An Experimental Study on Effect of Loading Conditions on Hydrodynamic Forces Acting on a Ship

Van Thuan MAI*, Thi Thanh Diep NGUYEN*, and Hyeon Kyu YOON*
*Changwon National University, 20 Changwondaehak-ro Uichang-gu, Gyeongsangnam-do 51140, Korea
nguyenthithanhdiep1994@gmai.com

Key words: Korea Autonomous Surface Ship, Hydrodynamic Forces, Experiment, Various Loading Conditions

ABSTRACT

Nowadays, shipping by sea is dramatically developing due to the low price and the safety of the goods. The ship is designed bigger to meet the need of this development. In the design stage, the investigation of the hydrodynamic forces acting on the ship hull is very important to predict the ship's maneuverability. However, the ship will be shipped to many ports to receive or return the goods in a journey. Therefore, the ship usually moves in various loading conditions depend on the request of the ship owner. Hence, it is necessary to investigate the effect of the loading condition on the hydrodynamic forces acting on the ship to most accurately determine the maneuverability of the ship. In this study, an experiment of Korea Autonomous Surface Ship (KASS) is carried out at towing tank of Changwon National University to measure the hydrodynamic forces acting on the KASS. The loading condition considered in this experiment is determined based on the draft. The draft is decreased 5 percent for each loading condition. The smallest draft is 85 percent of the design draft. The static test as Oblique Towing test (OTT), Circular Motion test (CMT), Circular Motion test with Drift (CMT) is performed in the various loading conditions. First, the hydrodynamic forces in the Oblique Towing test (OTT) are compared with the result of other institutes in case of the full loading condition. Second, the effect of the drift angle and yaw rate on the hydrodynamic forces are discussed. Third, the changing of the hydrodynamic forces in various loading conditions is measured. Therefore, the influence of the loading conditions on the hydrodynamic forces acting on the KASS is discussed.

1. Introduction

In recent years, shipping develops significantly due to the development of the industry and freight transport. In order to reduce the price, the ship is designed bigger to transport more goods in one time. However, the ship will be shipped to many ports to receive or return the goods in a journey. Therefore, the ship usually moves in various loading conditions depend on the request of the shipowner. To ensure that the ship has good maneuverability in given loading conditions such as the turning ability and course keeping ability, many researchers studied to investigate the hydrodynamic forces acting on the ship hull. Yun Sok Lee (2003) predicted the hydrodynamic forces in laterally berthing maneuvers using Computational Fluid Dynamics (CFD). Tae Chul Park (2018) investigated the effect of the vertical center of gravity on the hydrodynamic force acting on the ship hull. The numerical method was performed in various drift angles to estimate the hydrodynamic forces. Van Minh Nguyen (2019) studied the hydrodynamic forces acting on the ship hull with and without a propeller by performing the model test. In addition, the hydrodynamic forces in the regular waves were estimated. Kun Dai (2019) estimated the hydrodynamic forces and hydrodynamic derivatives of the KVLCC2 by the virtual captive model test. The OTT and CMT were carried out to estimate the hydrodynamic forces. Hua Ming Wang (2011) estimated the hydrodynamic forces in oblique motion by performing the experiment and numerical method. The effect of the drift angle is investigated. Hafizul Islam (2018) estimated the linear hydrodynamic derivatives using static drift simulation. The result of hydrodynamic forces was compared with experimental results. The RaNS based solver and SHIP_Motion were used for simulation. Xiao Yang (2019) investigated the hydrodynamic forces of the KVLCC2 model in various drift conditions by numerical method. In addition, the effect of the mesh conditions on the hydrodynamic forces was considered. In this study, an experiment of Korea Autonomous Surface Ship (KASS) is carried out at towing tank of Changwon National University to measure the hydrodynamic forces acting on the KASS. The loading condition considered in this experiment is determined based on the draft. The draft is decreased 5 percent for each loading condition. The smallest draft is 85 percent of the design draft. The static test as Oblique Towing test (OTT), Circular Motion test (CMT), Circular Motion test with Drift (CMT) is performed in the various loading conditions. First, the hydrodynamic forces in the Oblique Towing test (OTT) are compared with the result of other institutes in the case of the full loading condition. Second, the effect of the drift angle and yaw rate on the hydrodynamic forces are discussed. Third, the changing of the hydrodynamic forces in various loading conditions is measured. Therefore, the influence of the loading conditions on the hydrodynamic forces acting on the KASS is discussed.

2. Test facility and test conditions

2.1 Test facility

The experiment of KASS was performed in the towing tank in Changwon National University. Figure 1 shows the towing tank used in this experiment. Towing tank dimensions are 14 m breadth, 20 m long and 1.8 m deep. The limit of the carriage speed is 1.0 m/s. In this experiment, the water deep was set at 1.0 m. Two load cells with 2-component force transducer were used to measure the hydrodynamic force acting on the KASS's hull. The model of the load cell is MCL-2A01-60N, which was made by Wonbang Forcetech Company limited. The capacity of the load cell is ±60N for the force in-x direction and ±60N for the force in y-direction. Load cells that were used in this experiment are shown in Figure 2.

Figure 1. Towing tank

Figure 2. 2-component load cell

2.2 Test condition

The KASS model was selected to investigate the effect of the loading condition on the hydrodynamic. The model test was performed in the various drafts to obtain hydrodynamic coefficients of the KASS model. The model test has a scale ratio is 1/11. Figure 3 shows the KASS model used in this experiment. The principal dimensions of the real scale and model scale are listed in Table 1. The experiments were carried out at the condition of the model scale with the ship speed was set at 0.931 m/s (equivalent to 6 knots in real scale). The model test was performed in the Oblique Towing test (OTT), Circular Motion test (CMT) and Circular Motion test with Drift (CMTD) to investigate the effect of the drift angle and yaw rate on the hydrodynamic forces. The test conditions are listed in Table 2. In addition, the effect of the loading condition on hydrodynamic forces is investigated. The draft conditions are listed in Table 3.

Figure 3. KASS model

Table 1. Principal particular of KASS

Item	Unit	Real scale	Model scale
Scale ratio	-	1	1/11
Length overall	m	25.131	2.285
Length between perpendiculars	m	22.000	2.000
Breadth	m	6.000	0.545
Draft	m	1.250	0.114
Depth	m	4.138	0.376
Volume displacement	m^3	86.706	0.065
Displacement	kgf.	88873.641	66.772
Froude number	-	0.210	0.210
Ship speed	knots	6.000	1.809
Ship speed	m/s	3.087	0.931

Table 2. Test conditions

Type of test	Variable	Value
Oblique Towing Test (OTT)	β [°]	0, ±2, ±4, ±6, ±8, ±10, ±12, ±15
Circular Motion Test (CMT)	r' [−]	0.2, 0.3, 0.4, 0.5, 0.6
CMT with drift (CMTD)	r' [−]	0.2, 0.3, 0.4, 0.5, 0.6
	β [°]	3, 6, 9, 12, 15

Table 3. Draft conditions (Model scale)

Item	Unit	Draft			
		100%T	95%T	90%T	85%T
Draft	m	0.114	0.108	0.102	0.097
Displacement	kgf.	66.772	61.682	56.805	52.184

3. Experiment

3.1 Equation of motion

In this experiment, the ship maneuvering's mathematical model considers three degrees of freedom. Therefore, the surge force, sway force and yaw moment are measured. To describe the hydrodynamic force acting on the ship hull, two right-handed coordinate systems were used. A body-fixed coordinate system and an earth-fixed coordinate system are shown in Figure 4. The mathematical model can be described by the following surge motion, sway motion and yaw motion by Eq. (1). X, Y and N are denoted for hydrodynamic forces acting on the KASSs hull as surge force, sway force and yaw moment, respectively.

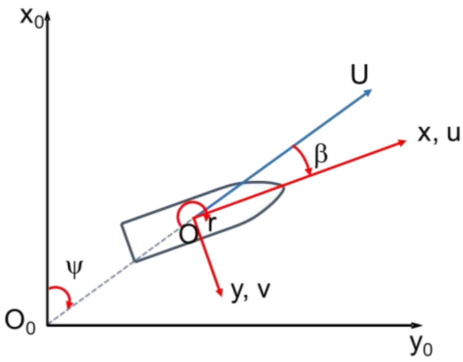

Figure 4. Coordinate system

$$\begin{cases} X = m(\dot{u} - vr - x_G r^2) \\ Y = m(\dot{v} + ur + x_G \dot{r}) \\ N = I_z + m x_G (\dot{v} + ur) \end{cases} \tag{1}$$

3.2 Ballasting and inertia test

Before performing the experiment, the mass distribution of the ship was checked to an exact match with the real scale. Figure 5 shows the ballasting of the KASS model ship in various loading conditions. In addition, the inertia table was used to obtain the mass moment of inertia I_{zz}. Figure 6 show the inertia test in full loading condition. The results of the inertia test are listed in Table 4.

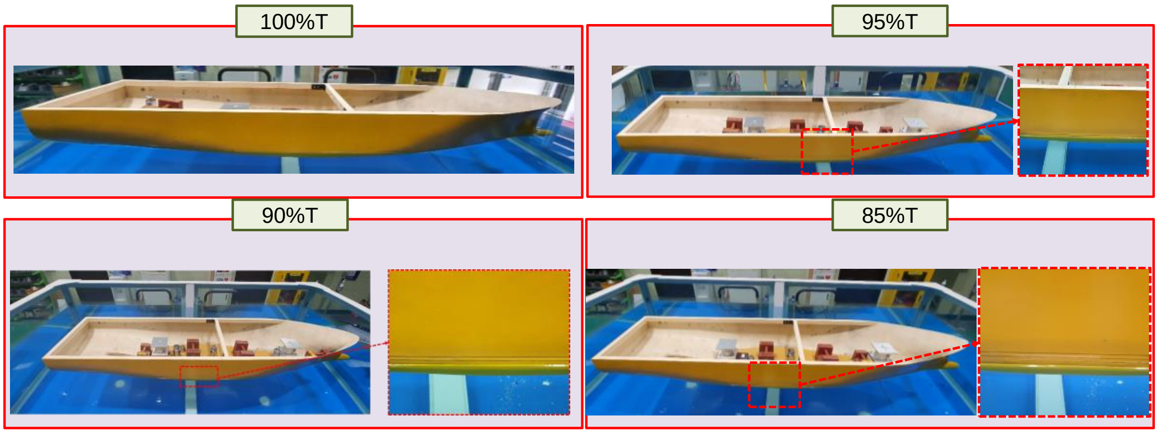

Figure 5. Ballasting in various loading conditions

Figure 6. Inertia test in full loading condition

Table 4. Result of inertia test in various drafts

Item	Unit	Draft			
		100%T	**95%T**	**90%T**	**85%T**
Target value I_{zz}	kgm^2	16.693	15.420	14.201	13.046
Measured value I_{zz}	kgm^2	16.969	15.061	13.803	13.574
Difference	%	1.626	2.387	2.807	4.050

3.3 Experimental setup

The KASS model test was carried at the towing tank in Changwon Nation University. The load cells are installed on the strong back near the bow and stern of the model ship. The potentiometers are connected between load cells and the measuring frame. The measuring frame is connected with the sub-carriage in the yaw table. During the test, the model test will be towed by the towing carriage. The yaw table can change the drift angle by rotating around its center. In the case of the circular test, the yaw table rotates with the yaw rate which was set. The signal obtained from the load cell will be transferred from the electrical signal into the digital signal by an A/D converter NI USB-6212 was made by National Instruments Corporation Company. The surge force and sway forces are measured by the total surge force and sway force obtained from the load cells. In addition, the yaw moment is obtained by the sway force of the load cells and the distance from the center of these load cells to the center of the model ship. Figure 7 shows the real experimental setup of the KASS.

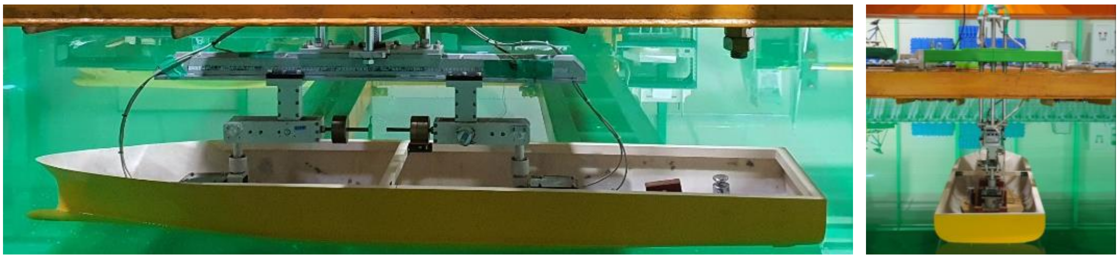

Figure 7. Real experimental setup in case of full loading condition

3.4 Data analysis

The measured data is recorded as the time series when the carriage speed reached the target speed of 0.931m/s and keep it is stable. After each run, the time series are checked to avoid obvious errors. The hydrodynamic forces obtained from two load cells are estimated by the mean value. X, Y and N are the hydrodynamic forces acting on the KASSs hull as surge force, sway force and yaw moment, respectively. X', Y' and N' are the non-dimensional of hydrodynamic forces acting on the KASSs hull as surge force, sway force and yaw moment, respectively. The definition of the non-dimensional hydrodynamic forces is shown in Eqs. (2) - (4).

$$X' = \frac{X}{0.5\rho L^2 U^2} \tag{2}$$

$$Y' = \frac{Y}{0.5\rho L^2 U^2} \tag{3}$$

$$N' = \frac{N}{0.5\rho L^3 U^2} \tag{4}$$

5. Result and discussion

5.1 Validation result

The experimental results of the sway force acting on the ship hull in the case of full loading condition are compared with the results from the Korean Research Institute of Ship and Ocean Engineering (KRISO) (Dong Jin Kim, et al. 2021). Figure 8 shows the comparison of this study result and KRISO's result. Sway force is a good agreement with the results from KRISO. In the large drift angle, the sway force is a small difference due to the model's hull. The length between perpendiculars of the KRISO's model ship is 5.789m. In the small drift angle, the error of the model's hull is not affected so much. However, when the drift angle increase, the effect of the error of the model's hull increased dramatically.

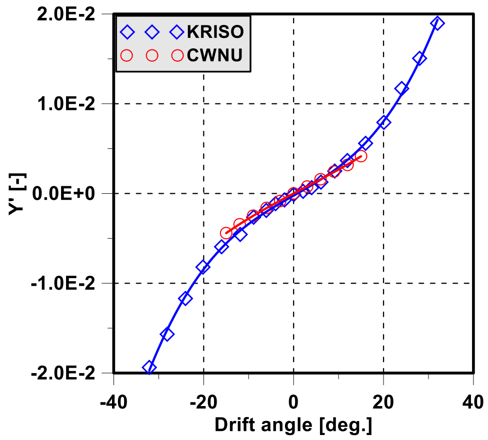

Figure 8. Comparison result with KRISO

5.2 Results

In the oblique towing test, the effect of drift angle is investigated. Besides the effect of drift angle, the effect of the loading condition is the main investigated in this study. The hydrodynamic forces acting on the model ship hull in various drift angles and various loading conditions are shown in Figure 9. The hydrodynamic forces increase slightly in various loading conditions. The effect of the loading condition is shown clearly in the large drift angle. The hydrodynamic forces are largest in the case of full loading condition and reduce when the loading condition decreases. The hydrodynamic forces are affected by the fluid's pressure around the ship's hull. When the loading condition decreases, the wetted area also decreases. Therefore, the fluid's pressure also decreases due to the decreasing of the wetted area. When the drift angle increases, the hydrodynamic forces acting on the ship hull increase significantly. The results of the hydrodynamic forces in various yaw rates and various loading conditions are shown in Figure 10. The loading condition clearly affects the hydrodynamic in CMT. In the case of full loading condition, the hydrodynamic forces increase dramatically and nearly 2 times in 85% loading condition. In addition, when the yaw rate increases, the hydrodynamic forces increase significantly. The effect of the drift angle, yaw rate and loading condition on hydrodynamic forces are shown in Figure 11. As the same trend of CMT's results, the loading condition affects slightly in small yaw rate. However, the hydrodynamic forces increase clearly in large yaw rate by the effect of loading conditions. Moreover, the hydrodynamic forces reduce and become positive value when the drift angle increases.

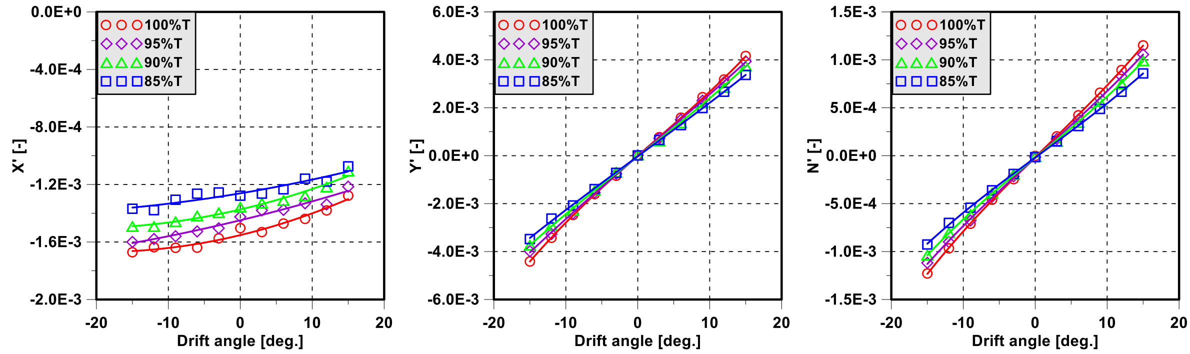

Figure 9. Results of OTT in various loading conditions

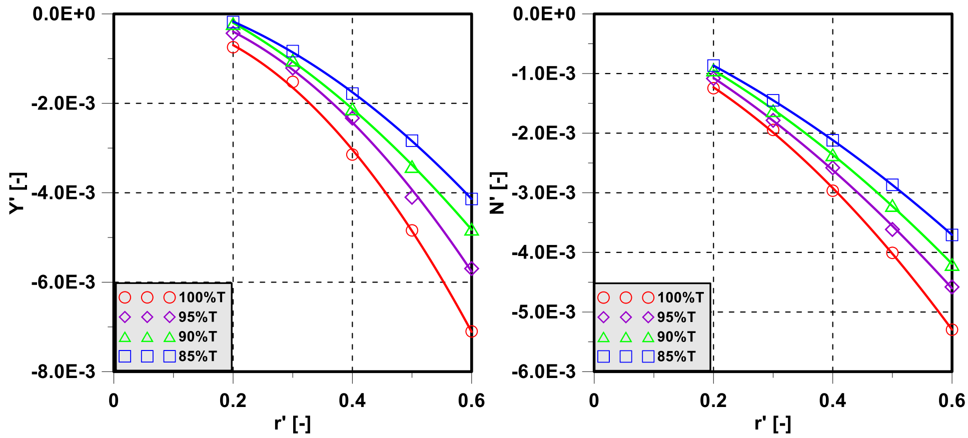

Figure 10. Results of CMT in various loading conditions

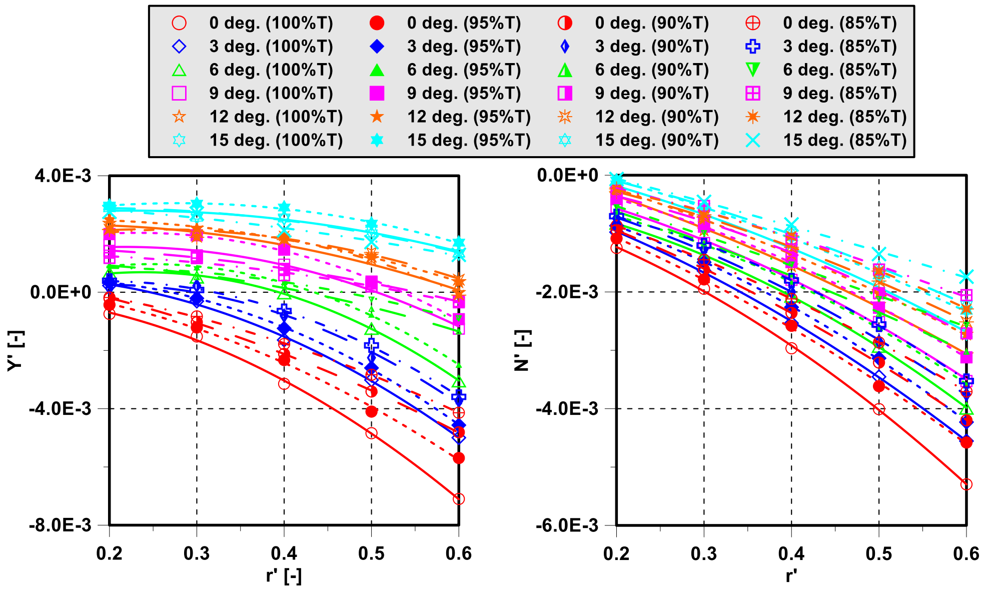

Figure 11. Results of CMTD in various loading conditions

6. Conclusion

In this study, the model test of KASS was carried out in towing tank at Changwon National University and the effect of the loading condition on hydrodynamic forces in various drift angles and various yaw rates was investigated. The concluding remarks are as follows:

First, the hydrodynamic forces increase slightly in various loading conditions. The effect of the loading condition is shown clearly in the large drift angle. The hydrodynamic forces are largest in the case of full loading condition and reduce when the loading condition decreases.

Second, the hydrodynamic forces change dramatically in various yaw rate due to the effect of loading condition. In the small yaw rate, the hydrodynamic forces changes slightly in various loading conditions. However, the hydrodynamic forces increase significantly in various loading conditions especially in the largest yaw rate. In the case of full loading condition, the hydrodynamic forces increase dramatically and nearly 2 times in 85% loading condition.

Finally, the effect of loading condition on the hydrodynamic forces in various yaw rates and various drift angles was investigated. As the same trend of CMT's results, the loading condition affects slightly in small yaw rate. However, the hydrodynamic forces increase clearly in large yaw rate by the effect of loading conditions. Moreover, the hydrodynamic forces reduce and become positive value when the drift angle increases.

Acknowledgements

This research was supported by the 'Development of Autonomous Ship Technology (PJT201313, Development of Autonomous Navigation System with Intelligent Route Planning Function)' funded by the Ministry of Oceans and Fisheries (MOF, Korea)

References

(1) Lee, Y.S., (2003): The prediction of hydrodynamic forces acting on ship hull in laterally berthing maneuver using CFD, *International Journal of Navigation and Por Research*, 253-258.
(2) Park, T.C., Lee, S.W., Paik, K.J. and Moon, S.H., (2018): Study on hydrodynamic forces acting on tanker hull with consideration of various vertical center of gravity in drift test, *Journal of Ocean Engineering and Technology,* 433-439.
(3) Nguyen, V.M., Seo, J.W., Yoon, H.K. and Kim, Y.G., (2019): Experimental study on hydrodynamic forces acting on ship hull and rudder behind the propeller in regular waves, *Proceeding of 11th International Workshop on Ship and Marine Hydrodynamics*, 1-12.
(4) Dai, K. and Li, Y., (2019): Manoeuvering prediction of KVLCC2 with hydrodynamic derivatives generated by a virtual captive model test, *Journal of Polish Maritime Research*, 16-26.
(5) Wang, H.M., Xie, Y.H., Liu, J.M., Zou, Z.J. and He, W., (2011): Experimental and numerical study of hydrodynamic forces on ship in oblique motion, *IEEE Xplore,* 328-331.
(6) Islam, H., Rahaman, M.M., Afroz, L. and Akimoto, H., (2018): Estimation of linear hydrodynamic derivatives of a VLCC using static drift simulation, *Proceeding of AIP conference*, 1-7.
(7) Yang, X., Yin, Y. and Lian, J.J., (2019): A numerical study on flow field and maneuvering derivatives of KVLCC2 model at drift condition, *Journal of Marine Engineering and Technology*, 1-12.
(8) Kim, D.J., Choi, H.J., Kim, Y.G. and Yeo. D.J., (2021): Mathematical model for harbor manoeuvers of Korea Autonomous Surface Ship (KASS) based on captive model test, *2021, Conference of the Korean Association of Ocean Science and Technology Societies*, 1-8.

Author's Biography

Thi Thanh Diep NGUYEN received the Bachelor's degree in Naval Architecture in Ho Chi Minh city University of Transport, Vietnam, in 2017. She got the Master's Degree in Changwon National University, in 2019. Now, she is a PhD. candidate student in Dept. of Smart Ocean Environmental Energy at Changwon National University, Korea. Her research interests are ship maneuvering and seakeeping.

Van Thuan MAI received the Bachelor's degree in Naval Architecture and Marine Engineering from the Danang University of Science and Technology, Vietnam, in 2019. He is currently a Master's candidate student in Dept. of Smart Ocean Environmental Energy at Changwon National University, South Korea. His research interests are seakeeping, obstacle avoidance, control systems.

Hyeon Kyu YOON is an professor in the department of Naval Architecture and Marine Engineering in Changwon National University, Korea. He got the Ph.D degree in the department of Naval Architecture in Seoul National University, Korea, in 2003. He worked for ADD and for KRISO. His main interests are the simulation of marine vehicles such as a ship and an underwater vehicle, and the model test in the water tank.