Investigation on the wake evolution of contra-rotating propeller using RANS computation and SPIV measurement

Kwang-Jun Paik¹, Seunghyun Hwang³, Jaekwon Jung², Taegu Lee²
Yeong-Yeon Lee³, Haeseong Ahn³ and Suak-Ho Van³

¹School of Mechanical Engineering, Ulsan College, Ulsan, Korea
²Samsung Ship Model Basin (SSMB), Samsung Heavy Industries, Daejeon, Korea
³Korea Research Institute of Ships and Ocean Engineering (KRISO), Daejeon, Korea

Received 18 July 2014; Revised 2 December 2014; Accepted 27 March 2015

ABSTRACT: The wake characteristics of Contra-Rotating Propeller (CRP) were investigated using numerical simulation and flow measurement. The numerical simulation was carried out with a commercial CFD code based on a Reynolds Averaged Navier-Stokes (RANS) equations solver, and the flow measurement was performed with Stereoscopic Particle Image Velocimetry (SPIV) system. The simulation results were validated through the comparison with the experiment results measured around the leading edge of rudder to investigate the effect of propeller operation under the conditions without propeller, with forward propeller alone, and with both forward and aft propellers. The evolution of CRP wake was analyzed through velocity and vorticity contours on three transverse planes and one longitudinal plane based on CFD results. The trajectories of propeller tip vortex core in the cases with and without aft propeller were also compared, and larger wake contraction with CRP was confirmed.

KEY WORDS: Contra-rotating propeller (CRP); Propeller wake; Stereoscopic particle image velocimetry (SPIV); Computational fluid dynamics (CFD); Reynolds averaged navier-stokes equation (RANS).

INTRODUCTION

The interests of ship owners, operators and shipyards in the development and installation of Energy Saving Devices (ESD) rapidly rise due to the increase of fuel oil expense and the regulation of International Maritime Organization to control the emission of CO₂ with Energy Efficiency Design Index. The well-known technologies as the ESD are Super Stream Duct (SSD), Semi-Duct System (SDS) and SAVER Fin (SAMSung Vibration and Energy Reduction Fin) as passive devices and air lubrication system and CRP as active devices. CRP, known as the most effective ESD, is a propulsion system having two propellers to recover the rotational energy loss of forward propeller with aft propeller rotating opposite direction.

The experimental measurement on the evolution of propeller wake using Pitot tube or Laser Doppler Velocimetry (LDV) has been moved to Particle Image Velocimetry (PIV) recently because PIV can measure wide area in relatively short time. Tukker et al. (2000) showed the possibility of two-dimensional PIV (2D-PIV) to measure the propeller wake in a towing tank.

Corresponding author: Kwang-Jun Paik, e-mail: kjpaik@uc.ac.kr
This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.
Felli et al. (2000) explained the wake evolution with velocity and vortex measured from the propeller operating behind a Series 60 ship model in a cavitation tunnel with free surface using SPIV. Paik et al. (2005) investigated the characteristics of tip vortex and trailing vortex from the propeller operating in open-water condition in a cavitation tunnel using 2D-PIV, which was compared with the results measured using SPIV to study the effect of perspective error on the in-plane velocity of the slip stream due to the out-of-plane velocity in their succeeding paper (Paik et al., 2007). Anschau and Mach (2007) measured the propeller wake on longitudinal and transverse planes around the propeller shaft in a towing tank and a cavitation tunnel using SPIV. Recently Hwang et al. (2012) studied the propeller wake field according to the variation of phase angle for the propeller operating behind KVLCC2 ship model using SPIV.

Flow measurement in model test is very important from the viewpoint of observation of real flow phenomena, but the measurement in large facilities such as a towing tank faces with time and cost issue. On the other hand, numerical simulation has advantage in cost and gives various information to understand whole flow field with single calculation. However, verification and validation for the numerical method are required through the comparison with experiment. Recent numerical simulations using CFD are performed by Di Felice et al. (2009) and Wang and Walters (2012). Di Felice et al. (2009) studied the wake evolution of a submarine propeller using OpenFOAM based on Large Eddy Simulation (LES). Wang and Walters (2012) investigated the effect of turbulence modeling using transition-sensitive model and k-ω SST model to study the characteristics of propeller wake.

Many researches (Tsakonas et al., 1983; Hoshino, 1994; Paik et al., 2000) using a numerical method based on potential theory for CRP were carried out continuously, but experimental measurement or numerical study based on a RANS solver to investigate the characteristics of CRP wake is very rare. Nevertheless, Paik et al. (2013) investigated the characteristics of wake as well as shaft forces according to the combination of number of blades for forward and aft propellers of CRP.

In this research, the wake characteristics of CRP were investigated with CFD simulation and SPIV measurement in three cases: without propeller, with forward propeller alone, and with both forward and aft propellers. The evolution of CRP wake was analyzed through velocity and vorticity contours on three transverse planes and a longitudinal plane from CFD. The trajectories of propeller tip vortex core in the cases with and without aft propeller were also compared showing larger wake contraction in CRP.

METHOD OF NUMERICAL SIMULATION

In this research, numerical simulation was performed using FLUENT Ver. 14, and numerical method applied in the simulation was summarized in Table 1. The numerical method was used for similar grid system and turbulence modeling in Kim et al. (2011), and good agreement with experiment in propeller open water, resistance and self-propulsion analysis for various ship types was confirmed. Also the same numerical method was applied and verified for the simulation of CRP in Paik et al. (2013).

<table>
<thead>
<tr>
<th>Governing equation</th>
<th>RANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence model</td>
<td>RSM</td>
</tr>
<tr>
<td>Pressure-velocity coupling</td>
<td>SIMPLEC</td>
</tr>
<tr>
<td>Pressure solver</td>
<td>Standard</td>
</tr>
<tr>
<td>Momentum solver</td>
<td>2nd order upwind</td>
</tr>
</tbody>
</table>

The main particulars of the object ship, a 70K Product Carrier, used in this study are summarized in Table 2. The scale ratio of the model ship is 32.7273. The number of blade is four for both propellers. The diameter of the aft propeller is 88.9% of the forward propeller diameter. The CRP was designed to maximize propulsion efficiency using backward rake for forward propeller and forward rake for aft propeller, which was proposed by Inukai (2011). The main particulars of the CRP are summarized in Table 3.
Table 2 Main particulars of 70K PC.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LBP (m)</td>
<td>219.0</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>32.2</td>
</tr>
<tr>
<td>Draught (m)</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Table 3 Main particulars of CRP.

<table>
<thead>
<tr>
<th></th>
<th>Forward propeller</th>
<th>Aft propeller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (m)</td>
<td>7.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Number of blades</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>P/D @ 0.7 r/R</td>
<td>0.739</td>
<td>0.882</td>
</tr>
<tr>
<td>C/D @ 0.7 r/R</td>
<td>0.210</td>
<td>0.204</td>
</tr>
<tr>
<td>Rotation direction</td>
<td>LH</td>
<td>RH</td>
</tr>
</tbody>
</table>

Fig. 1 Computational domain and boundary conditions.

Fig. 2 Grid structure of sliding blocks for forward and aft propellers.

A grid system including a hull form to simulate the CRP operating behind a ship is shown in Fig. 1. Sliding grids were applied to simulate the rotation of forward and aft propellers as shown in Fig. 2. Pyramid cells were used on the surface of the
propellers and the boundaries of the sliding block, and tetrahedral cells were filled inside of the block. On the other hand, structured grids were applied to the other domains except the sliding blocks. Multi-blocks for the wake region of CRP and a block of the gap between forward and aft propellers are shown in Fig. 3, which depicts the outline of grid system including boundary conditions and the interface between sliding and other blocks. To investigate the effect of forward and aft propellers on the wake, three cases as shown in Table 4 were simulated in this research. A rudder was not installed in all cases for the convenience of SPIV measurement. The total number of grids is 1.9M for Cases 1, 2.4M for Case 2 and 3.0M for Case 3. The number of grids is summarized in Table 5.

![Fig. 3 Multi-block structure for propeller and wake blocks.](image)

Table 4 Configuration of model ship for test cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Forward propeller</th>
<th>Aft propeller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Case 2</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Case 3</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Table 5 Number of grids for CFD.

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block I</td>
<td>49K</td>
<td>592K</td>
<td>592K</td>
</tr>
<tr>
<td>Block II</td>
<td>49K</td>
<td>49K</td>
<td>618K</td>
</tr>
<tr>
<td>Others</td>
<td>1,793K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,891K</td>
<td>2,434K</td>
<td>3,003K</td>
</tr>
</tbody>
</table>

The forward and aft propellers are installed with the phase angle difference of 45°. The notations for forward and aft propeller blades are described in Fig. 4. The phase angle of propeller blade ($\theta$) follows the rotational direction of forward propeller. Apparent advance coefficients ($J$) of forward and aft propellers are 0.821 and 0.923, respectively. Propellers were rotated with a constant time step, 0.0005578 sec, corresponding to the rotation angle of 1.5° to obtain 240 data during one revolution.
SETUP AND ANALYSIS OF EXPERIMENT

Flow measurement using SPIV was carried out in KRISO towing tank. The underwater SPIV probe used in this study is shown in Fig. 5. The focal lengths of the camera’s lens are 85 mm (front) and 105 mm (rear). The arrangement and the viewing angle of cameras in the probe can be set as shown in Fig. 6. The size of FOV defined as the overlap region between the front and rear cameras was 290 mm×215 mm. The FOV corresponds to the spatial resolution of about 3.5 mm for 48×48 interrogation windows with 50% overlap. Polystyrene powder was used as the seeding particles of which the mean diameter is 20 μm and density is 1.05 g/cm³. The particulars of the SPIV system are described in Hwang et al. (2012) in detail. Model ship and propellers were manufactured by SSMB. The flow measurement was also carried out in three cases described in Table 4. The model ship was towed with 1.349 m/s in the model test and fixed at the carriage to prevent the trim and sinkage during the test. The forward and aft propellers rotate to opposite direction each other with the same speed of 7.47 rps. The temperature of the water in the towing tank was constantly maintained as 12.5°C. The model ship was painted with matt black color to reduce the reflection of laser sheet from the ship surface as shown in Fig. 7. The propellers, ring and cap shown in Fig. 7 were painted with black for SPIV measurement.

Measured images were analyzed using a commercial code, La Vision DaVis 8. To improve the contrast of the measured image, local min-max filter (Adrian and Westerweel, 2011) of 4×4 pixels was applied. Adaptive PIV calculation method (Wieneke and Pfeiffer, 2010) was applied to analyze the velocity field. The final interrogation window size was 48×48 pixels. Two dimensional velocity fields analyzed from each camera were transferred to three dimensional velocity fields using the method proposed by Wieneke (2005). Five hundred instantaneous velocity fields were used for the statistical analysis of flow field.
Fig. 6 Schematic view of underwater stereoscopic PIV probe.

The flow measurements using SPIV were carried out at Position C, which is located at 66.1 mm from after perpendicular (A.P.), while CFD analysis was performed at Position A and B located at 103.0 mm and 146.5 mm apart from A.P. as well as Position C. The configuration of the analyzed positions is depicted in Fig. 8.

Fig. 7 Stern of model ship with CRP.

Fig. 8 Wake observation positions (Position A, B and C).
RESULT AND DISCUSSION

Time-averaged velocity contours and vectors measured using SPIV at Position C of Cases 1, 2 and 3 are compared with CFD results in Fig. 9. Dotted circle in the figure denotes the propeller disk of forward propeller, and the view is looking upstream. To investigate in detail the deviation between SPIV and CFD, the circumferential variations of axial, radial and tangential velocities at 0.3 r/R, 0.5 r/R, 0.7 r/R and 0.9 r/R are compared in Fig. 10. The axial, radial and tangential velocities are normalized by the towing speed of model ship. The r/R stands for the normalized radial position based on the radius of forward propeller. The vorticity contours at Position C are also compared in Fig. 11. The SPIV and CFD shows very similar tendency in velocity and vorticity distributions for all three cases.

![Time-averaged velocity contours and vectors at Position C from SPIV (top) and CFD (bottom).](image)

(a) Case 1. (b) Case 2. (c) Case 3.

In Case 1, without propeller, the velocity and vector distributions in Fig. 9 show generally good agreement between SPIV and CFD except for the region of slow axial velocity below the center of propeller disk. The difference in the region below the center of propeller disk is clearly observed in 0.7 r/R of Fig. 10. As presented in Fig. 11, two pairs of bilge vortex generated from the bilge of hull are observed in port and starboard sides (port/starboard bilge vortex, PBV/SBV). PBV and SBV in the lower part are developed along to stern skeg, and their strength from the numerical simulation is somewhat stronger than the experimental measurement.

In Case 2, with forward propeller alone, the axial velocity of port side is more accelerated because of the propeller rotation to counterclockwise direction as shown in Fig. 9. The amplitude of rotational velocity is increased in starboard side and decreased in port side due to the propeller rotational direction. Consequently, the merging region of rotational flow moves to 11 o'clock position. These phenomena can be explained with the tangential velocity distribution shown in Fig. 10. The axial velocities on port side at 0.5 r/R and 0.7 r/R are higher than those on starboard side due to the propeller rotation. Since the direction of propeller rotation is same as the direction of phase angle in Fig. 4, the tangential velocities in 0.3 r/R and 0.5 r/R are
distinctly increased. The merging region mentioned from Fig. 9 can be indirectly interpreted with the zero position of tangential velocity located around 20° in 0.7 r/R and 0.9 r/R. But there are some discrepancies between SPIV and CFD in the tangential velocities of 0.7 r/R and 0.9 r/R around the phase angles of 30° and 330°, and the zero position angles of the tangential velocity are larger in CFD than in SPIV. The axial velocities in 0.3 r/R ~ 0.7 r/R are accelerated due to the propeller operation; especially the increment of axial velocity in inner radii is about 150%, whereas there is no noticeable change in 0.9 r/R because the radius of propeller wake is smaller than 0.9 r/R at Position C. A strong negative vortex (WSV, Wake Shear Vortex), generated by crossing flow of the rotational components in hull wake and propeller swirl, is observed on the top of propeller disk in Fig. 11. However, the position of WSV appears around 11 o'clock position in the simulation result, while that is close to the center in the experiment result. And PBV and SBV observed in Case 1 are still remained in the propeller wake of Case 2. The negative vorticity generated by the tip vortex of forward propeller is observed at about 84% of forward propeller radius except for the top region of propeller disk. The strong positive vorticity at the center of propeller disk is the root vortex of propeller blade, which is biased to starboard side.

Fig. 10 Circumferential variation of time-averaged velocity distribution at Position C from SPIV (solid line) and CFD (dashed line).
In Case 3 of Fig. 9, with both forward and aft propellers, concentric-circular velocity distribution is observed, while asymmetric axial velocity distribution is almost disappeared. The asymmetric rotational velocity vector is also disappeared, and the merging region of PBV and SBV as well as WSV move to starboard side. It can be more clearly understood with the circumferential variation of axial and tangential velocities in Fig. 10. Even though the average of the axial velocities in 0.3 \( r/R \) and 0.5 \( r/R \) is increased about 20% as compared with Case 2, the variation of the axial velocities is obviously reduced. The tangential velocities in 0.5 \( r/R \) ~ 0.9 \( r/R \) are almost symmetry with opposite sign at 180° and the zero position of the tangential velocities is close to 0° and 180°, which means no rotational flow is induced by the propeller operation. The principle for the energy saving of CRP, recovery of the rotational loss of forward propeller by aft propeller, can be explained indirectly with these phenomena. The tip vortex of aft propeller is positive in axial vorticity as shown in Fig. 11. And its radial position is about 88% of aft propeller radius and about 78% of forward propeller radius. The root vortex of aft propeller with negative vorticity is mixed with the root vortex of forward propeller with positive vorticity, and the vortices are located at the center of propeller disk.

Instantaneous velocity and vorticity distributions at Position A of Case 2 and Positions A and B of Case 3 simulated using CFD are compared in Fig. 12 and Fig. 13 for the blade phase angles of 0°, 30° and 60° based on the key blade of forward propeller (F_B1). The axial velocity of Case 2 shows similar pattern with the time-averaged axial velocity illustrated in Fig. 9, and the rotational velocity presents no significant difference according to the change of blade phase angle. The characteristics of the wake according to the phase angle of propeller blade can be explained more clearly with axial vorticity distribution in Fig. 13. In Case 2, tip vortices (F_B1_TV, F_B4_TV) of forward propeller are shown as negative in the upper part of propeller disk at the phase angle of 0°. A propeller blade and its tip vortex show the phase angle difference of 45° due to the effect of propeller pitch. The tip vortex (F_B4_TV) rotates with shed vortex (F_B4_SV) and root vortex (F_B4_RV). On the other hand, the positions of WSV on the top of propeller disk as well as PBV and SBV are not changed. Position A of Case 3 shows similar vorticity distribution with Position A of Case 2, which means there is almost no influence on the wake field of
forward propeller due to the rotation of aft propeller. At Position B of Case 3, the tip vortices of forward propeller are almost disappeared, whereas the tip vortices (A_B1_TV, A_B4_TV) of aft propeller are observed. The strength of tip vortex (A_B1_TV) increases due to the interaction with WSV when it passes on the top of propeller disk as shown in the phase angle of 30°. Then the size of tip vortex (A_B1_TV) grows bigger until 4 o'clock position. The shape of shed vortex (A_B1_SV, A_B4_SV) connecting between root vortex and tip vortex is more noticeable in aft propeller than in forward propeller. The negative root vortex (A_B1_RV) generated from aft propeller is mixed with the positive root vortex (F_B4_RV) generated from forward propeller.

![Instantaneous velocity contours for Case 2 and Case 3 from CFD](top: θ = 0°, middle: θ = 30°, bottom: θ = 60°).

Fig. 12 Instantaneous velocity contours for Case 2 and Case 3 from CFD.
Fig. 13 Instantaneous axial vorticity contours for Case 2 and Case 3 from CFD
(top: $\theta = 0^\circ$, middle: $\theta = 30^\circ$, bottom: $\theta = 60^\circ$).

Axial vorticity distributions on longitudinal plane on the propeller shaft are shown in Fig. 14 for the phase angles of $0^\circ$, $30^\circ$, and $60^\circ$ to compare the evolution of propeller wake of Cases 2 and 3. It can be observed from Case 2 that the propeller tip and shed vortices are developed at regular intervals according to propeller rotation. The shape of the shed vortex is straight when it is detached from propeller blade, as shown in the blade phase angle of $30^\circ$. However, the shape of the shed vortex gradually inclines and contracts due to the velocity difference between shed vortex region and tip vortex region shown in Fig. 12 and the difference of vortex strength between shed vortex and tip vortex shown in Fig. 13, and then it finally disappears due to the viscous dissipation. In the lower part of propeller disk the shape of the shed vortex is distorted and the contraction of propeller wake increases significantly because the axial velocity of propeller wake in the lower part is faster than in the upper part. The evolution of tip vortex in CRP is more complicated due to the interaction of forward and aft propellers. As the tip vortex of
forward propeller (F_B4_TV) encounters the tip vortex of aft propeller (A_B1_TV) rotating to opposite direction, it moves inside and makes a pair with the tip vortex of aft propeller located outer radius while the strength of vortex becomes weaker. This interaction of the tip vortices of forward and aft propellers makes WSV stronger, resulting in increase of the wake contraction in the upper part.

Fig. 14 Instantaneous axial vorticity contours for Case 2 (left) and Case 3 (right) from CFD (top: $\theta = 0^\circ$, middle: $\theta = 30^\circ$, bottom: $\theta = 60^\circ$).

Transverse vorticity distributions on the longitudinal plane on the propeller shaft for Cases 2 and 3 are compared in Fig. 15 for the phase angle of $30^\circ$. As discussed in Fig. 14, the tip vortex in Case 2 has constant intervals. In contrast, in Case 3 the tip vortex of forward propeller disappears and the contraction of tip vortex of aft propeller increases, when the tip vortex (F_B4_TV) of forward propeller encounters with the tip vortex of aft propeller. The trajectories of the tip vortex in the upper
and lower parts show a considerable difference in Case 2. Because the flow speed of propeller wake in the lower part is relatively faster than that in the upper part, the shed vortex moves faster and the tip vortex is shrunk more. The contraction of tip vortex in the upper part is small due to the weak WSV rotating to same direction with the propeller rotation, and then the tip vortex expands where the strength of WSV is weaker. In Case 3, since the rotational direction of tip vortex in the upper part is opposite to that of WSV, the WSV is stronger, resulting in larger contraction of tip vortex than Case 2. The contraction of tip vortex in the lower part increases due to the interaction between the tip vortices of forward and aft propellers as compared with Case 2. As a result, the trajectory of tip vortex in Case 3 is almost symmetry in the upper and lower part regardless of hull wake, and the tip vortex is contracted to about 70% of forward propeller radius at the position apart as much as forward propeller diameter.

The trajectories of tip vortex core achieved from CFD and SPIV are compared for Cases 2 and 3 in Fig. 16. The horizontal and vertical axes of the plot denote the axial distance from the propeller reference line of forward propeller and the radial distance from the propeller shaft center line, which are normalized with the radius of forward propeller. The positions of tip vortex core for CFD results were obtained from the transverse vorticity distribution shown in Fig. 15. However, the positions of tip vortex core for SPIV results were estimated from the peak position of axial velocity gradient shown in Fig. 9 because transverse vorticity were not measured in the experiment. The results of SPIV show good agreement with CFD in the tendency.
CONCLUSIONS

The characteristics of wake evolution for CRP were investigated using numerical simulation and flow measurement for three cases: without propeller, with forward propeller alone, and with both forward and aft propellers. The numerical simulation was carried out with CFD based on a RANS solver, and the flow measurement was performed with SPIV system. The validity of the numerical simulation was evaluated through the comparison with the result of SPIV. The loading of forward propeller was higher in port side and the aft propeller recovered the rotational energy loss of forward propeller, resulting in the balance of the propeller loads in port and starboard sides. The vortex generated from the bilge of hull was still observed at the wake of CRP.

Flow structures on longitudinal and transverse planes were investigated at various phase angle of propeller using CFD. While the tip vortex generated from forward propeller was almost disappeared, the tip vortex and shed vortex generated from aft propeller were observed clearly. Through the axial vorticity distribution on the longitudinal plane along the propeller shaft, it was noticed that the tip vortex of aft propeller became stronger and its contraction increased due to the interaction between the tip vortices of forward and aft propellers. The trajectory of tip vortex of CRP was almost symmetry in the upper and lower parts of propeller center even in behind-hull condition.

From these results, it is concluded that numerical analysis based on potential theory for CRP might be necessary to modify the special wake alignment to improve the accuracy of performance prediction because the wake evolution of CRP is different from that of conventional propeller.

ACKNOWLEDGEMENTS

This work was partially carried out in the research grant, Development of New Propulsion System for Fuel Saving of Ships (No. 2011-10040081), funded by the Korean Ministry of Trade, Industry and Economy.

REFERENCES


