Full Scale Measurement of The Flow Field at The Stern by Using Multi-Layered Doppler Sonar (MLDS)

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ABSTRACT

A scale effect on flow field from model to ship scale has been a big concern for researchers in a ship industry for a long time. Although a Computational Fluid Dynamics (CFD) is expected to clarify this problem, the validation data for the full-scale CFD calculation is very few so far. The direct measurements of full-scale flow field are confined by their complexity with heavy prices in the measurement system. To break through this situation, the world's first new measurement system, Multi-Layered Doppler Sonar (MLDS) was applied in this study. MLDS is a Doppler sonar capable of measuring relative water velocity at multiple arbitrary points along ultra-sonic beams. MLDS was installed on a 14,000 TEU container ship and full scale measurement was carried out. As a result, MLDS worked very well and showed good agreements with the CFD calculation.

In this paper, we introduce about the MLDS, the flow velocity measurement results and cavitation pattern observed onboard.

Keywords

Full Scale, Flow Measurement, CFD, MLDS, Cavitation

1 INTRODUCTION

How to deal with a scale effect on flow field around the hull is one of the most important issues for ship designers. It is difficult to optimize the hydrodynamic performance of a ship unless the flow field in which the propeller or the energy saving device works is appropriately given as the design condition.

To understand characteristics of a flow field at full scale, some attempts on measurements of full scale flow field have been made in the past. In 1970s, measurements by using five-hole pitot tubes were reported from several research groups (Yokoo et al 1971, Namimatsu et al 1973). This method has an advantage to measure flow velocity in three components, i.e. velocity in x, y and z directions, independent of the water quality. However, it has been rarely used since then because very large structures supporting the pitot tubes are required outside the hull. Since 1980s to 1990s, Laser Doppler Velocimetry (LDV) was applied to full-scale measurement as more promising technique and the flow fields just in front of a propeller were measured in several projects (Kux et al 1982, Lammers et al 1987, Tanibayashi et al 1990). Their results have been repeatedly compared with the CFD calculation (ex. Visonneau 2005) and contributed as the valuable validation data. Recently, an attractive work by using Partical Imaging Velocimetry (PIV) was conducted in the joint R&D project "KonKAV II" (Kleinwachter et al 2015). Although the PIV technique has been widely used in model tests, it was the first application for full scale measurement of propeller inflow velocity. They measured the wake-field in front of the propeller for the ConRo-ship successfully. The most advantage of PIV is to achieve higher data rate compared with LDV and consequently more accurate data is expected. Following this successful work, the Japanese industrial project "i-Shipping" (MLIT 2016) and the joint research project "JoRes" (JoRes 2019) have been launched. Flow field measurements by PIV will be planned in these projects.

Although various measurements of flow velocity at full scale have been carried out in this way, the number is still not enough to prove the reliability of the CFD calculation which is expected to clarify the scale effect. The necessity of the full-scale measurement and accumulation of the validation data are industrial consensus. Thus, we should continue to gather as much data as possible.

The largest obstacle against the measurements of flow field at full scale is their complexity with heavy prices in the measurement system. To break through this situation, we tried to apply a Multi-Layered Doppler Sonar (MLDS) which is an acoustic Doppler sonar capable of measuring relative water velocity at multiple arbitrary depths along an ultra-sonic beam. It is less expensive and easier to install and handle compared with other methods such as LDV or PIV. The MLDS was developed by Furuno Electric Co. Ltd, (FURUNO) and MTI Co. Ltd, (MTI). Sudo et al (2017) measured a depth distribution of flow velocity under the bow bottom of a pure car carrier by using MLDS and confirmed its capability. We extended this application of MLDS to more complicated flow field at the stern in this study.

In this paper, we introduce the features of MLDS and the measurement results of flow velocity for a 14,000 TEU container ship in the joint research project of FURUNO, MTI, Japan Marine United Corporation (JMU) and

Nippon Yusen Kaisha (NYK) (Inukai et al 2018). It also includes a comparison of cavitation pattern observed onboard and in model tests. This research project is still ongoing and we plan to install multiple MLDSs on the sister ship in this spring for more comprehensive investigation. This paper is an intermediate report to summarize the current status of this project

2 MLDS

2.1 Principal

As illustrated in Figure 1 (Ishii et al 1986), a transducer equipped at a ship bottom transmits an ultrasonic beam and receives the reflection back from particles in the water. The frequency in the ultrasonic beam changes proportional to a relative water velocity in the beam direction. It is a so-called Doppler shift. The water velocity can be calculated by measuring the Doppler shift, f_d.

$$f = f_0 \frac{C+V}{C-V} = f_0 \frac{C^2+2CV+V^2}{C^2-V^2} \tag{1}$$

$$f_d = f - f_0 \cong \frac{2Vf_0}{C} \tag{2}$$

$$V \cong \frac{Cf_d}{2f_0} \tag{3}$$

Where f_0 = transmitted frequency [Hz], f = received frequency [Hz], f_d = Doppler shift frequency [Hz], C = Acoustic wave velocity [m/s] and V = relative water velocity in the beam direction.

The elapsed time from the transmission to the reception of the ultrasonic beam is simply proportional to the distance between the transducer and the particles. Accordingly, the velocity at the depth of interest can be extracted by setting appropriate time interval between the transmission and the reception.

In the ordinary measurement of a log speed by using Doppler Sonar, the ship speed in three components is derived by combining the velocities in directions of three ultrasonic beams transmitted at the same time. Although this principle is applicable under an assumption that the velocities of the particles from all reflected beams are same, it is not the case for the flow field at the stern.

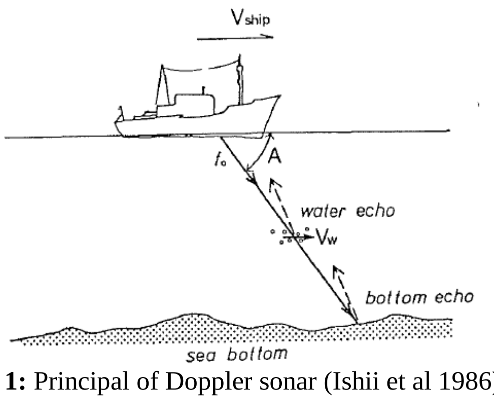

Figure 1: Principal of Doppler sonar (Ishii et al 1986)

Thus, it is noted that the measurement at the stern by MLDS is limited to the velocity of only one component in the direction of the ultrasonic beam. In order to obtain the three velocity components, more than three MLDSs are necessary.

2.2 Configuration of MLDS

We used the latest Doppler Sonar, Model: DS-60 (FURUNO 2019) developed by FURUNO in 2010, which is widely used as a speed logger. Only data processing algorithms are modified in MLDS so that velocities at arbitrary depths can be measured. The nominal measurement accuracy in water tracking mode is ± 1.0% or ± 0.1knots whichever is greater. The biggest advantage of MLDS is that it is easier to install and less expensive compared with other measurement systems such as LDV or PIV because it uses the same hardware as the commercially available DS-60.

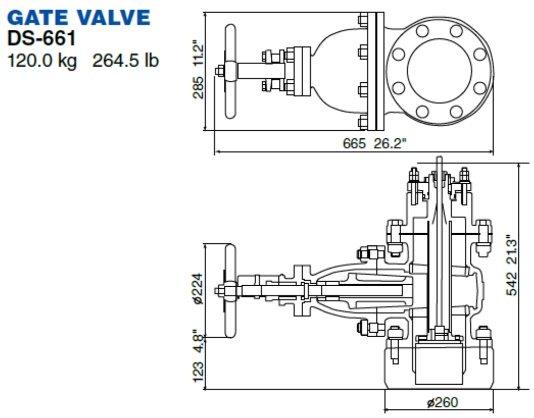

Figure 2: Dimension of gate valve "DS-661"(FURUNO 2019)

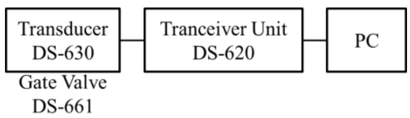

Figure 3: Configuration of system for MLDS equipped on 14,000TEU container ship

Figure 4: MLDS equipped on 14,000TEU container ship (Left: the gate valve for the transducer of the MLDS at the bottom, Right: the transceiver of the MLDS and PC for analysis in the steering gear room)

The diameter of the transducer is compact as 125mm and the gate valve is also designed to be minimal as shown in Figure 2. Thus, it can be mounted anywhere as long as there is a void space. Furthermore, it is highly resistant to the environmental conditions (e.g. high humidity). The configuration of the measurement system is very simple as shown in Figure 3. Figure 4 shows the MLDS installed on the subjected vessel in this study. The transducer was attached to the bottom and measured data was directory transferred to the PC via the transceiver in the steering gear room.

2.3 Features of MLDS

In order to measure the Doppler shift accurately, DS-60 transmits wideband ultrasonic beams with multiple spectral peaks (=N) as shown in Figure 5 (Kawanami 2011). A pulse signal with central frequency of 320 kHz is transmitted at the designated interval. By measuring the Doppler shifts of N^{th} spectral peaks simultaneously, the accuracy is conceptually $\sqrt{N}$ times higher than using an ultrasonic beam with one spectral peak. Three ultrasonic beams are transmitted at the same time. The beam direction can be changed by 180 degrees so that we can measure the flow velocity in six directions at every 60 degrees as shown in Figure 6.

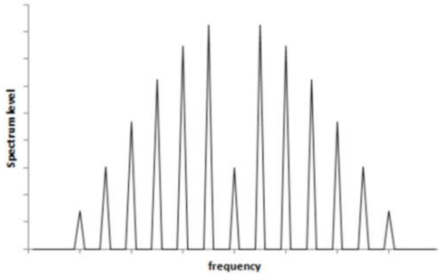

Figure 5: Example of spectra using wideband signal (Kawanami 2011)

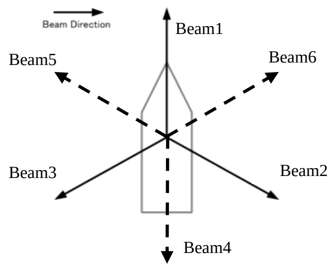

Figure 6: Example of ultrasonic beam direction of Doppler sonar

2.4 Measuring area of MLDS

The measuring area by MLDS is different from that by LDV or PIV. All past measurements by LDV or PIV aimed to grasp the axial flow velocity at constant x position just in front of a propeller. They were mainly intended to know the wake distribution at the propeller plane which is the basis of the propeller design. Further, it should be noted that the installing multiple devices at various locations were costly and the installation space were limited for full scale vessel. Eventually, measurement by LDV or PIV could be done in detail but limited to a narrow area.

On the other hand, the measuring area by MLDS locates a little bit forward of the propeller to avoid the reflection of ultrasonic beams on the propeller blades. By taking the advantage as mentioned in the section 2.2, it is possible to measure a wider flow field by installing multiple MLDSs. Though it is necessary to select the proper measuring system according to the research purpose, MLDS can be an useful tool to investigate flow field in wider range, such as growth of the boundary layer at the stern part of vessel.

3 MEASUREMENT

3.1 Subject of Study

A subjected ship was a 14,000 TEU container ship built by JMU in 2017 and operated by NYK. Table 1 shows the principal particulars. The measurement was performed in 2017 on the way from the Suez Canal to Rotterdam. The water depth was deep enough not to affect the measurement. Table 2 shows wind velocities and significant wave height during the measurements. The weather was generally good during the measurements.

Table 1: Principal particulars of ship

Length overall	364m
Breadth	50.6m
Depth	29.5m
Summer load draft	15.8m

Table 2: Wind velocity and wave height during measurement

Date	Absolute wind velocity [m/s]	Significant wave height [m]
25 July, 2017	4.4	0.5
26 July, 2017	10.5	1.5
27 July, 2017	11.4	2.0
28 July, 2017	4.1	0.8
29 July, 2017	5.9	1.0

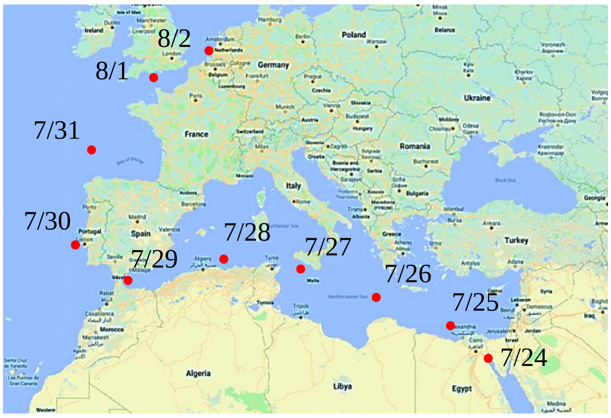

Figure 7: Measurement location and date

3.2 Flow Field Measurement

Figure 8 shows the measuring area by the MLDS. The velocities on the lines of the hexagonal pyramid within about 6m from the transducer were measured. Figure 9 shows the velocity distribution in the ultrasonic beams direction with respect to the distance from the transducer to measuring points. The velocity is normalized by the ship log-speed, V_s, measured by a DS-60 equipped at the bow. Each mark represents a mean velocity of all day's measurement except 29th when the measured velocity was accounted for outlier as described later. The numbering of the ultrasonic beams in the figure corresponds to that in Figure 6. The estimated velocity by CFD calculation is also shown by the solid lines in the figure. The calculation was done using the CFD code "SURF" (Hino 1997), which is an incompressible Reynolds averaged Navier Stokes solver, developed by the National Maritime Research Institute, Japan. In this calculation, free surface was taken into account and the trim set to be free. The infinite-bladed propeller model, in which inhomogeneous body forces are distributed according to the local flow, and k-ω SST as a turbulence model were applied. The y^+ value is set to be about 1.

We can see that the CFD calculation agrees well with the measurements in all directions of six ultrasonic beams. The existence of the boundary layer can be clearly seen since the velocities decrease as the distance from the transducer gets shorter.

In the beginning of the project, we were concerned about the influence of propeller noise and rich air near the water surface on measured data quality. Unlike our concerns, we confirmed that MLDS worked well except that the flow velocity about 6m away from the transducer was not measured due to the reflection of the ultrasonic beams on the propeller blade and hull surface. Although more insights to both results of measurement and CFD calculation are necessary, the results encouraged us very much.

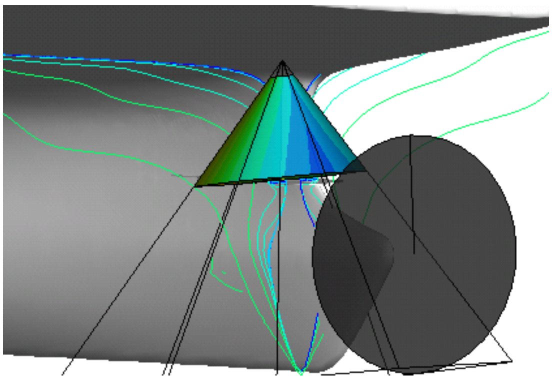

Figure 8: measuring area by MLDS

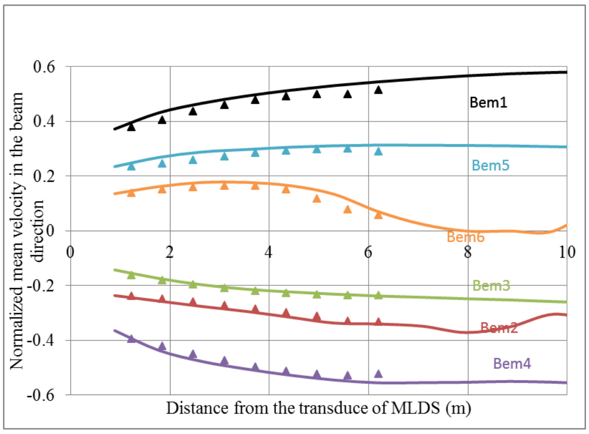

Figure 9: Comparison of normalized mean velocity in the beam direction between CFD (lines) and Measurement (marks)

3.3 Measurement Accuracy

To maintain the data quality, only data above the threshold of signal-noise (SN) ratio were extracted. The measurements were done for about 10 minutes at a constant ship speed when no maneuvering was taking place. The interval of the transmission of the beams was selected once per second. Consequently, about 500 data samples were obtained in one measurement for a velocity near the transducer while the number of the effective data samples decreased half in the deeper area due to the deterioration of the SN ratio. Figure 10 shows the velocity, the standard deviation and the uncertainty by type A evaluation (JCGM 2008) in one measurement on each day. Although the velocity in the direction of the beam 1 measured on July 29 was obviously detached, the standard deviation and the uncertainty on the other days show low values within 4% V_s and 0.2% V_s respectively. The reason of the inconsistency of the 29th with the other days was not clear. It might be due to the influences of the current or the distribution of plankton and air in the water. To clarify the condition under which abnormality occurs is one of the future tasks.

Figure 11 shows the standard deviation and the uncertainty of a daily measured velocity against the averaged value from 25th to 28th. Good reproducibility can be seen. The standard deviation and the uncertainty by type A evaluation were very low values within 0.6% V_s and 0.3% V_s respectively in all beams within the area of 4m from the transducer. The maximum standard deviation and the uncertainty were about 3% V_s and 1% V_s respectively in the beam 1 at the deepest point. We can say that the measuring accuracy of MLDS was good at least within the measurable area.

The positioning accuracy, i.e. the accuracy in locations of the measuring points, is difficult to quantify. The inaccuracy of the transmitted direction of the ultrasonic beam is attributed to the precision in the installation of the transducer and the influence of water temperature and salinity concentrations. As the water temperature changes by ±5%, the sonic speed changes by ±1% and then the direction of the ultrasonic beam changes by ±1%, which leads to the difference of the velocity by 0.5% V_s in the original and new ultrasonic directions. Although it is expected that the influence on the velocity by the positioning inaccuracy is not so large, it depends on hull form and the location of MLDS. Thus, we should consider how to quantify the positioning inaccuracy for more reliable comparison with the calculation.

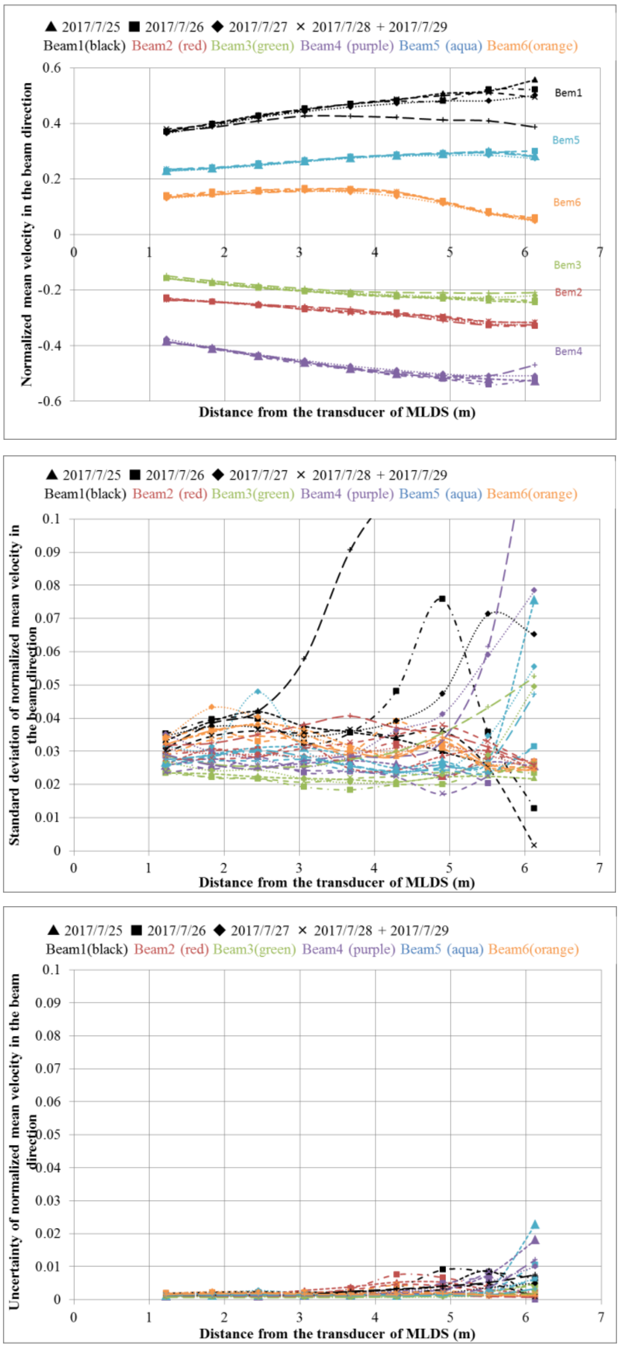

Figure 10: Measured normalized velocity in the beam direction (top), standard deviation (middle) and uncertainty by type A evaluation (bottom) on each day

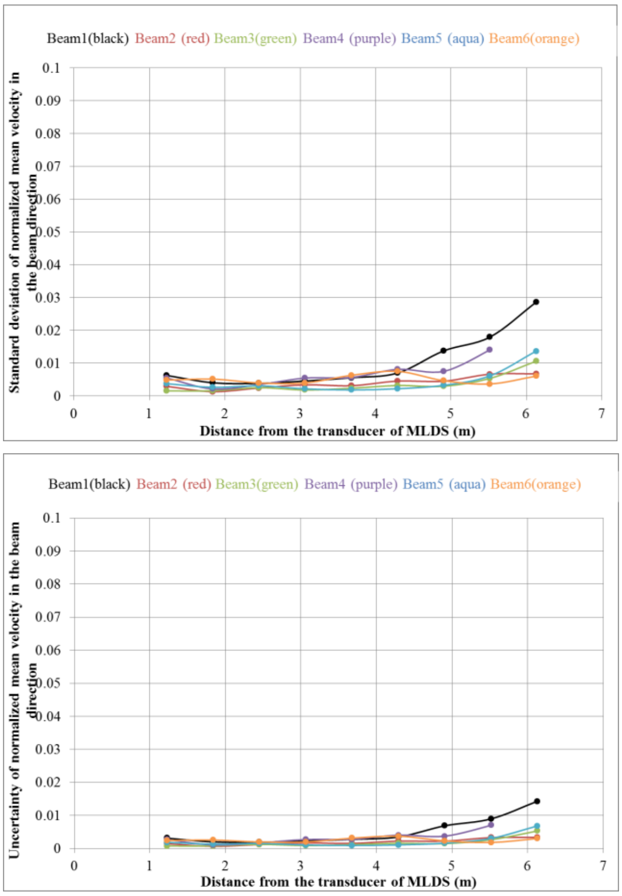

Figure 11: Standard deviation (top) and uncertainty by type A evluation (bottom) of measurements of normalized velocity in the beam direction from 2018/7/25 to 7/28

3.4 Tasks and Challenges

Following the abovementioned experience, we plan to install three MLDSs on the sister ship and measure the flow field in a wider area than the present study. The tasks and challenges to be tackled toward the next measurement are summarized as follows,

- The measuring area is limited within about 6m from the transducer. There are two reasons. One is that if one of three beams hit the propeller or the hull, the velocities in the directions of other two beams are affected by it. Another is that the SN ratio gets worse in the deeper area. In the next measurements, we will limit the number of the ultrasonic beam transmitted simultaneously from three to one in order to use the single beam which doesn't hit on obstacles. The SN ratio is also expected to improve because the signal level increases by preventing the sound source from the dispersion of multiple ultrasonic beams. Consequently, we expect to enlarge the measuring area. MLDS has an advantage of measuring the velocity in a wide area. By utilizing this characteristic, we explore the new way to evaluate the CFD calculation.
- It is impossible to specify the velocity components, i.e. u, v, w, by single MLDS. We will install three MLDSs and create the cross point of three ultrasonic beams to know the three velocity components there.

- The reason of the inconsistency of the 29th with the other days is not clear. We will investigate the condition under which abnormality occurs by increasing the measuring samples.
- The positioning accuracy is unclear. We will investigate the way to quantify it.

4 CAVITATION

4.1 Wake distribution

It is well known that the wake distribution in the propeller plane influences much on the cavitation pattern. Since the full-scale CFD calculation agreed well with the measurement by MLDS, it is expected that the CFD calculation can estimate the wake distribution at the propeller plane as well. We conducted cavitation tests in the JMU cavitation tunnel of 2,600mm(L) ×600mm (H)× 600mm (W) by using the wake mesh screen reproducing the full scale nominal wake distribution estimated by the CFD calculation. By comparison purpose, we used a wake mesh reproducing the wake distribution extrapolated from the model scale wake by using Sasajima-Tanaka method (Sasajima et al 1966). Figure 12 shows a comparison of the circumferential axial velocity distribution at 0.9R between the CFD and the Sasajima-Tanaka method where apparent difference can be seen between two methods. In the CFD wake, the wake peak at the blade top position (0 degree) is smaller and the change in the circumferential direction is more moderate compared with the Sasajima-Tanaka wake.

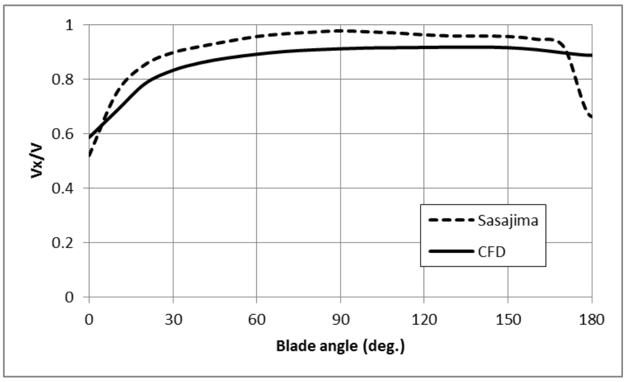

Figure 12: Circumferential axial velocity distribution at 0.9R estimated by CFD (solid line) and Sasajima-Tanaka method (dotted line)

4.2 Cavitation pattern

Figure 13 shows pictures of cavitation observed in the model tests and onboard. As imagined by the wake distribution, the cavitation volume in the CFD wake was less than that in the Sasajima-Tanaka wake. Consequently, the pressure fluctuation at the 1st and the 2nd blade frequency decreased in the CFD wake as shown in Figure 14. However, it is obscure which one is more similar to the onboard observation. Except that the tip vortex got stronger at full scale, the cavitation pattern in the both wakes generally agreed with the onboard observation. Since we will measure the pressure fluctuation in the next measurement, we will reevaluate the difference of the both wakes.

From the author's experience, cavitation in the CFD wake is likely to be more moderate than that in the Sasajima-Tanaka wake. If it is confirmed that the CFD calculation can simulate more accurately than the Sasajima-Tanaka method, it is possible to reduce the propeller blade area which leads to the improvement of the efficiency. Thus, from a view point of GHG reduction, it's important to clarify the accuracy of the CFD calculation.

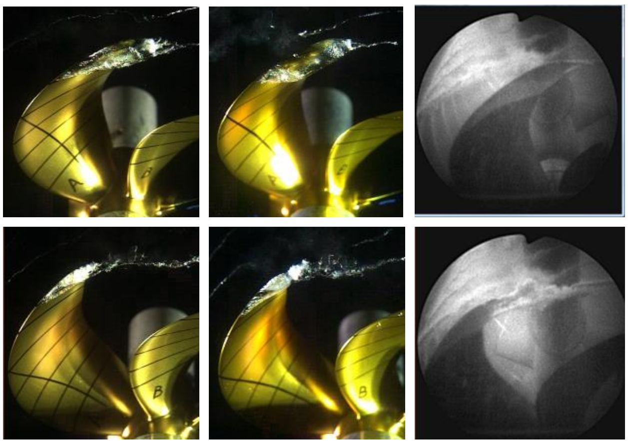

Figure 13: Cavitation pattern (left: model test in CFD wake, middle: model test in Sasajima wake, right: ship observation, upper: at the 35 degrees, lower: blade at the 55 degrees)

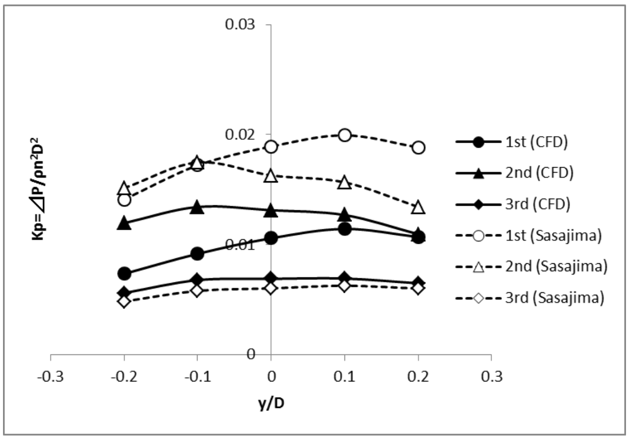

Figure 14: Pressure fluctuation in model tests (solid lines: model test in CFD wake, dotted lines: model test in Sasajima wake)

5 CONCLUSION AND FUTURE WORK

The world's first measurement system, MLDS was applied to the full-scale measurement of the flow velocity at the stern. We confirmed that MLDS could measure the flow velocity within an allowable standard deviation and uncertainty. Thus we consider MLDS could be an effective tool for the validation of the full-scale CFD calculation.

It is implied that the CFD calculation can predict the full-scale flow field reasonably from the following facts.

- The flow velocity distribution estimated by the CFD calculation agreed well with the measurements by MLDS.
- The cavitation pattern observed onboard was similar to that observed in the model test by using the wake mesh

screen reproducing the full scale nominal wake distribution estimated by the CFD calculation.

To evaluate the accuracy of the full-scale CFD calculation more precisely, we will expand the measuring items in the next comprehensive measurement for the sister vessel.

During this measurement, wider range of flow field measurement with multiple MLDSs, direct measurement of propeller thrust and pressure fluctuation, and cavitation observation will be executed. The measuring accuracy of MLDS and the possibility to enlarge its measuring area will be investigated further in the next measurement.

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