4th MASHCON, Hamburg - Uliczka et al. (eds) - © 2016 Bundesanstalt für Wasserbau ISBN 978-3-939230-38-0 (Online)
DOI: 10.18451/978-3-939230-38-0_32

EXPERIMENTAL STUDY ON THE MANOEUVRABILITY OF KVLCC 2 IN SHALLOW WATER

D J Yeo, K Yun and **Y Kim,** Korea Research Institute of Ships and Ocean engineering, Rep. of Korea

SUMMARY

Manoeuvring of ships in shallow water region is known as hard and risky, so phenomena in the shallow water region should be carefully studied for the safe voyages of ships. Ship manoeuvring in shallow and confined waters has become an issue again to people those have been interested in safe manoeuvring. Reflecting this interest, KRISO (Korea Research Institute of Ships and Ocean Engineering) had conducted a project entitled "Enhancement of simulation technique for navigation of a ship in confined waterway [PES171E]". As a part of the project, experimental studies on the manoeuvring characteristics of KVLCC 2 were conducted. Both Free Running Model Tests (FRMTs) and Horizontal Planar Motion Mechanism (HPMM) tests were conducted on false bottom of KRISO's towing tank. Based on the hydrodynamic coefficients estimated from HPMM test results, numerical simulations of turning and zigzag manoeuvres were conducted. The simulation results were compared with the results of FRMTs, especially focusing on the change in manoeuvrability due to change of water depth.

1 INTRODUCTION

Recently, several studies on a ship's manoeuvrability in shallow water were conducted. This movement is meaningful not only because manoeuvring of ships in shallow water region is known as hard and risky, but also is inevitable for most ships. Furthermore, in shallow water region, there happens many interesting hydrodynamic phenomena of a ship such as squat. Therefore, phenomena happened in the shallow water region should be carefully studied for the safe navigation of ships. SIMMAN 2014 of which purpose was to benchmark the capabilities of different ship manoeuvring simulation methods including systems based and CFD based methods, set manoeuvring in shallow water as one of its' theme.
To match the purpose of SIMMAN 2014, KRISO (Korea Research Institute of Ships and Ocean Engineering) conducted a project entitled "Enhancement of simulation technique for navigation of a ship in confined waterway [PES171E]". As a part of this project, captive manoeuvring model tests for three different ships (KCS, KVLCC 2, KLNG) were conducted to estimate manoeuvring characteristics of ships in shallow waters [4] [5] [6] [7]. Some manoeuvring trials were simulated based on hydrodynamic coefficients estimated through the captive model tests of KVLCC 2 [6]. Simulated results were compared with free running model tests conducted in the KRISO's towing tank, using false bottom facility [8].

2 HPMM MODEL TEST

2.1 SETUP & DEVICES

2.1 (a) Towing Tank

All the tests were conducted in the KRISO's towing tank. Since 1978, towing tank of the KRISO has made all the efforts to provide accurate and reliable experimental results and numerical simulations for almost 1,600 model ships over 38 years with the most sophisticated facilities and highly experienced staffs. The dimensions & characteristics of the KRISO towing tank & carriage are shown in Table 1. In Figures 1 and 2, the top view and photograph of towing tank are displayed.

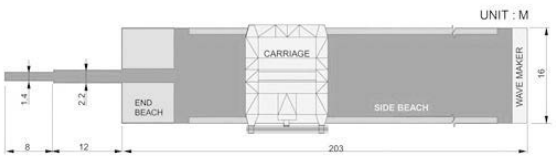

Figure 1. Top view of towing tank.

Figure 2. Photograph of KRISO towing tank.

Table 1. Dimensions & characteristics of KRISO towing tank.

	Items	Value	Remark
Towing Tank	Length	200 m	
	Breadth	16 m	
	Depth	7 m	
Carriage system	Low speed	0.04 ~ 1 m/s	2 small motors
	General speed	0.04 ~ 6 m/s	8 large motors
	Max. acceleration	1 m/s^2	

Figure 3. Picture of KRISO's false bottom facility.

2.1 (b) False-bottom

To mimic the shallow water condition, a false-bottom facility was used. The false-bottom facility was built in the KRISO's towing tank in 2011, and had been used for several purposes including these captive manoeuvring model tests. The vertical position of false-bottom facility is adjustable to make 0~7m water depth. In Fig 3, a picture of false bottom facility (L x B: 54m x 10m) is displayed [3].

2.1 (c) HPMM Device

A Horizontal Planar Motion Mechanism (HPMM) device was used for the captive manoeuvring model tests. KRISO's HPMM device has been used for estimating a ship's manoeuvrability over 30 years. The specification of KRISO's HPMM device is summarized in Table 2.

Table 2. Specification of KRISO's HPMM device.

Specifications		**Value**
Item	***unit***	
Max. Sway amplitude	*m*	1.5
Max. Yaw amplitude	*deg*	40.0
Drift available	*deg*	±360

Figure 4. HPMM device and model ship on the false-bottom.

Table 3. Principal dimensions of KVLCC 2 (model).

Dimensions		**Value**
Item	*unit*	
Scale ratio	-	39.44
Lpp	*m*	8.1136
Breadth	*m*	1.4706
Depth	*m*	0.7606
Draft	*m*	0.5273
Displacement	m^3	5.0958
Rudder area	m^2	0.1757
DP	*m*	0.25
U	*m/s*	0.5734

2.2 MODEL SHIP

A 1:39.44 scale model ship was used for the shallow water captive manoeuvring model test. Principal dimensions of the model are shown in Table 3. In figure 4, KVLCC 2 model mounted to HPMM device is displayed.

2.3 TEST MATRIX

2.3 (a) Depth over Draft (H/T) Cases and Self-Propulsion Point

Depths to draft conditions were set to be H/T = 1.2, H/T = 1.5, and H/T = 2.0. Tests were conducted with model's self-propulsion condition. To find propeller revolution at self-propulsive condition, simple self-propulsion tests were conducted. Propeller RPS at self-propulsion condition were found to be 4.28, 4.31 and 4.47 at H/T = 2.0, H/T = 1.5, and H/T=1.2 respectively.

2.3 (b) Test Matrix

Test matrices were set as Table 4 and 5 considering conventional HPMM test matrix in deep water condition and the specification of HPMM device.

Table 4. Static test matrix.

Type of Test	**Drift Angle (°)**	**Rudder Angle (°)**	**rps (1/sec)**
Static Rudder	0^o	$0^o, \pm5^o, \pm10^o, \pm15^o, \pm25^o, \pm35^o$	4.47 (H/T=1.2) 4.31 (H/T=1.5) 4.28 (H/T=2.0)
Drift & Rudder	$0^o, \pm4^o, \pm8^o, \pm12^o$	3 Rudder Angles	
Static Drift	$0^o, \pm2^o, \pm4^o, \pm6^o, \pm10^o, \pm15^o, \pm20^o$	0^o	

Table 5. Dynamic test matrix.

Type of Test	Drift Angle	Independent Variable (nondimensionalized)	rps (1/sec)
Pure Sway	0^o	$\dot{v}'$ =-0.24, -0.28, -0.32, -0.36 (- sign means the start direction of motion)	4.47 (H/T=1.2)
Pure Yaw	0^o	r' =0.45, 0.48, 0.51, 0.54, 0.57	4.31 (H/T=1.5)
Yaw with Drift	4^o 8^o 12^o	r' =0.45, 0.48, 0.51, 0.54, 0.57	4.28 (H/T=2.0)

3 ANALYSIS & SIMULATION

3.1 COORDINATES SYSTEM

The following right handed orthogonal coordinates system are used for the modeling of a ship's manoeuvring motion. The coordinate is moving with a body, with the origin fixed at the midship of the body [1]. The sign conventions are shown in figure 5.

3.2 MATHEMATICAL MODEL

To describe a ship's manoeuvring motion, a modular type manoeuvring equations of motion was used, based on the prescribed coordinates system.

$$\mathrm{m}(\dot{u} - vr - x_G r^2) = X_H + X_P + X_R$$
$$\mathrm{m}(\dot{v} - ur + x_G \dot{r}) = Y_H + Y_R$$
$$I_Z \dot{r} + m x_G(\dot{v} + ur) = N_H + N_R$$

where the terms with subscripts H, P and R represent the hull forces, the propeller forces and the rudder forces, respectively.

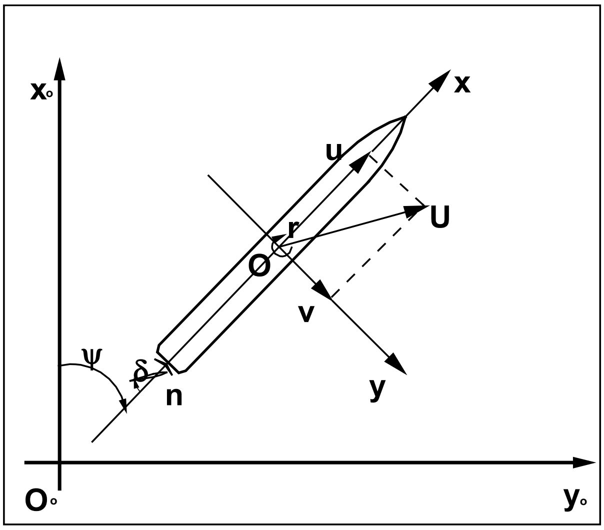

Figure 5. Coordinates system.

3.2 (a) Hull Forces

Hull forces are described as follows.

$$X_H = X_{\dot{u}}\dot{u} + \mathrm{X}_{vv}v^2 + \mathrm{X}_{vr}vr + \mathrm{X}_{rr}r^2 + X(u)$$
$$Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + \mathrm{Y}_v v + \mathrm{Y}_r r + \mathrm{Y}_{v|v|}v|v| + \mathrm{Y}_{r|r|}r|r| + \mathrm{Y}_{vvr}v^2 r + \mathrm{Y}_{vrr}vr^2$$
$$N_H = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + \mathrm{N}_v v + \mathrm{N}_r r + \mathrm{N}_{v|v|}v|v| + \mathrm{N}_{r|r|}r|r| + \mathrm{N}_{vvr}v^2 r + \mathrm{N}_{vrr}vr^2$$

where resistance force $X(u)$ is obtained from the resistance test.

3.2 (b) Propeller Force

Propeller force was considered as follows.

$$X_P = (1-\mathrm{t})\rho n^2 D^4 K_T(J_P)$$

where
$J_P = u(1-w_P)/(nD)$, n: rps, D: diameter

where
t: thrust deduction factor and w_P: the effective propeller wake fraction.

3.2 (c) Rudder Forces

Rudder forces model are described as follows.

$$X_R = -(1-\mathrm{t}_R)F_N sin\delta$$
$$Y_R = (1-\mathrm{a}_H)F_N cos\delta$$
$$N_R = (\mathrm{x}_R + \mathrm{a}_H \mathrm{x}_H)F_N cos\delta$$

$$F_N = \frac{1}{2}\rho \mathrm{A}_R \mathrm{U}_R{}^2 f_\alpha sin\alpha_R$$

where
A_R: rudder area, U_R: effective inflow velocity, f_α: rudder normal force coefficient, α_R: effective inflow angle, F_N: rudder normal force, t_R: rudder force deduction factor, a_H: hull force factor, x_H: hull moment factor, x_R: rudder position in x-axis, and δ: rudder angle.

3.3 SIMULATION CASES

Based on the mathematical model described in the previous section and the manoeuvring coefficients estimated from the captive manoeuvring model tests, numerical simulations for 1:39.44 scale model KVLCC 2 were conducted. Numerical turning and zigzag simulations were conducted, and results of those simulations were compared with free running model tests results those were conducted also on the false-bottom in KRISO's towing tank.

In table 6, cases for numerical simulations are summarized.

Table 6. Cases for numerical simulations & FRMTs.

Type	Rudder	Direction	H/T
Turning Circle	35°	STBD, PORT	1.2, 1.5 and 2.0
Zigzag	20°/10°	STBD, PORT	1.2 and 1.5
	20°/5°	STBD, PORT	1.2 and 1.5

4 COMPARISON OF TEST RESULTS

4.1 FREE RUNNING MODEL TEST

FRMTs in shallow water condition were carried out to obtain data to be compared with simulation results from HPMM tests. All of the data were converted into 1:39.44 scale to be drawn with the simulation results from the scale of HPMM tests model.

4.1 (a) Model Ship

1:83.74 scale model ship was selected for FRMTs when the size of the false-bottom and the speed of KVLCC2 were taken into consideration. Principal dimensions of selected model are shown in table 7. Figure 6 shows the figure of KVLCC 2 model with FRMTs devices on the false-bottom.

4.1 (b) Devices & Setup

FRMTs in shallow water depth were conducted indoor with navigational devices. To obtain position data and other navigation data, the devices in table 8 were installed in the model ship and the facility.

Table 7. Principal dimensions of KVLCC 2 (model for FRMTs).

Item	*Unit*	Value
Scale ratio	-	83.7403
Lpp	*m*	3.8213
Breadth	*m*	0.6926
Depth	*m*	0.3583
Draft	*m*	0.2484
U	*m/s*	0.3935

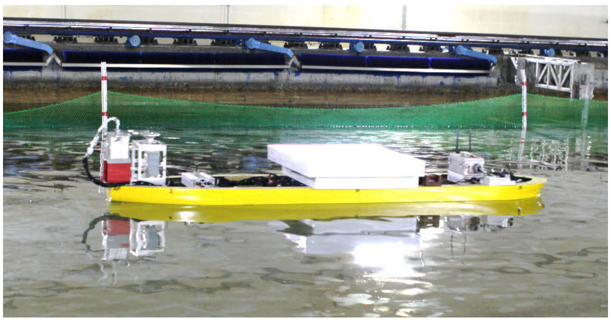

Figure 6. KVLCC2 model ship on the false-bottom.

Table 8. Devices in model ship and facility [8].

Item	Name	Specification
Camera	Sony, XCG-5005E	2448/2048 pixels, 15FPS
Lens	-	56.3° HFOV, 43.7° VFOV
Gyro	Hitachi, HOFG-1(A)	-180 to 180°, -60 to 60°/s
Inclinometer	Tamagawa, TA4270	-45 to 45°
DAQ	NI 9239	4CH, 24bit
Modem	Acksys, WLg-Link	802.11 a/b/g/h

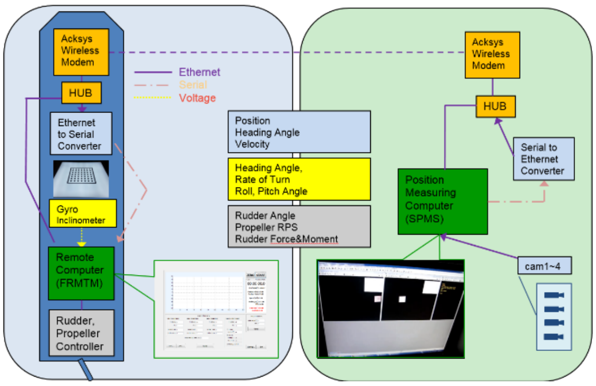

Figure 7. Diagram of data exchange [8].

Figure 7 shows the flow of navigation data and control data between the model ship and the control devices.
The model ship was loaded with devices and weights to meet test conditions such as GM, Izz, and Ixx. Final GM value was within 96.5% of designed value. Final moment of inertia for z and x axis were within 106.5% and 93.5% of designed values respectively.

4.1 (c) Test Matrix

Turning circle tests (±35°) and zigzag tests (±20° /5°, ±20° /10°) were carried out in three water depth conditions: 1.2, 1.5, and 2.0. Test matrix for FRMTs is shown in table 6. This test matrix was selected considering the model test specification by SIMMAN 2014 [2].
Before the model ship enters the test scenario, it has to go straightly along the false-bottom while the speed of the model ship reaches the design speed of 0.3935m/s. PD controller was adapted with neutral rudder angle in this stage. After turning circle and zigzag tests, all of the result values from FRMTs were averaged with STBD and PORT tests due to asymmetry of the model ship which has a propeller and a rudder. Figure 8 shows the process of turning circle test to STBD in H/T condition of 1.5.

Figure 8. Turning circle test

Because of the limit of the false-bottom size, the graphs only show initial stages of turning tests and the 1st overshoots of zigzag tests.

4.2 COMPARISONS

4.2 (a) Turning

Figures 9-11 show comparisons of numerical simulations and FRMT results of 35° turning. Both numerical simulations and FRMT results show the tendency that heading angle changes slower in relatively shallower water cases. By comparisons of results of different water depth, the tendency is more clearly shown when the results of H/T conditions between 1.2 and 1.5 are compared. With this results, and considering hydrodynamic forces grows exponentially with decrease of water depth, it can be suspected that the shallow water effect on manoeuvrability also grows exponentially according to water depth.

4.2 (b) Zigzag

Figures 12~15 show comparisons of numerical simulations and FRMT results of 20°/5° and 20°/10° zigzag. Both numerical simulations and FRMT show the tendency that 1st overshoot of heading angle becomes slightly larger in H/T=1.5 condition. It can also be seen that the time to reach 1st overshoot is faster in H/T=1.2 condition. With these results, it can be deduced that a ship becomes more stable as H/T becomes small.

4.3 OVERALL COMPARISON

Both FRMT results and numerical simulation results show asymmetry between port and starboard, but asymmetric tendencies are relatively small at numerical simulation results.
Even though FRMT results seem to have slight initial turning rate to starboard side in all cases, the results of FRMT are somewhat different from those of numerical simulation.
In all cases, it can be found that the heading changes of FRMTs are faster than simulated results. Times to reach 1st overshoot are smaller at FRMT cases. The tendency to have more turning rate to port-side is more clearly seen in FRMT cases.
These differences are suspected to have relation with the difference of model scale and test condition of self-propulsion. As are mentioned in the previous sections, 1:83.74 and 1:39.44 models were used for FRMTs and captive manoeuvring model tests, respectively. Both tests were conducted at self-propulsion condition of each model scale, so it can be suspected that the rudder effectiveness at FRMT condition is larger than that at captive manoeuvring model test condition. Therefore, it can be expected that a FRMT model has better response to rudder movement, due to better rudder effectiveness condition.

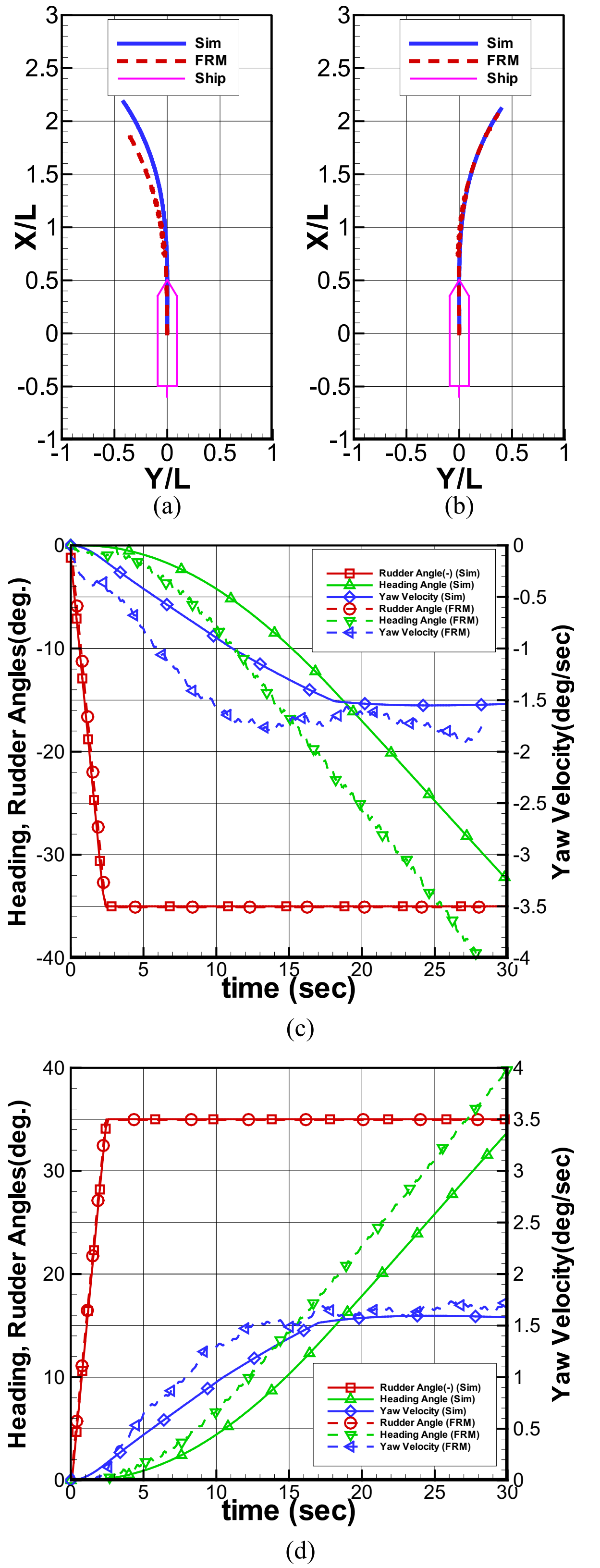

Figure 9. Comparison of 35° turning, H/T=1.2 ((a): PORT-trajectory, (b): STBD-trajectory, (c) PORT-Angles (d): STBD-Angles).

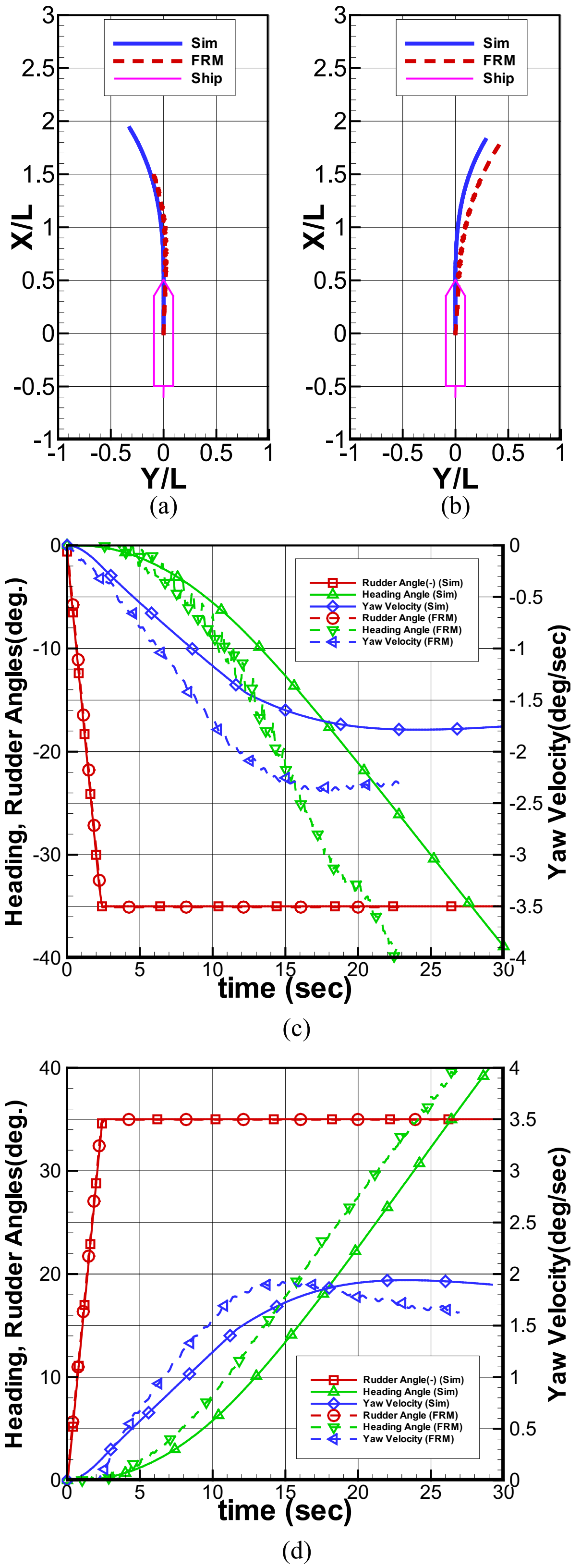

Figure 10. Comparison of 35° turning, H/T=1.2 ((a): PORT-trajectory, (b): STBD-trajectory, (c) PORT-Angles (d): STBD-Angles).

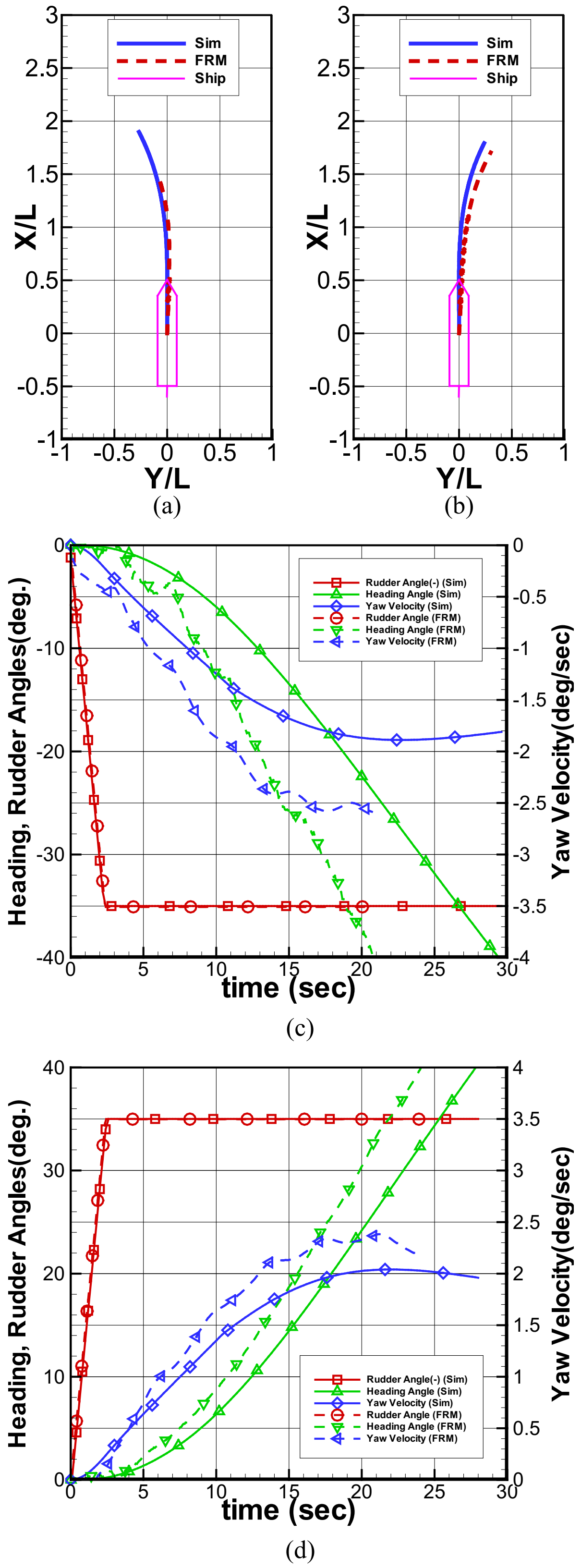

Figure 11. Comparison of 35° turning, H/T=1.2 ((a): PORT-trajectory, (b): STBD-trajectory, (c) PORT-Angles (d): STBD-Angles).

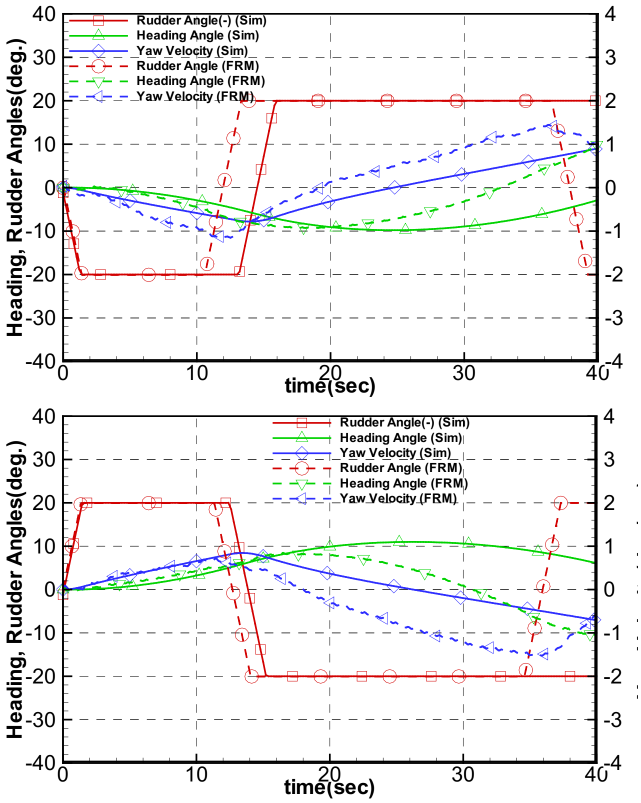

Figure 12. Comparison of 20°/5° zigzag, H/T=1.2 (upper: PORT, lower: STBD).

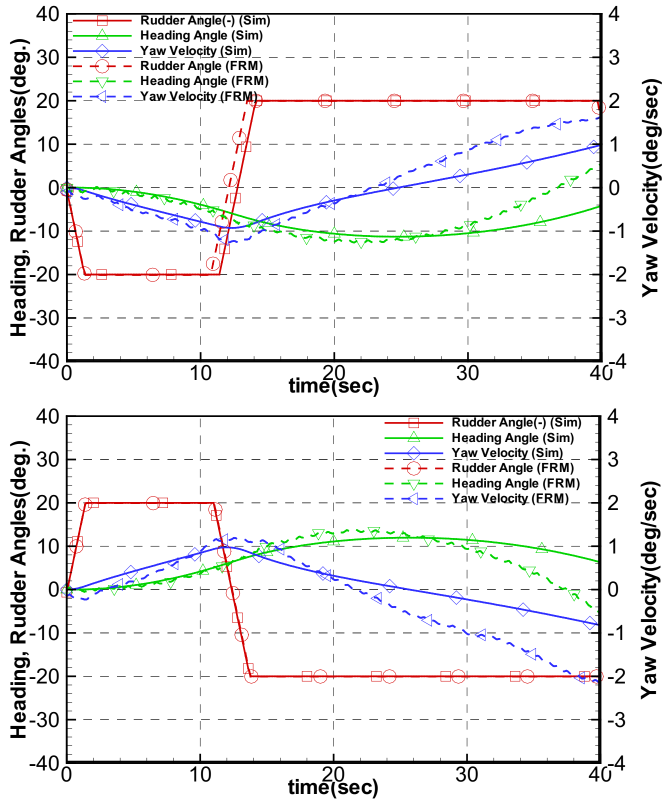

Figure 14. Comparison of 20°/5° zigzag, H/T=1.5 (upper: PORT, lower: STBD).

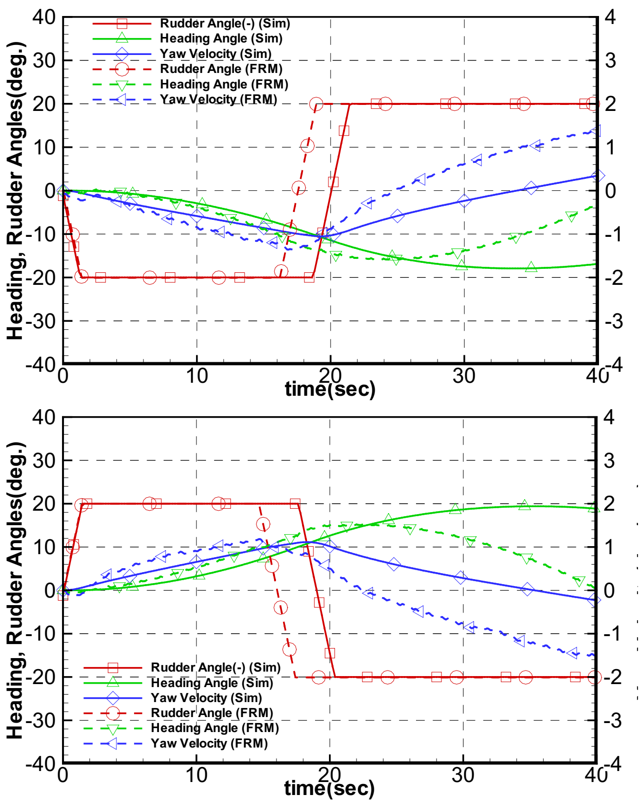

Figure 13. Comparison of 20°/10° zigzag, H/T=1.2 (upper: PORT, lower: STBD).

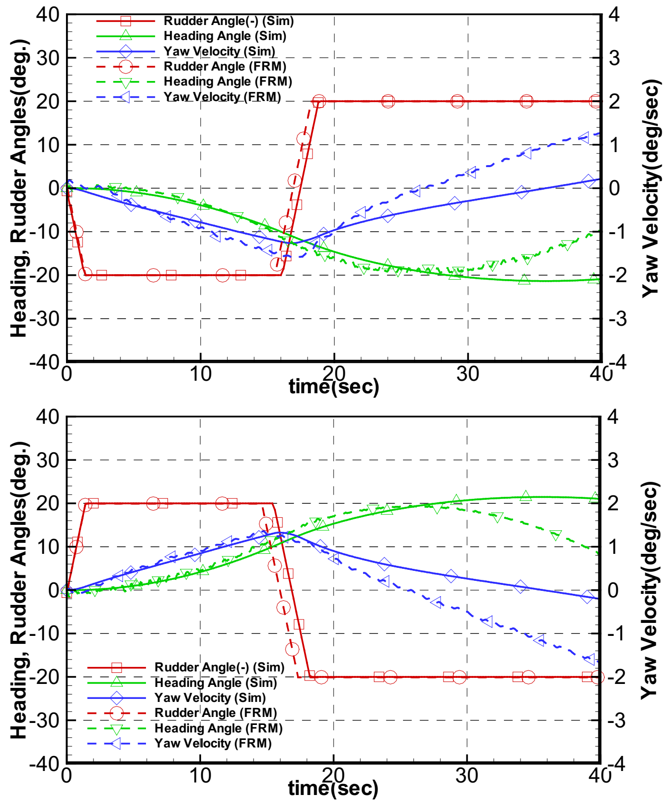

Figure 15. Comparison of 20°/10° zigzag, H/T=1.5 (upper: PORT, lower: STBD).

5 CONCLUSIONS

In this paper, the manoeuvrability of KVLCC 2 in shallow water region was investigated through experimental studies. FRMTs and captive manoeuvring model tests were conducted in KRISO's towing tank with false-bottom facility. The results of captive manoeuvring model tests were used to estimate the manoeuvring coefficients of KVLCC 2, and then numerical simulations of turning and zigzag manoeuvres were conducted based on the estimated coefficients. By comparisons between the simulation results and the results of FRMTs, these conclusions can be deduced:

- Both numerical simulations and FRMTs show the tendency that heading angle changes slower in relatively shallower water cases.
- Both numerical simulations and FRMTs show the well-known tendency that a ship becomes more stable as H/T becomes small.
- It can be suspected that the shallow water effect on manoeuvrability also grows exponentially according to water depth.

The heading changes of FRMTs were faster than simulated results, and tendencies to have more turning rate to port-side were more clearly seen in FRMT cases. These differences are suspected to have relation with the difference of model scale and propulsion conditions for each model.

6 ACKNOWLEDGEMENTS

This study was supported by the projects: "Enhancement of simulation technique for navigation of a ship in confined waterway [PES171E]" and "Development of core technology for the analysis & reproduction of maritime accidents through simulations [PES2200]".

7 REFERENCES

1. Kim, S. Y.; Yang, S.I.; Gong, I.Y.; Kim, B.Y. (1988). Development of manoeuvring evaluation procedure. *KIMM report, UCE4061328.D.*

2. Tonelli, R. (2014). Experimental fluid dynamics - free running model tests. *Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods (SIMMAN)* 2014, Copenhagen, Denmark.

3. Van, S. H.; Ahn H.; Lee, Y.Y.; Kim, C.M.; Hwang, S.; Park, Y., Moon, I.S.; Park, C.S.; Seol, H.; Kim, G.D.; Lee, C.J.; Cho, S.R.; Jeong, S.Y.; Rim, D.W.; Lee, J.; Ha, I.; Bae, S.G.; Hwang, I.S.; Kwon, K.J.; Lee, C.Y.; Gong, I.Y.; Kim, Y.G.; Son, N.S.; Kim, S.Y.; Yun, K.H. (2012). Development of New Experiment Technique for Towing Tank and Large Tunnel Facility. *KORDI report.*

4. Yeo, D. J.; Yun, K.; Kim, Y.G.; Ryu, K.H. (2012). Manoeuvring captive model tests of KCS container ship in shallow water. *Proceedings of the 12th Asian Conference on Maritime System and Safety Research (ACMSSR),* Philippines.

5. Yeo, D. J.; Yun, K.; Kim, Y.G.; Kim, S.Y. (2013). Benchmark HPMM test of KCS container ship in shallow water. *Proceedings of the 3rd International Conference on Ship Manoeuvring in Shallow and Confined Water,* Ghent, Belgium.

6. Yeo, D. J.; Yun, K.; Kim, Y.G. (2014). Manoeuvring Captive Model Tests of KVLCC 2 in Shallow Waters. *Proceedings of the 14th Asian Conference on Maritime System and Safety Research (ACMSSR),* Tainan, Taiwan.

7. Yeo, D. J.; Yun, K.; Kim, Y.G.; Park, B. (2015). Manoeuvring Captive Model Tests of KLNG in Shallow Waters. *Proceedings of the 15th Asian Conference on Maritime System and Safety Research (ACMSSR),* Tokyo, Japan.

8. Yun, K.; Yeo D.J.; Ryu, G.; Lee, Y.J. (2015). Experimental study on manoeuvrability of KVLCC2 in shallow water by free running model test. *Proceedings of the International Conference on Ship Manoeuvrability and Maritime Simulation (MARSIM)*, Newcastle, UK.

8 AUTHORS' BIOGRAPHIES

Dong Jin Yeo holds the current position of principal researcher at Korea Research Institute of Ships and Ocean Engineering. He is responsible for identification, performance prediction, and control of ocean vehicles' dynamics. His previous experience includes design of optimal inputs for the identification of ocean vehicles' dynamics, modeling of ocean vehicles' dynamics, etc.

Kunhang Yun holds the current position of senior researcher at Korea Research Institute of Ships and Ocean Engineering. He is responsible for manoeuvring simulation of maritime vehicles and maritime simulator.

Yeon-gyu Kim holds the current position of principal researcher at Korea Research Institute of Ships and Ocean Engineering. He is responsible for prediction of manoeuvrability of ships and submersible bodies.