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Experimental study on hydrodynamic forces acting on ship hull and rudder behind the propeller in regular waves

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ABSTRACT

In recent years, intensive efforts are being concerned toward the predicting ship maneuvering performance in waves. Since ship maneuverability highly influenced by the wave on the water surface, enhancement of ship maneuverability at the ship design state is an important method. In this paper, the model test is performed for investigating the impact of wavelength and wave direction on the hydrodynamic force of a ship hull and rudder. The number of propeller revolution is determined for the model speed corresponding to full-scale service speed in calm water is kept constant during the test. The hydrodynamic force of rudder and ship hull have measured in calm water and in regular waves. In order to confirm the experimental result, the added resistance in wave in head sea is compared with results from other institutes. The added resistance in wave in head sea shows fair agreement with experimental results of different institutes. The changing of hydrodynamic forces of a ship and rudder in various wavelengths is discussed in various wave directions and rudder angle. Hydrodynamic forces acting on the ship hull and rudder behind propeller are compared with one without propeller.

1 INTRODUCTION

In the past, the prediction of ship maneuvering performance usually estimated in calm water was not associated with seakeeping performance. Accuracy estimating of the changing hydrodynamic force of a ship and rudder in waves is essential to predict ship maneuvering performance in wave such as the course-keeping ability and the turning performance. Many studies have been performed to predict ship maneuvering in waves. Kring et al. (2001) developed the numerical method for computing maneuvering forces in waves. The numerical result was estimated based on a three-dimensional potential flow method with corrections from viscous flow solvers. Fang et al, (2005) proposed a six degree of freedom mathematical model unified seakeeping and maneuvering to simulate the ship turning circle in regular waves. They used strip theory to estimate hydrodynamic force acting on the ship hull in regular waves. On the other hand, Yasukawa (2006) proposed a New Strip Method for estimating the hydrodynamic force in wave. He divided the basic motion equation into 2 groups such as high frequency wave induced motion problem and low frequency maneuvering problem. Yasukawa (2006) performed the free-running model tests in regular waves using SR108 container ship. The experiment was only carried out in various wavelengths in head sea and beam sea. Chou and Fu (2007) introduced the method to simplify the wave modeling to obtaining the acceleration and angular velocity of a ship. Skejic and Faltinsen (2007, 2008, 2013) developed unified theory for seakeeping and maneuvering. The time domain of the maneuvering simulation was divided into two time scales such as slowly and rapidly varying. Yasukawa (2008) simulated the zig-zag maneuvers and stopping maneuvers in regular waves. The simulation result was compared to the free-running model test of SR108 container ship. Seo et al. (2011) applied linear and nonlinear ship motion analysis for analysing ship characteristics in waves. They discussed about the maneuvering performance of S-175 container ship with respect to wave slope. Seo and Kim (2011) used the time-domain nonlinear ship motion program to investigate maneuvering performance in waves. In their study, the wave drift force is calculated using direct pressure integration method. Seo and Kim (2011) used the time-domain nonlinear ship motion program to investigate maneuvering performance in waves. In their study, the direction pressure integration method was proposed for estimating the wave drift force. Veedu and Krishnankutty (2016) performed the maneuvering simulation of a container ship in regular wave based on unified state space model. The simulation was carried out in head sea in various wave heights and wavelengths and wave significantly affects on ship maneuvering characteristics. Zhang et al. (2017) proposed the method for predicting ship maneuvering in waves. Sprenger et al. (2017) studied on the added resistance and drift force of KVLCC2 and DTC by performing model tests for establishment validation database in different environmental conditions and water depths. Wang et al. (2017) performed the numerical simulation of standard zig-zag maneuver in both calm water and regular head waves.

However, the accurate estimation of the force and moment acting on the rudder in waves is necessary because rudder significantly affects the ship's course-keeping and turning abilities. In the author's former works, the hydrodynamic forces acting on the rudder without propeller was investigated (Nguyen, et al., 2018). On the other hand, the rudder, propeller and hull interactions are an important key. It is essential to investigate the hydrodynamic force acting on the ship and rudder behind the propeller. In this paper, hydrodynamic forces acting on the ship and rudder behind the propeller have investigated in various wavelengths and various wave directions. The experiment is performed for well-known KRISO container ship (KCS). A model test with and without the operation of the propeller has conducted at Changwon National University's towing tank (CWNU). The hydrodynamic forces acting on the ship and rudder in the various rudder angle are measured in calm water and regular waves. The comparison result of hydrodynamic forces of a ship and rudder with and without the operation of the propeller is discussed.

2 MATHEMATICAL MODEL

2.1 Coordinate system

Mathematical model for maneuvering motion in 3DOF can be described by following equation of motion. Two right-handed coordinate systems are adopted, namely, an earth-fixed coordinate system Ox_0y_0 and a body-fixed coordinated system Oxy . In addition, wave direction is defined as shown in Figure 1.

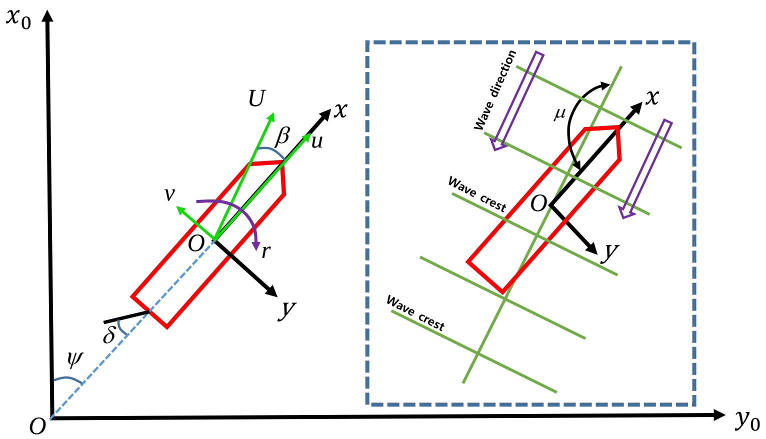


Figure 1: Coordinate systems and definition of wave direction

2.2 Equation of motion

In order to predict ship maneuverability, two kinds of hydrodynamic models are mostly used such as Abkowitz model and MMG (Maneuvering Modeling Group). In this experiment, MMG model for maneuvering motion in 3DOF is used and it can be described by Eq. (1). m is the ship's mass and x_G is the longitudinal position of ship's gravity center. u and v are the component of the velocity in the x-axis and y-axis direction, respectively. $\dot{r}$ is the angular acceleration and I_{zz} is the moment of inertia about z-axis.

X, Y are the hydrodynamic forces and N is the moment around z-axis. The subscripts H, R, and P denote the hydrodynamic forces due to hull, rudder and propeller in calm water, respectively. The subscripts W denotes the hydrodynamic force due to waves. The hydrodynamic forces due to hull, rudder and propeller in calm water can be obtained from the model test from other institutes. The hydrodynamic forces due to wave are obtained from the model test in this study.

$$\begin{cases} m(\dot{u} - rv - x_G r^2) = X_H + X_R + X_P + X_W \\ m(\dot{v} + ur + x_G \dot{r}) = Y_H + Y_R + Y_W \\ I_{zz}\dot{r} + m x_G(\dot{v} + ur) = N_H + N_R + N_W \end{cases} \tag{1}$$

3 EXPERIMENT

3.1 Test condition

The experiment was conducted in the square wave tank in CWNU, Korea. The experiment was performed in calm water and regular waves for well-known KRISO container ship (KCS). The ship model used in this experiment with a scale factor of λ = 230. The principal particulars of the real and scaled model are listed in Table 1.

Table 1. Principal particular of KCS

Item	Symbol	Unit	Full	Model
Scale	-	-	1	230
Ship length	L	m	230	1.000
Breadth	B	m	32.2	0.140
Depth	D	m	19	0.083
Draft	d	m	10.8	0.047
Displacement	∇	m^3	52030	0.004
Froude number	Fn	-	0.26	0.26
Pitch radius of gyration	k_{yy}	-	0.25 L	0.25 L
Rudder area	A_R	m^2	54.45	1.03E-03
Mean chord length	$\overline{C}$	m	5.5	2.39E-02
Rudder height	b	m	9.9	4.30E-02

Table 2. Test condition

Item	Real ship	Model
Speed [m/s]	12.35	0.814
Wave direction [deg.]	180, 135, 90, 45, 0	
λ / L [-]	0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0	

The model is equipped with rudder and propeller for investigating the force and moment acting on the rudder and hull in regular waves. The model is free to heave and pitch at a service speed of 0.814 m/s, corresponding to Fn = 0.24. According to ITTC (2017), the wave condition of this experiment is chosen for a range of wavelengths from $0.4L_{PP}$ to $2.0L_{PP}$ are listed in Table 2.

3.2 Wave test

Since the quality of the wave will affect the result, it is essential to check the accuracy of the wave generated by the wave maker system. Time record of wave profile observed at three positions of finding the input stroke in the wave maker system. If the wave moves in the positive x direction, the wave profile can be expressed as a function of both x and t by Eq. (2). ω is wave frequency and k is wave number. ς_a and ε_ς are wave amplitude and phase angle, respectively. The measured time series of the wave for KCS model is shown in Figure 2. Results of measured wave heights and target wave heights are listed in Table 3. Differences between measured values and target values are less than 3.7%.

$$\zeta = \zeta_a \cos(kx - \omega t + \varepsilon_\zeta) \tag{2}$$

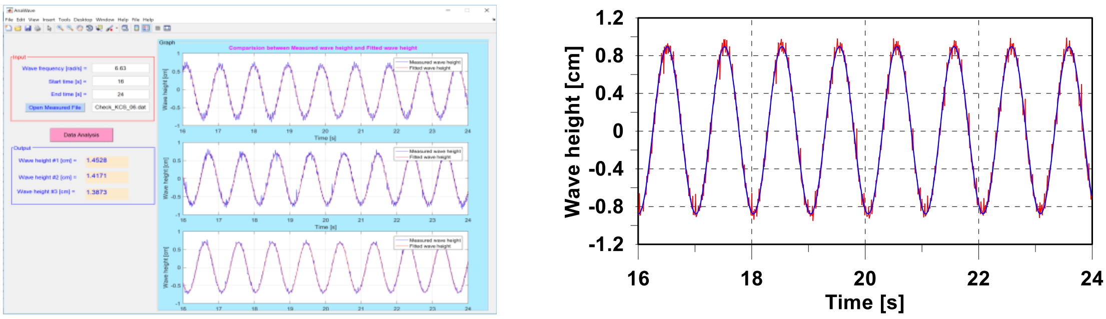


Figure 2: Time series from wave test at ω = 6.21 rad/s

Table 3. Accuracy of wave generated by wave maker system

Input Stroke [cm]	Wave period [s]	Measured wave height [cm]	Target wave height [cm]	Difference [%]
1.16	0.51	0.85	0.82	3.42
0.95	0.62	0.84	0.82	2.33
0.92	0.72	0.84	0.82	2.10
1.55	0.80	1.39	1.41	1.26
1.54	0.88	1.36	1.41	3.66
1.57	0.95	1.42	1.41	0.51
1.98	1.01	1.77	1.74	1.86
2.00	1.07	1.74	1.74	0.10
2.03	1.13	1.76	1.74	1.10

3.3 Experimental setup

Inertia test was performed to obtain the pitch radius of gyration listed in Table 4. The model was attached to the load cells in the sub-carriage of CWNU's towing tank. Figure 3 shows the detailed of this experiment as shown in Figure 3. The number of propeller revolution was determined for the model speed corresponding to full-scale service speed in calm water, which the propeller thrust T was balanced with the extrapolated full-scale resistance as shown in Figure 4. The propeller RPS was adjusted for self-propulsion for finding self-propulsion point of model speed and was kept constant during the test. The hydrodynamic forces acting on the rudder and ship were measured in calm water and regular waves.

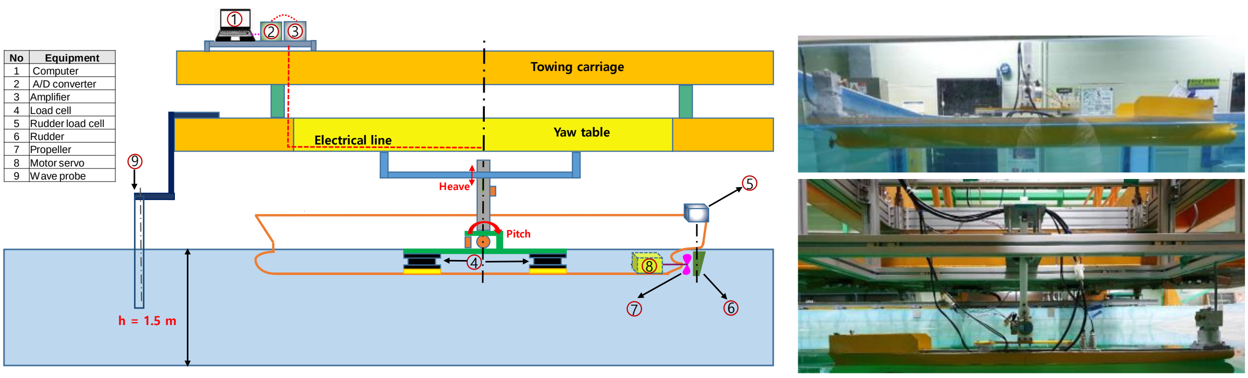


Figure 3: Diagram of experimental setup

Table 4. Wave conditions for KCS model

Item	Unit	Value
Measured I_{yy}	kgm^2	0.2640
Target I_{yy}	kgm^2	0.2668
Difference	%	1.03

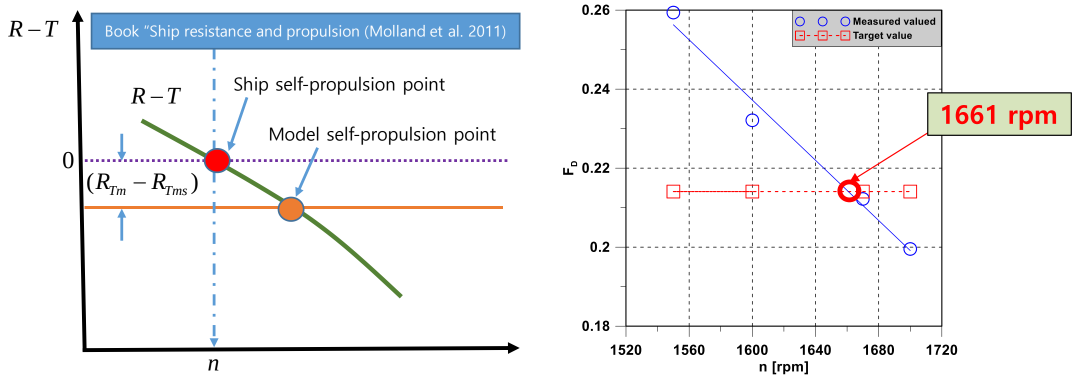


Figure 4: Finding rpm for a model in CWNU

3.4 Data analysis

For the test in calm water, the time traces are processed to obtain the average value of hydrodynamic forces acting on the ship and rudder. For the test in wave, time traces are processed by the least square method to obtain the 1st harmonic amplitude of hydrodynamic force acting on the ship and rudder in various wavelengths and in various waves direction by Eq. (3). When the ship moves with speed U and wave direction μ, hydrodynamic forces in waves can be expressed as a harmonic function by Eq. (3). The time traces of hydrodynamic forces in waves are processed to obtain, the mean value (zeroth order term) and the 1st harmonic amplitude of hydrodynamic forces in wave.

$$F = F_o + F_a(kx - \omega_e t + \varepsilon_{F\zeta}) = F_o + \mathrm{F}_{ac}\cos\omega_e t + \mathrm{F}_{as}\sin\omega_e t \tag{3}$$

where, $\omega_e = \omega - kU\cos\mu$, $F_{ac} = F_a\cos(kx + \varepsilon_{F\zeta})$, $F_{as} = F_a\sin(kx + \varepsilon_{F\zeta})$

The 1st harmonic amplitude of hydrodynamic forces due to the wave F_w can be obtained by Eq. (4). The 1st harmonic amplitude of non-dimension value of drag force and lift force of rudder can be estimated by Eq. (5). Furthermore, the 1st harmonic amplitude of hydrodynamic forces of KCS model in wave can be estimated by Eq. (6) based on Ueno's suggestion (2000).

$$F_w = \sqrt{F_{ac}^2 + F_{as}^2} \tag{4}$$

$$C_{Dw} = \frac{D_w}{0.5\rho A_R U^2},\ C_{Lw} = \frac{L_w}{0.5\rho A_R U^2} \tag{5}$$

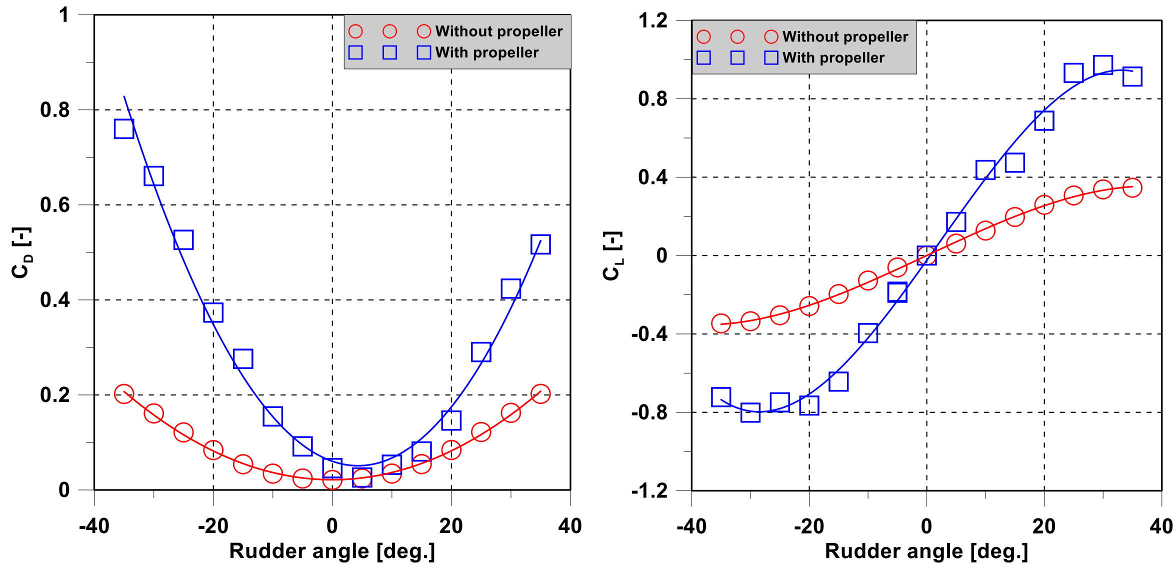
$$X'_w = \frac{X_w}{0.5\rho g L \zeta_a^2},\ Y'_w = \frac{Y_w}{0.5\rho g L \zeta_a^2},\ N'_w = \frac{N_w}{0.5\rho g L^2 \zeta_a^2} \tag{6}$$

where, L, A_R, C_{Dw}, C_{Lw}, ρ, ζ_a are ship length, rudder area, drag coefficient in wave, lift coefficient in wave, water density and wave amplitude, respectively.

4 RESULT

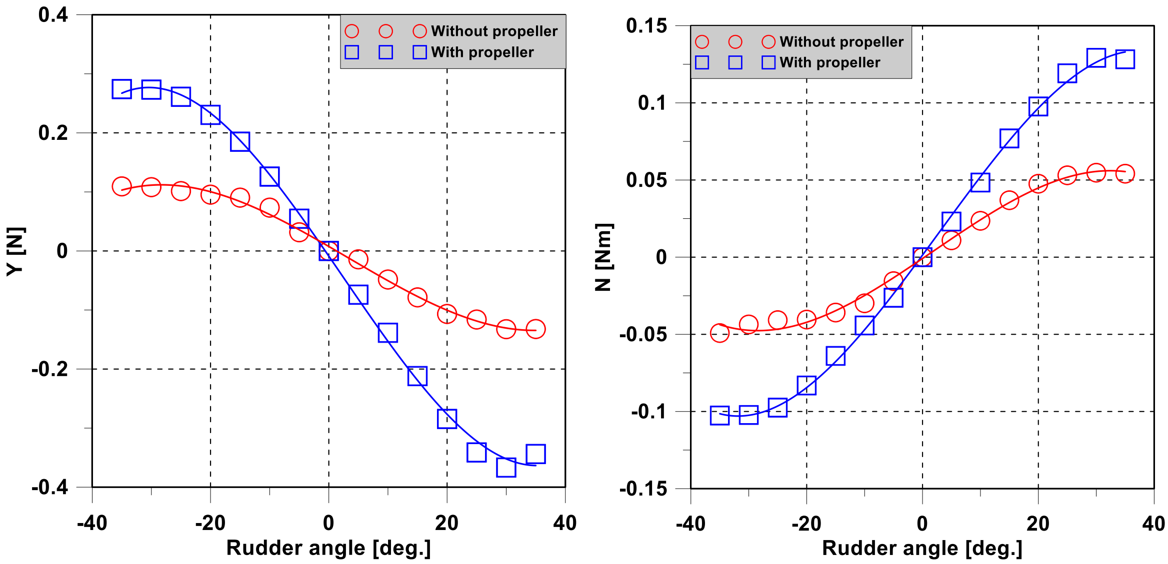
4.1 Test in calm water

Figure 5 shows the comparison result of drag coefficient and lift coefficient of the rudder with propeller and without a propeller. In case of the rudder behind the propeller, the drag and lift of a rudder increase significantly in various rudder angles. It is because the axial velocity over the rudder increased when the ship moves during the operation of the propeller. This is the same opinion as Simonsen (2000), flow around the tip of the rudder affected by the propeller. That is a reason why drag and lift of a rudder increase significantly in case with the propeller. Figure 6 shows the comparison result of the hydrodynamic force of a ship in calm water with and without the propeller. Sway force and yaw moment of a ship hull with propeller increase significantly than with one without propeller. Furthermore, the tendency of force acting on the ship and rudder in various rudder angle is reasonable.



(a) Drag coefficient (b) Lift coefficient

Figure 5: Drag coefficient and lift coefficient of rudder in calm water



(a) Sway force (b) Yaw moment

Figure 6: Sway force and yaw moment of a ship

4.2 Test in wave

Added resistance is the difference between the resistance in wave and resistance in calm water. In this study, the average value of the surge force of ship in head sea has been used for the comparison. The added resistance R_{aw} has been non-dimensioned and the added resistance coefficient has been estimated using Eq. (8). B, R_{AW} and g is the breath of a ship, added resistance and gravitational acceleration. ITTC (2018) recommended that there are two methods to tow the ship model in waves, such as constant thrust (model free to surge) and constant speed (surge restricted) for estimation of added resistance in waves. ITTC (2018) suggested that both methods show the compatible result for added resistance while allowing surge motion using soft-springs, a small oscillation of instantaneous forces should be measured.

In this study, surge is fixed during performing model test and the added resistance coefficient σ_{AW} has been compared with EFD's results (Experimental Fluid Dynamics) and CFD's result (Computational Fluid Dynamics) from other institutes for a wide range of λ / L as shown in Figure 7. Simonsen et al. (2013), suggested that peak value of added resistance of KCS occurs when the condition $f_e = f_n$ is met for a given speed corresponding to $\lambda / L = 1.15$. f_n and f_e are natural frequency and excitation frequency, respectively. The experimental result in this study shows fair agreement with that of the EFD measurement of different institutes. The maximum added resistance in wave occurs near λ / L = 1.15 that suggested by Simonsen et al. (2013). Since wavelength is close to the length of the ship, the stern region is also in a wave crest and mid-ship section "hangs" in the wave trough. With the increase of λ / L, vertical motion increase and consequently σ_{AW} increase until it reachs to peak value near λ / L = 1.15. Hossain et al. (2018) suggested that the ship moves up vertically as the wave amplitude and pitch angle follows the wave slope in long waves, hence σ_{AW} drops down gradually. In this study, the added resistance in short wave at λ / L = 0.5 is a little larger than result of other institutes because in our study model surge is fixed during the test that agreement with opinion's Wu et al. (2014) and Hamid et al. (2013). They suggested that free and fixed surge in experiment affected on pitch motion on added resistance in short waves.

$$\sigma_{AW} = \frac{R_{AW}}{g \rho \varsigma_a^2 (B^2 / L)} \qquad (7)$$

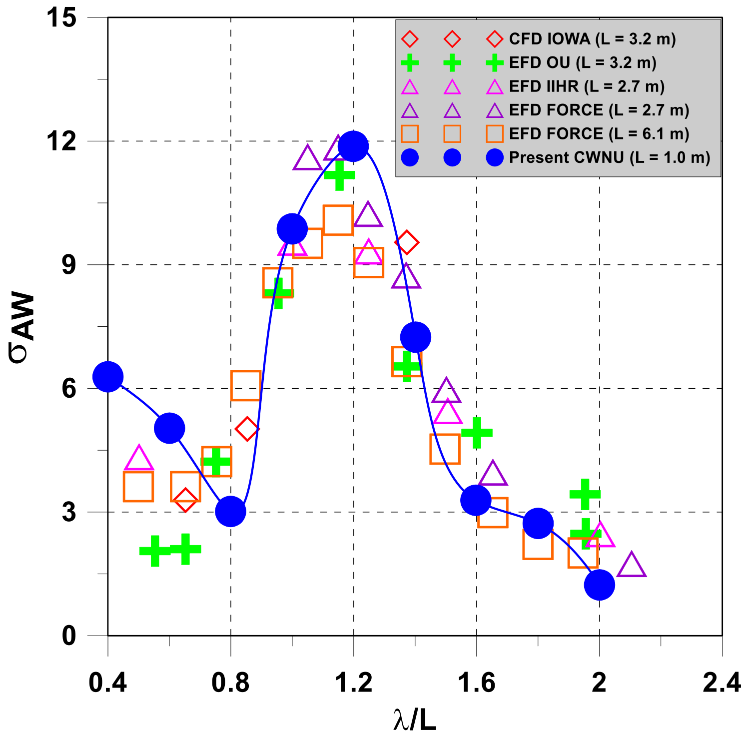
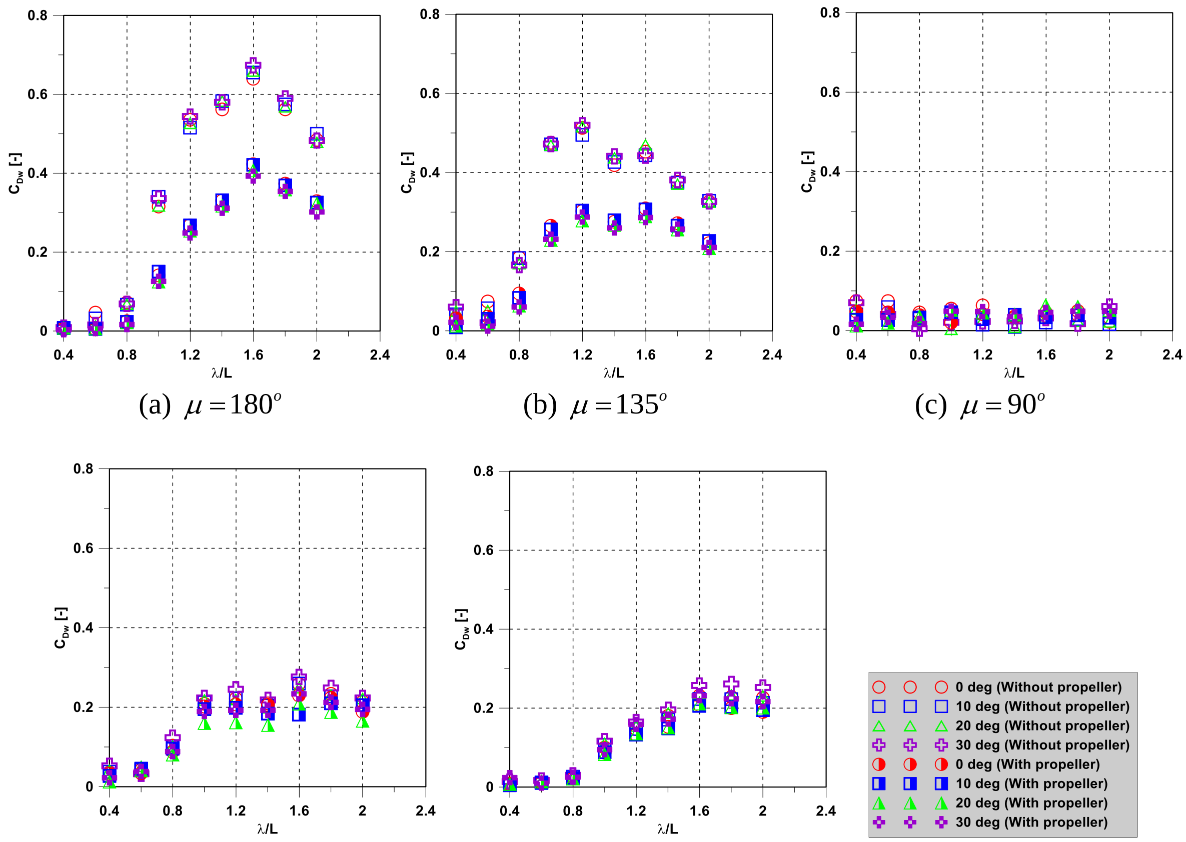


Figure 7: Comparison result of added resistance coefficient in head sea (without propeller)

Figure 8 shows the drag coefficient of a rudder in regular waves in various wave directions. It can be seen that drag force of a rudder becomes largest in head sea and smallest in the beam sea. With the increase of λ / L, drag force increase and reach to the peak value in very long wave in head sea. Drag force in regular waves changes slightly when rudder angle increases. Figure 9 shows the lift coefficient of a rudder in regular waves in various wave directions. On the other hand, lift force becomes largest in oblique waves, especially when wave direction approaches 135 degrees. Lift force increases significantly when rudder angle increases. Figures 10 -12 show the comparison of the non-dimensional 1st harmonic amplitude of hydrodynamic force acting on a ship hull in regular waves with propeller and without a propeller. It can be seen that 1st harmonic amplitude of surge force of the ship is less affected wave has a propeller. It can be seen that the surge force reaches the maximum value in short wave and reaches the maximum value at the wave direction of 150 degrees and at λ / L = 0.8. Surge force of the ship decreases and is smallest in the following sea.

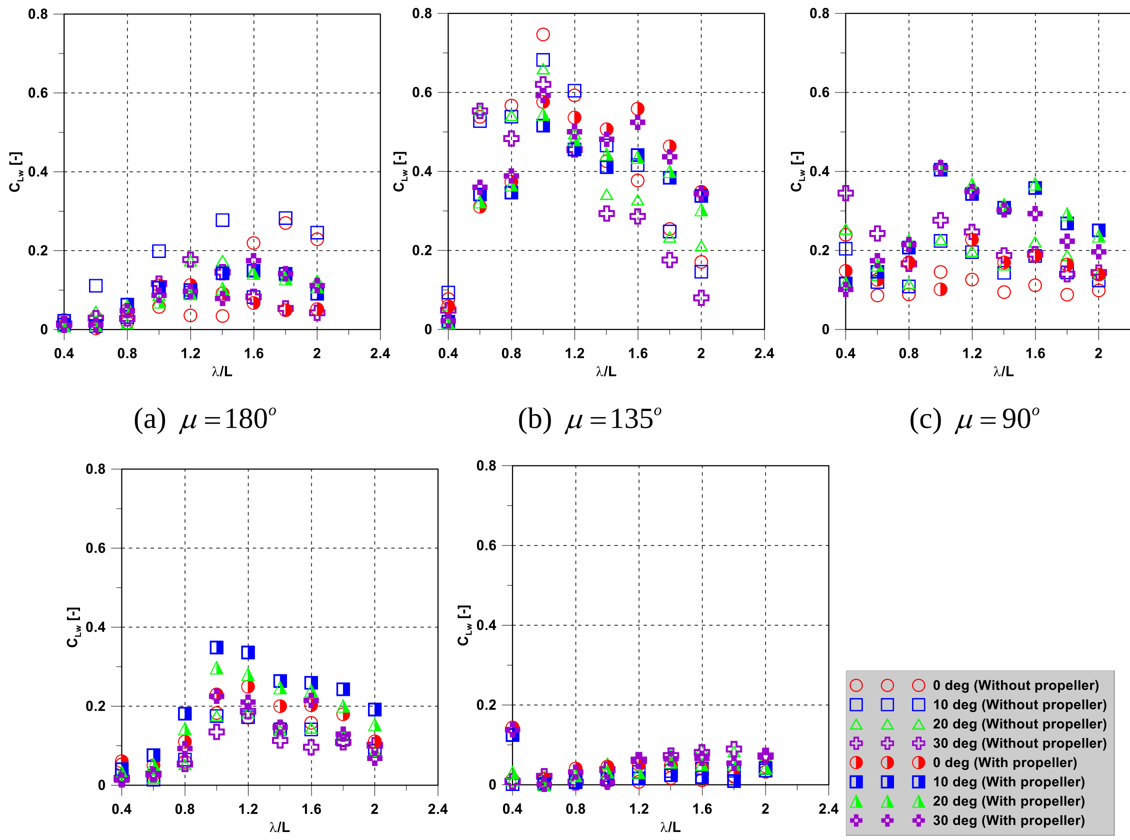
Figure 11 shows the sway force changing at different wave directions and it can be seen that 1st harmonic of sway force reaches the maximum value in the beam sea. Effect of a propeller to sway amplitude is small and sway force changes slightly when rudder angle increases. Sway force decreases when wave direction approaches 180 degrees and 0 degrees. Figure 12 shows the comparison of non-dimensional 1st harmonic amplitude of yaw moment acting on a ship hull in regular waves with propeller and without propeller. It can be seen that yaw moment is largest when wave direction approaches 135 degrees, and 45 degrees. Yaw moment changes significantly when rudder angle increases. The non-dimensional 1st harmonic amplitude of yaw moment is clearly affected when the ship moves in regular waves during operation of a propeller when the wave direction approaches 135 degrees.



(a) $\mu = 180^o$ (b) $\mu = 135^o$ (c) $\mu = 90^o$

(c) $\mu = 45^o$ (d) $\mu = 0^o$

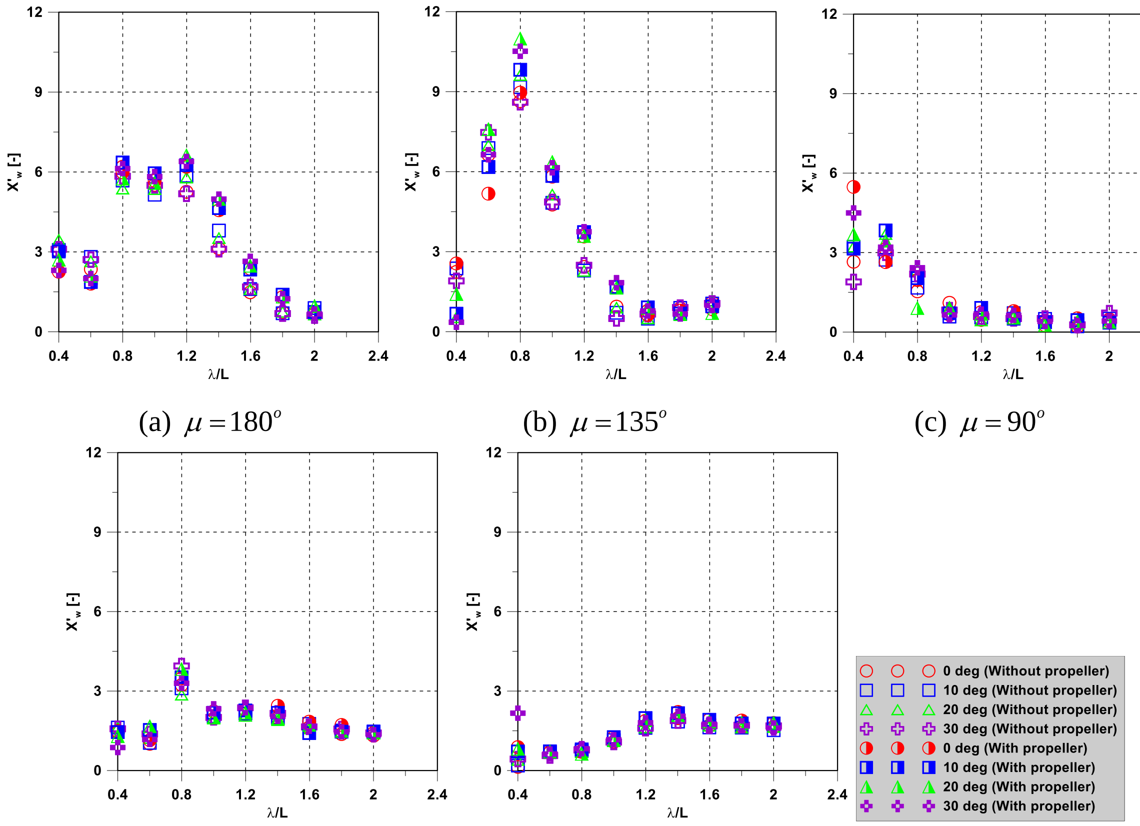
Figure 8: 1st harmonic amplitude of drag coefficient of rudder in regular waves



(a) $\mu = 180^o$ (b) $\mu = 135^o$ (c) $\mu = 90^o$

(c) $\mu = 45^o$ (d) $\mu = 0^o$

Figure 9: 1st harmonic amplitude of lift coefficient of rudder in regular waves



(a) $\mu = 180^o$ (b) $\mu = 135^o$ (c) $\mu = 90^o$

(c) $\mu = 45^o$ (d) $\mu = 0^o$

Figure 10: 1st harmonic amplitude of surge force of a ship in regular waves

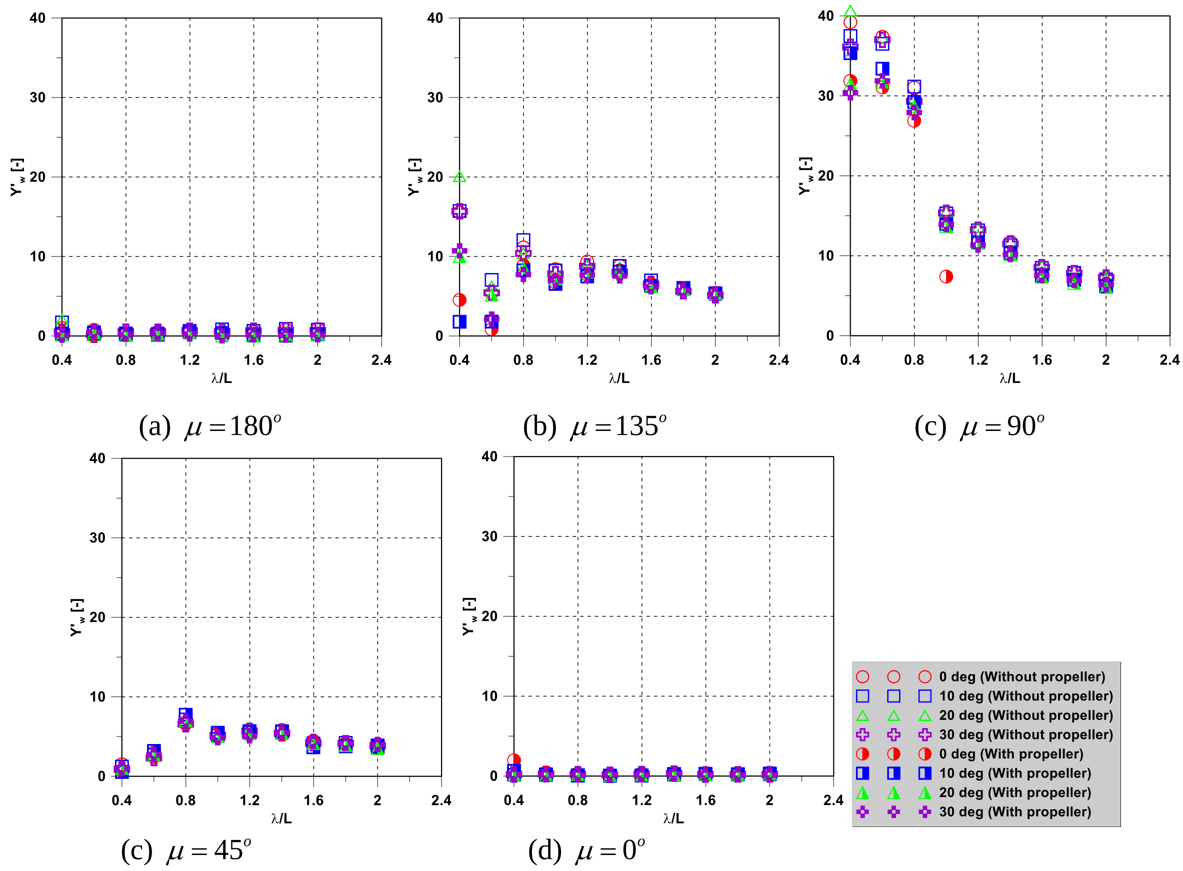


Figure 11: 1st harmonic amplitude of sway force of a ship in regular waves

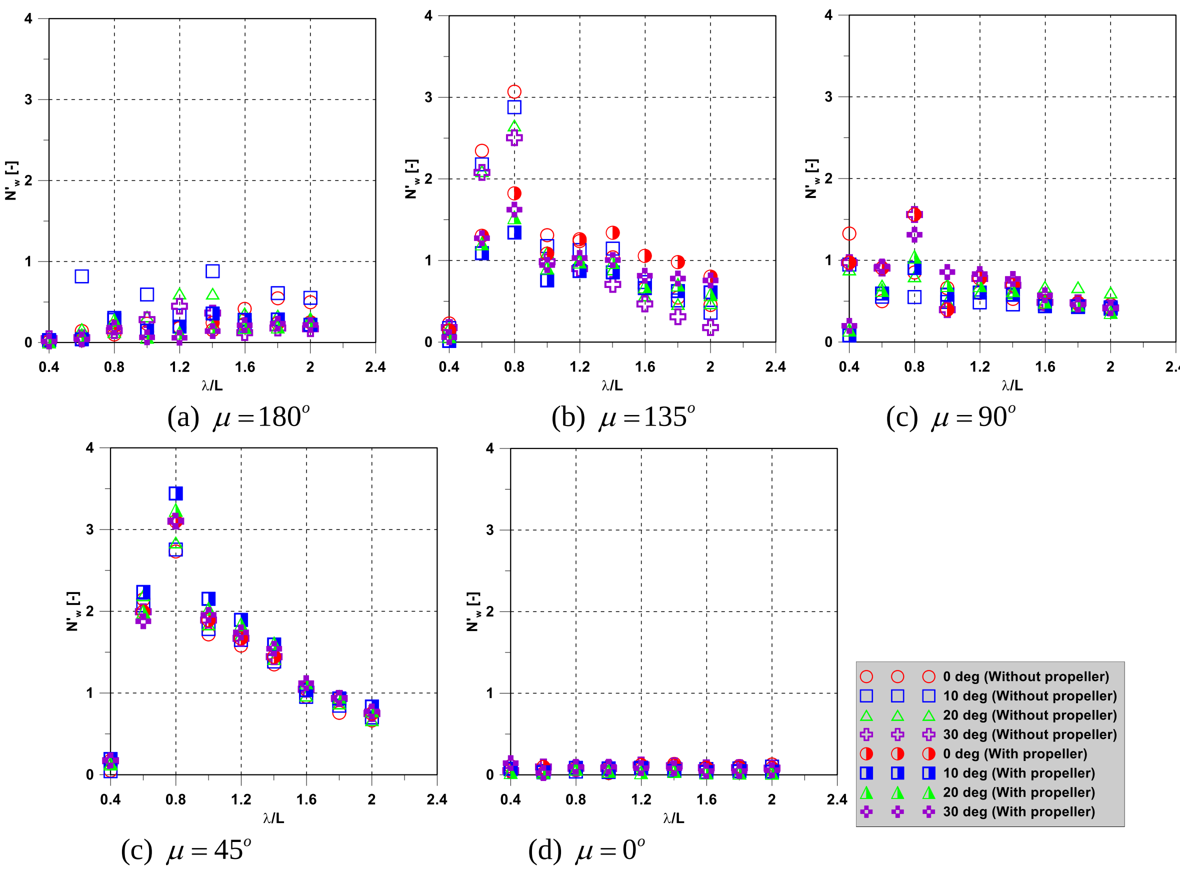


Figure 12: 1st harmonic amplitude of yaw moment force of a ship in regular waves

5 CONCLUSION

In this paper, the model test of KCS was carried out in Changwon National University's square wave basin, and the hydrodynamic forces acting on the ship and rudder in the various rudder angle are measured in calm water and regular waves. The hydrodynamic forces of a ship and rudder in regular waves during operation of the propeller are compared with one without propeller. The concluding remarks are as follows:

First, the propeller RPS is adjusted for self-propulsion for the model speed corresponding to full-scale service speed in calm water and is kept constant during the test. Hydrodynamic forces acting on the rudder at different rudder angles in calm water with the propeller are larger than one with without propeller. The propeller has a clear influence on the hydrodynamic force of rudder at a different rudder angle that is the same opinion's Simonsen (2000).

Second, in order to confirm the result of this experiment, the added resistance coefficient σ_{AW} has been compared with the result from other institutes for a wide range of λ / L in head sea and its shows fair agreement with the experimental results of different institutes. Drag and lift force of rudder behind the propeller in regular waves become larger than one without propeller.

Finally, the impact of wavelengths and wave directions on hydrodynamic forces of a ship and rudder is significant. Surge force and sway force of a ship change slightly during operation of the propeller while the yaw moment of a ship change significantly in comparison with one without propeller when wave direction approaches 135 degrees.

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