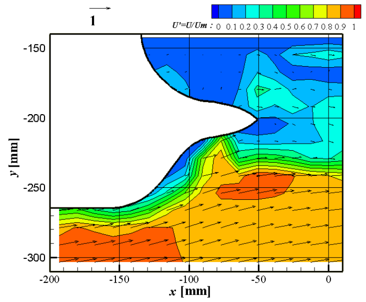


(a) Measurement section : C.L.

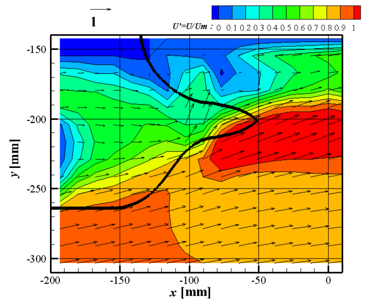


(b) Measurement section : 0.7R

Fig. 10 Average velocity vectors and contour of magnitude mainstream velocity
(Resistance test, in still water)

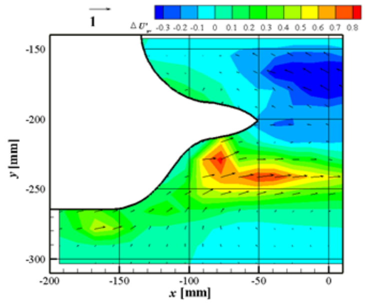


(a) Measurement section : C.L.

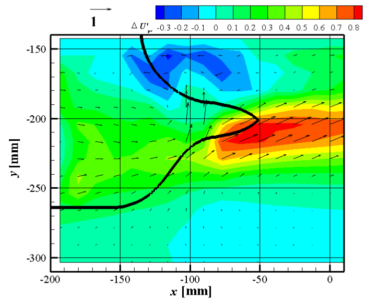


(b) Measurement section : 0.7R

Fig. 11 Average velocity vectors and contour of magnitude mainstream velocity
(Self propulsion test, in still water)

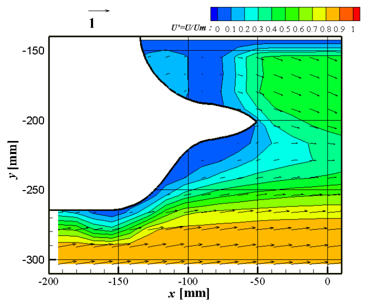


(a) Measurement section : C.L.

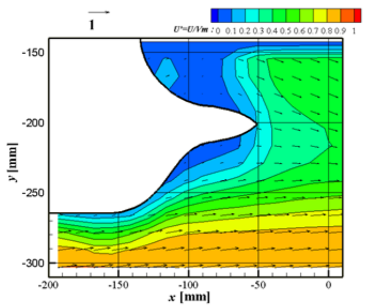


(b) Measurement section : 0.7R

Fig. 12 Difference between the resistance test and self propulsion test

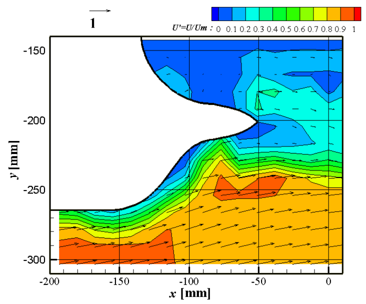


(a) λ/L=0.4 at C.L.

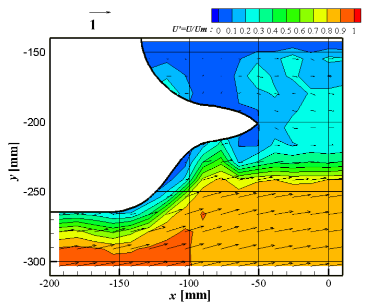


(b) λ/L=1.1 at C.L.

Fig. 13 Average velocity vectors and contour of magnitude mainstream velocity
(Resistance test, in waves)

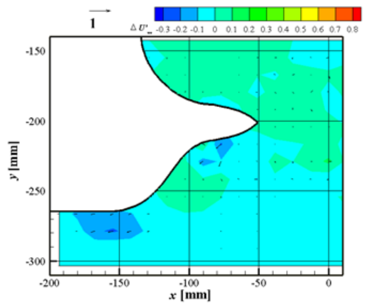


(a) λ/L=0.4 at C.L.

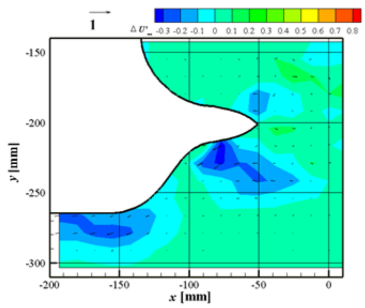


(b) λ/L=1.1 at C.L.

Fig. 14 Average velocity vectors and contour of magnitude mainstream velocity
(Self-propulsion test, in waves)



(a) λ/L=0.4 at C.L.



(b) λ/L=1.1 at C.L.

Fig. 15 Difference between the waves and still water
(Self propulsion test)

A difference between the average flow velocity in the resistance test and that in self propulsion test, $\Delta\overline{U'_{pr}}$, is shown in Eq. (1) and the distribution is shown in Fig.12.

$$\Delta\overline{U'_{pr}} = \overline{U'_p} - \overline{U'_r} \tag{1}$$

where U'_p is flow velocity in self propulsion test, $\overline{U'_r}$ is flow velocity in resistance test.

It is shown in Fig.12 the faster and slower flow around the stern tube at C.L., but for the restriction of the present system it is not accurately measured.

5.2 Ship flow in waves

In succession to the measurement in still water condition, measurement of the ship flow in regular head waves is carried out both for resistance test and self propulsion test. The measurements are carried out at two wave length. One is in short waves, wave length-ship length ratio (λ/L) is 0.4, and another is in long waves, λ/L is 1.1. Ship speed of the model (U_m) is 0.6 m/s (F_n = 0.094) and wave height is 2.6cm which corresponds to 2m in full scale ship.

The results of the resistance test and self propulsion test are shown in Fig. 13 and Fig.14, respectively. (a) and (b) show the result of λ/L=0.4 and λ/L=1.1 at C.L.. Since the analyzed results are the average value in space-fixed coordinate system, it is not considered that the model ship position and the measurement position are changed by ship motion.

Comparing with the flow of resistance test in short waves, Fig.13(a), and in still water, Fig.10(a), the difference between the two are not seen. In case of comparing with flow of resistance test in long waves, Fig.13(b), and in still water, Fig.10(a), the significant difference are not seen.

In order to see the difference of self propulsion test in still water and in waves, the difference of the average flow velocity between in waves and in still water in self propulsion test, $\Delta\overline{U'_{ws}}$, is shown in Eq (2) and the distribution is shown in Fig.15.

$$\Delta\overline{U'_{ws}} = \overline{U'_w} - \overline{U'_s} \tag{2}$$

where $\overline{U'_w}$ is flow velocity in waves of self propulsion test, $\overline{U'_s}$ is flow velocity in still water of self propulsion test.

From Fig.15, the significant difference of average velocity are not seen, but in long waves slow speed are shown in below of the stern tube and x=-150mm. This difference in flow velocity near the hull is considered that the average velocity involves the effect of ship motion in averaging process.

Thereafter, in order to make a difference of the test results in still water and in waves, time series of flow velocity of resistance test at x = -90mm and y = -290mm of C.L. are shown in Fig.16. From the time series data, the amplitude of the flow in long waves are significantly different from that in short waves. This is the effect of ship motion and it is understood the relative motion in waves is important to evaluate the stern flow.

6 Conclusion

PIV measurement system using micro-bubbles as tracer in ship model basin has been developed and the validation by uniform flow and regular waves are shown. Analyzed flow around ship stern are shown as well. The results of this study are summarized as follows.

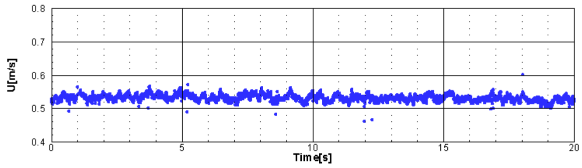
1) From the validation in the uniform flow, it is found that the analyzed value by the present system has a high correlation with the measured by current meter. The results are confirmed by the other model basins.

2) From the validation in regular waves, it is found that the analyzed value by the present system has a good agreement with the theoretical value.

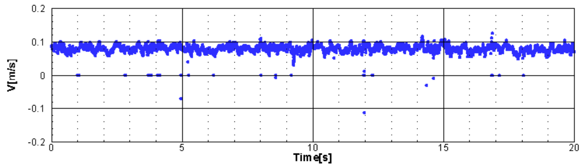
3) From the comparison of the flow around the ship stern between the resistance test condition and the self-propulsion condition, it is possible to analyze the effect of the suction caused by the propeller.

4) Flow around a ship in waves can be analyzed by the present system and the analyzed results provide a deep understanding of the flow which is caused by relative motion of ship motion and waves.

$\bar{U}$: 0.529[m/s], S_U : 0.012[m/s]

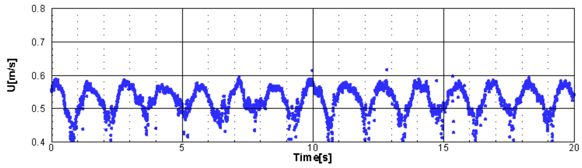


$\bar{V}$: 0.078[m/s], S_V : 0.017[m/s]

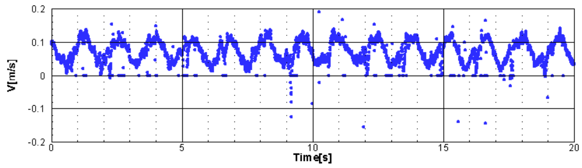


(a) (Resistance test, Still water), U(top), V(bottom)

$\bar{U}$: 0.526[m/s], S_U : 0.041[m/s]



$\bar{V}$: 0.070[m/s], S_V : 0.039[m/s]



(b) (Resistance test, λ/L =1.1) , *U*(top), *V*(bottom)

Fig.16 Time series of measurement velocity
(*x*=-90mm, *y*=-290mm)

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