Dongyoung Kim
Sang-Hyun Kim
Ji-Soo Han
Su-Jeong Kim
Kwang-Jun Paik

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A STUDY ON THE SENSITIVITY ANALYSIS OF THE HYDRODYNAMIC DERIVATIVES ON THE MANEUVERABILITY OF KVLCC2 IN SHALLOW WATER

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Summary

To assess the manoeuvrability of ships in shallow water at the early design stage, reliable simulation models which present shallow water effect are required. However, studies on the manoeuvrability of ship at low speeds in shallow water have been performed less than manoeuvrability in deep water. Also, the limitation of model that the effects of the keel clearance on manoeuvrability are applied to has been validated through previous studies. In this study, the manoeuvrability characteristics of the ship sailing in shallow water at low speed are evaluated by applying the mathematical model considering the shallow water effect. And the sensitivity analysis on shallow water manoeuvring simulation is performed in order to determine hydrodynamic derivatives which are necessary to be derived exactly due to the limitation of the shallow water model used in previous studies. Through this study, it could be confirmed that great importance of estimation of manoeuvrability could be found through the sensitivity index factor of hydrodynamic derivatives changing in the situation operating the shallow water at low speed.

Key words: *Sensitivity Analysis; Hydrodynamic Derivatives; Maneuverability; Mathematical Model; Shallow Water; Low Speeds;*

1. Introduction

The maneuverability of a vessel is an essential factor in its design stage. Accurate assessment of maneuverability is required according to maneuverability standards and the needs of the ship owner. In particular, because the maneuverability of a ship sailing in shallow water at low speeds is directly related to the safety, its assessment is important and must be considered seriously. However, fewer studies have been conducted on the maneuverability of ships at low speeds in shallow water than for ships in deep water. And also, the limitation of the model applied to study the effects of the keel clearance on maneuverability has been validated from previous studies. For this reason, the maneuvering simulation model must be verified for shallow water. Furthermore, one of the objectives of the 27th ITTC Maneuvering Committee was to study possible criteria for maneuvering in shallow water at low speeds. Additionally, in the SIMMAN 2014 workshop, free sailing model tests in shallow water were specified. Accordingly, there is a growing need to study the maneuverability of ships at low speeds in shallow water.

Sensitivity analyses are generally performed to specify the effects of hydrodynamic derivatives on maneuverability. The first study on the sensitivity analysis of a ship's maneuverability was conducted by Hwang (1980). Hwang defined the sensitivity index as the maximum difference of the state variable changes by changing the value of the hydrodynamic derivatives, and investigated their importance on maneuvering based on the sensitivity analysis. Rhee and Kim (1999) indicated a problem with sensitivity as originally defined by Hwang. The same authors also revised the original definition of sensitivity as proposed in Hwang's study as the total number of parameter variations in the entire process, and changed it to the analysis sensitivity of the hydrodynamic derivatives regarding various trial methods. Subsequently, a sensitivity analysis was conducted by Sen (2000) on the hydrodynamic derivatives of underwater vehicles, and additional studies have been completed since on the sensitivity analysis.

In this study, the maneuverability characteristics of the ship sailing in shallow water at low speeds are evaluated by applying the maneuvering and motion model, considering the shallow water impact. Additionally, a sensitivity analysis on the simulation of shallow water maneuvering is performed in order to determine the hydrodynamic derivatives that are necessary to be derived exactly due to the limitation of the shallow-water model used in previous studies. An Abkowitz-type mathematical model is used to simulate maneuvering and ship motion in deep water, and the maneuverability prediction results in deep water are compared with the study of Otzen et al. (2008) in order to verify the maneuvering simulation. A shallow-water model is selected to include the effect of shallow waters in the hydrodynamic derivatives, thereby affecting significantly the maneuvering by using the sensitivity analyses results. Through this study, the maneuvering motion characteristics of a ship sailing at low speeds in shallow-water areas are confirmed by configuring a low-speed maneuvering mathematical model in shallow-water areas. Moreover, performing a sensitivity analysis for deep-water and shallow-water areas, the influence of the hydrodynamic derivatives can be determined depending on the operation conditions.

2. Principal particulars of KVLCC2

KVLCC2 is used as one of the case vessels in the SIMMAN 2008 and the SIMMAN 2014 workshops for comparing the estimation of maneuverability with other research institutes. The main particulars of KVLCC2 are presented on Table 1. The model test results are derived from the PMM test, which was performed using a 1:58 scale model ship at MOERI in 1999, and which considered only deep-water conditions. The values of the hydrodynamic derivatives presented in the Abkowitz-type mathematical model (Abkowitz, 1964) are obtained by analyzing the model test results.

Table 1 Principal dimensions of KVLCC2 (SIMMAN2008)

L_{pp}	320.0 m
B	58.0 m
D	30.0 m
T	20.8 m
∇	312622 m^3
C_B	0.8098
U_0	15.5 knots (7.973m/s)
k_{zz} / L_{pp}	0.25
x_G'	0.0348

3. Equation of manoeuvring motion

3.1 Coordinate system

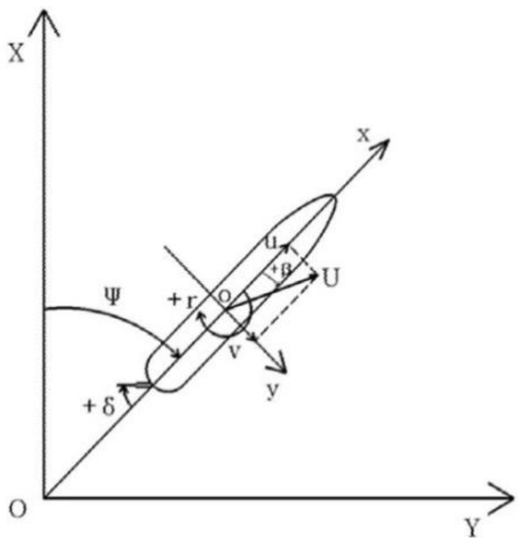

Fig. 1 Coordinate systems

The mathematical model describing ship maneuverability is based on three equations of motion and on an equation of ship propulsion equilibrium. The motion variables and the coordinate system for the vessel are presented in Fig. 1. Two right-handed coordinate systems are used, namely, an earth-fixed coordinate system $O-XY$, and a body-fixed coordinate system $o-xy$, where o is taken on the midship of the ship, and x, y, z-axes point towards the ship's bow, towards the starboard and vertically down wards respectively. The body-fixed axis is moving with the body, and the standard notation for position, forces, and velocities, are referred to SNAME and ITTC. Heading angle ψ is defined as the angle between X and x-axes, δ the rudder angle and r the yaw rate. u and v denote the velocity components in x and

y directions, respectively, drift angle at midship position β is defined by $\beta = \tan^{-1}(-v/u)$, and the total velocity $U = \sqrt{u^2 + v^2}$. Center of gravity of ship G is located at (x_G,0,0) in $o-xyz$ system.

3.2 Motion equation

Maneuverability of surface ships only considers the horizontal motions (surge, sway, and yaw). Basic dynamics of the maneuvering are described using the Euler–Lagrange equations of motion as listed in Eq. 1, and whole ship mathematical model is used.

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

3.3 Mathematical model

The Abkowitz-type polynomial model, which was utilized in the study of Otzen et al. (2008), is used for maneuvering motion, and is described in accordance with Eq. 2 The equations of motion express the outcome of external forces and moments acting on the ship by using expansion terms up to the third order. In this way, the external forces acting on the hull in the longitudinal direction and the propulsion force which are expressed mathematically are equilibrated to maintain the approach speed under the condition that torque rich is not occurred. When a propeller inflow velocity is changed by the maneuvering motion of the ship, the propulsion force is altered and the speed of the ship is changed at the corresponding equilibrium speed.

$$\begin{aligned} X = {} & X_0 + X_u u + X_{uu} u^2 + X_v v + X_{vv} v^2 + X_r r \\ & + X_{rr} r^2 + X_{vr} vr + X_\delta \delta + X_{\delta\delta}\delta^2 + X_{u\delta} u\delta \\ & + X_{u\delta\delta} u\delta^2 + X_{v\delta} v\delta + X_{vv\delta} v^2\delta + X_{v\delta\delta} v\delta^2 \\ & + X_{r\delta} r\delta + X_{rr\delta} r^2\delta + X_{r\delta\delta} r\delta^2 + (X_{\dot{u}}\dot{u}) \\[6pt] Y = {} & Y_0 + Y_{0u} u + Y_v v + Y_{vv} v^2 + Y_{v|v|} v|v| \\ & + Y_{uv} uv + Y_r r + Y_{rrr} r^3 + Y_{vrr} vr^2 + Y_{r|v|} r|v| \\ & + Y_\delta \delta + Y_{\delta\delta}\delta^2 + Y_{\delta\delta\delta}\delta^3 + Y_{u\delta} u\delta + Y_{u\delta\delta} u\delta^2 \\ & + Y_{u\delta\delta\delta} u\delta^3 + Y_{v\delta} v\delta + Y_{|v|\delta} |v|\delta + Y_{v\delta\delta} v\delta^2 \\ & + Y_{r\delta} r\delta + Y_{rr\delta} r^2\delta + Y_{r\delta\delta} r\delta^2 + (Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r}) \\[6pt] N = {} & N_0 + N_{0u} u + N_v v + N_{vv} v^2 + N_{v|v|} v|v| \\ & + N_{uv} uv + N_r r + N_{rrr} r^3 + N_{vrr} vr^2 + N_{r|v|} r|v| \\ & + N_\delta \delta + N_{\delta\delta}\delta^2 + N_{\delta\delta\delta}\delta^3 + N_{u\delta} u\delta + N_{u\delta\delta} u\delta^2 \\ & + N_{u\delta\delta\delta} u\delta^3 + N_{v\delta} v\delta + N_{|v|\delta} |v|\delta + N_{v\delta\delta} v\delta^2 \\ & + N_{r\delta} r\delta + N_{rr\delta} r^2\delta + N_{r\delta\delta} r\delta^2 + (N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r}) \end{aligned} \tag{2}$$

4. Validation of manoeuvring simulation in deep water

4.1 Turning manoeuvre in deep water

In order to verify the turning ability of KVLCC2, numerical simulations on 35° starboard, and port turning test are conducted. Simulation results on the advance and tactical diameters of KVLCC2 are compared with the study of Otzen et al. (2008). These are presented in Table 2. The simulation model of the maneuvering motion was implemented using MATLAB, which is a simulation development environment program. The Euler method was used as the integral method. The Helm rate and the initial speed were set to 2.32 deg/s and 15.5 knots. Fig. 2 shows the trajectories about the starboard and port turns of the KVLCC2, and it is verified that the simulation results are similar to the study of Otzen et al.(2008). It is determined that a little error is occurred by integration method in simulation model because Euler integral has a weak point that error occurrence probability is high when the variation of the integrated value is large.

Table 2 Summary of turning test simulation results comparison with FORCE Technology values

Maneuvers		FORCE Technology	Present method
Turning Circle 35° to Port	Advance	1162 m (3.63 L)	1163 m (3.63 L)
	Tactical	1251 m (3.91 L)	1226 m (3.83 L)
Turning Circle 35° to Stbd	Advance	1264 m (3.95 L)	1245 m (3.89 L)
	Tactical	1294 m (4.04 L)	1244 m (3.88 L)

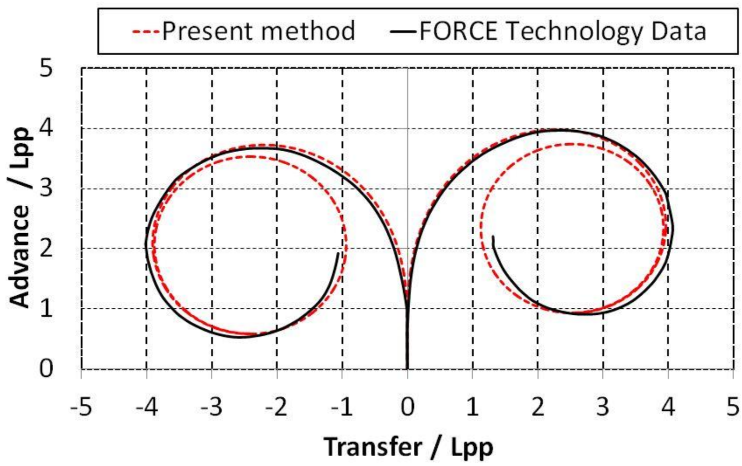

Fig. 2 35° port & starboard turning trajectories of KVLCC2

4.2 Zig-zag maneuverer in deep water

In order to verify the course changing ability of KVLCC2, numerical simulations on 10°/10° and 20°/20° zig-zag tests were conducted, and the simulation results are presented in Table 3. These results are compared to the results from the study of Otzen et al. (2008). Figs. 3~4 depict the heading angle variations of KVLCC2 according to time in the 10°/10° and 20°/20° zig-zag tests.

Table 3 Summary of zig-zag test simulation results comparison with FORCE Technology values

Maneuvers		FORCE Technology	Present method
10°/10° Zig-Zag	1st O.S. angle	7.0°	6.58°
	2nd O.S. angle	10.5°	8.71°
20°/20° Zig-Zag	1st O.S. angle	10.1°	10.04°

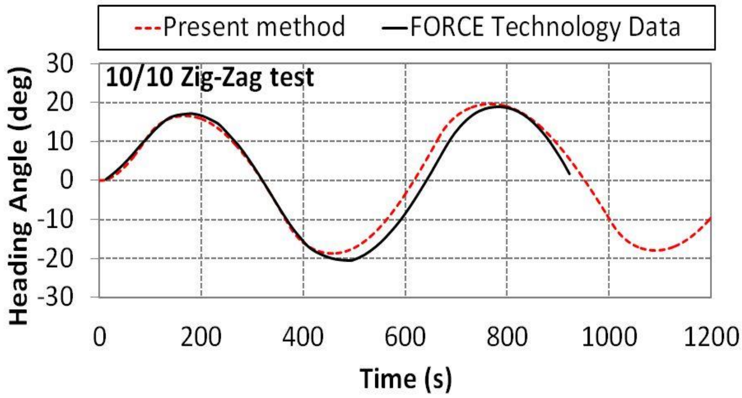

Fig. 3 10°/10° zig-zag test heading angle of KVLCC2

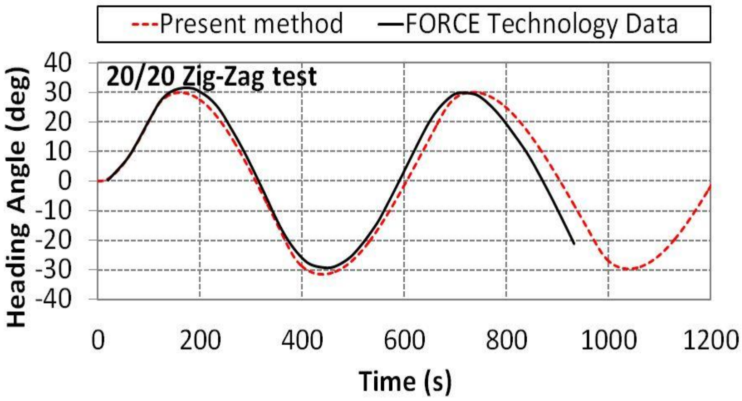

Fig. 4 20°/20° zig-zag test heading angle of KVLCC2

5. Manoeuvring simulation in shallow water

5.1 Shallow water mathematical model

Maneuvering descriptions of shallow water are more complicated due to the depth/draft (h/T) ratio, and the parameters have a more extended range. An arbitrary distinction is made in regard to water depths, as water is considered shallow when h/T is less than 1.5, and deep water when h/T is larger than 3. The ship senses the effect of the depth at shallow water. The reason for this is that the water depth changes the pressure distribution around the vessel and causes a decrease in the maneuverability.

A previous study on the effect of shallow water accounted for the effect of the water depth by incorporating equations in the mathematical models depending on the parameter. In the present study, the shallow-water mathematical models that can be applied to the Abkowitz-type polynomial model are adapted. These models reflect the particular nonlinear hydrodynamic derivatives, which have great effect on maneuverability, according to the sensitivity analysis results of deep-water maneuvering simulations. Accordingly, the expressions derived in the study of Ankudinov et al. (1990) are applied to the sway-yaw terms, surge terms, resistance, and propulsion terms. The added inertia coefficients proposed by Li and Wu are applied to the added mass and the added moment inertia terms. The validation of these expressions was investigated in the studies of Petersen (1999) and Vantorre (2001) about the verification of shallow water models on Esso Osaka.

Ankudinov et al. proposed a water-depth correction matrix based on the ratios reported in Clarke's expressions (1983), but was extended to a greater range of water depths and ship parameters. The expressions are valid for 1.085<h/T<5 and $C_B \le 0.85$. The shallow-water effects on the hull coefficients are given in accordance with Eqs. 3~5. The values of K_0, K_1, K_2 are predetermined constants that account for shallow water. (Ankudinov et al., 1983)

$$
\begin{aligned}
&\frac{Y_{\dot{v}}'}{(Y_{\dot{v}}')_\infty} = gv; \quad \frac{Y_{\dot{r}}'}{(Y_{\dot{r}}')_\infty} = gv; \quad \frac{N_{\dot{v}}'}{(N_{\dot{v}}')_\infty} = gv; \\
&\frac{N_{\dot{r}}'}{(N_{\dot{r}}')_\infty} = gnr; \quad \frac{Y_{v}'}{(Y_{v}')_\infty} = fyv; \quad \frac{Y_{r}'}{(Y_{r}')_\infty} = fyr \\
&\frac{N_{v}'}{(N_{v}')_\infty} = fnv; \quad \frac{N_{r}'}{(N_{r}')_\infty} = fnr
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
&\frac{Y_{v|v|}'}{(Y_{v|v|}')_\infty} = \frac{9}{4} fnv - \frac{5}{4}; \quad \frac{Y_{r|r|}'}{(Y_{r|r|}')_\infty} = fnr \\
&\frac{Y_{vrr}'}{(Y_{vrr}')_\infty} = \frac{Y_{r|v|}'}{(Y_{r|v|}')_\infty} = fyv \\
&\frac{N_{v|v|}'}{(N_{v|v|}')_\infty} = \frac{9}{4} fnv - \frac{5}{4}; \quad \frac{N_{r|r|}'}{(N_{r|r|}')_\infty} = gv \\
&\frac{N_{vrr}'}{(N_{vrr}')_\infty} = \frac{N_{r|v|}'}{(N_{r|v|}')_\infty} = gnr
\end{aligned}
\tag{4}
$$

$$\frac{X_{\dot{u}}'}{(X_{\dot{u}}')_\infty} = gv; \quad \frac{X_{rr}'}{(X_{rr}')_\infty} = gnr$$
$$\frac{X_{vr}'}{(X_{vr}')_\infty} = frv; \quad \frac{X_{vv}'}{(X_{vv}')_\infty} = frv \tag{5}$$

Where,

$$gv = K_0 + \frac{2}{3}K_1\frac{B_1}{T} + \frac{8}{15}K_2(\frac{B_1}{T})^2$$
$$gnr = K_0 + \frac{8}{15}K_1\frac{B_1}{T} + \frac{40}{105}K_2(\frac{B_1}{T})^2$$
$$fyv = 1.5fnv - 0.5$$
$$fyr = K_0 + \frac{2}{5}K_1\frac{B_1}{T} + \frac{24}{105}K_2(\frac{B_1}{T})^2 \tag{6}$$
$$fnv = K_0 + K_1\frac{B_1}{T} + K_2(\frac{B_1}{T})^2$$
$$fnr = K_0 + \frac{1}{2}K_1\frac{B_1}{T} + \frac{1}{3}K_2(\frac{B_1}{T})^2$$

Li and Wu (1990) formulated the shallow-water effect on added inertia coefficients, as indicated by Eq. 7.

$$\frac{m_{11}}{m_{11\infty}} = 1 + \frac{3.77 + 1.14\frac{B}{T} - 0.233\frac{L}{T} - 3.43C_B}{F^{1.30}}$$
$$\frac{m_{22}}{m_{22\infty}} = 1 + \frac{0.413 + 0.032\frac{B}{T} + 0.0129(\frac{B}{T})^2}{F^{0.82}} \tag{7}$$
$$\frac{m_{66}}{m_{66\infty}} = 1 + \frac{0.413 + 0.0192\frac{B}{T} + 0.00554(\frac{B}{T})^2}{F^{0.82}}$$

$F = h/T - 1$ is a function of water depth and draft, $B_1 = C_B B(1 + B/L)^2$ is a function of breadth, length and block coefficient. The standard SNAME expression for the resistance and propulsion contributions to the longitudinal force is shown in Eq. 8, and η being a relative propeller advance ratio, Ankudinov et al. (1990) published expressions that are summarized in accordance with Eq. 9 for the water depth dependency of the coefficients.

$$\frac{1}{2}\rho L^2 U^2 (a_p + b_p\eta + c_p\eta^2) \tag{8}$$

$$\frac{a_p}{a_{p\infty}} = \frac{1}{4}fnr + \frac{3}{4}; \quad \frac{b_p}{b_{p\infty}} = \frac{c_p}{c_{p\infty}} = \frac{1}{8}fnr + \frac{7}{8} \tag{9}$$

5.2 Turning maneuvers in shallow water

In the SIMMAN 2014 workshop, free sailing model tests for shallow water depths were specified. Zig-zag tests (10°/2.5° and 20°/5°), as well as a 35° turning test were performed. The approach speed was 7 knots, which corresponds to a Froude number of 0.064. The shallow water tests have been conducted at h/T=1.2, 1.5, and 1.8. For that reason, 35° turning test simulations are conducted at shallow water with h/T ratios of 1.2, 1.5, and 1.8, and with an approach speed of 7 knots. In a similar manner to the previous study on the maneuverability in shallow water, the simulation result indicates that increased shoal depths of sailing areas lead to larger turning circles. The simulation results are not compared with SIMMAN 2014 workshop data because the free model test results in shallow water will not be available until after publishing of validation data of SIAMMN 2014 workshop.

Table 4 Summary of turning test simulation results depending on the water depth

h/T	1.2	1.5	1.8	Deep water
Advance	2243 m (7.63 L)	1477 m (4.62 L)	1298 m (4.06 L)	1163 m (3.63 L)
Tactical Diameter	3439 m (10.75 L)	1838 m (5.74 L)	1487 m (4.65 L)	1226 m (3.83 L)

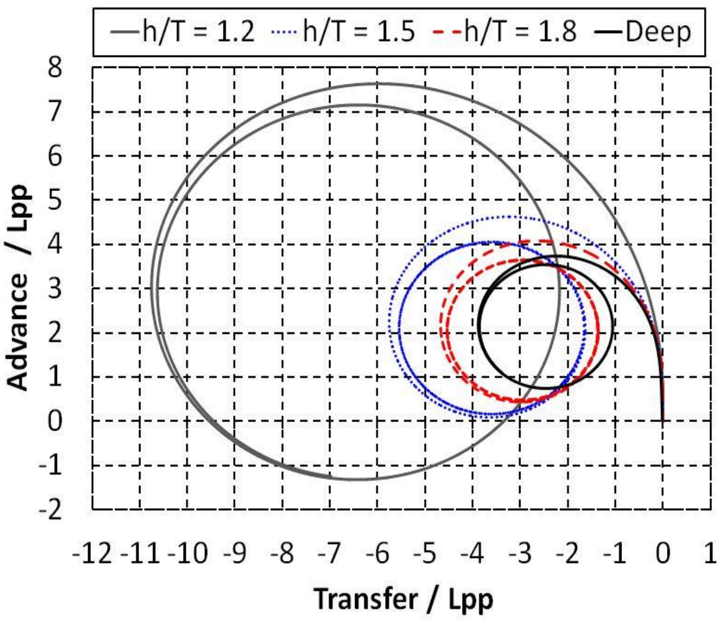

Fig. 5 35° Port turning trajectory depending on the water depth

5.3 Zig-zag manoeuvres in shallow water

10°/2.5° and 20°/5° zig-zag tests were conducted at shallow water with an approach speed of 7.0 knots and h/T ratios of 1.2, 1.4, 1.8. The results are given in Figs. 6~7. The overshoot angles decrease and the initial turning time increases at shallower waters.

Table 5 Summary of zig-zag test simulation results depending on the water depth

h/T	1.2	1.5	1.8	Deep water
1st Overshoot (10°/2.5°)	0.44°	1.22°	1.57°	1.87°
2nd Overshoot (10°/2.5°)	0.37°	1.48°	2.22°	2.96°
1st Overshoot (20°/5°)	0.91°	2.35°	2.80°	3.52°
2nd Overshoot (20°/5°)	1.01°	3.42°	4.89°	6.26°

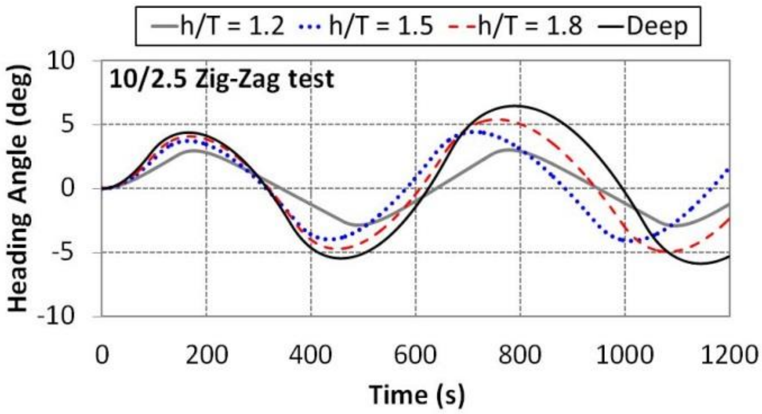

Fig. 6 10°/2.5° Zig-zag test heading angle depending on the water depth

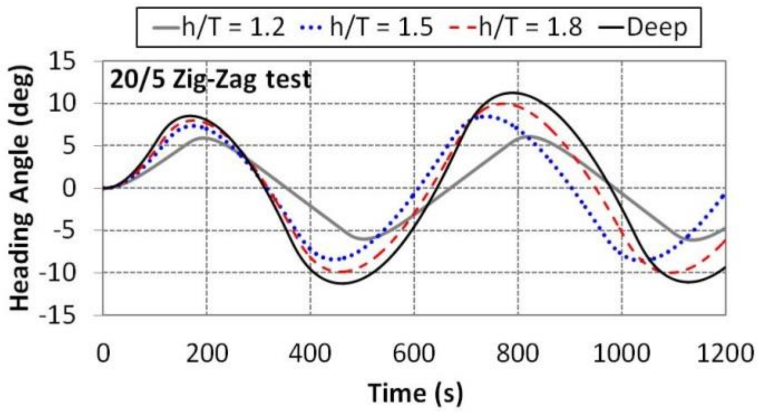

Fig. 7 20°/5° Zig-zag test heading angle depending on the water depth

5.4 Variation of hydrodynamic derivatives in shallow water

The methods presented in the studies of Kvale (2014) which is partly based on Falch (1982), Clark (1997), and Kijima (1990) and the model test results of Yasukawa (2014) are used to obtain shallow water ratios. Clarke's formulae are not valid for h/T<1.2. Kijima's ratio for Y_r is not given explicitly but includes non-dimensional mass and surge acceleration derivatives (Vantorre, 2001). Therefore, these are not incorporated in the ratios. The conclusion also included that Kijima's formulae and the method partly based on Falch generally tend to underestimate the most of linear hydrodynamic coefficients.

According to the ratios of the coefficients between deep and shallow water, the shallow water effects on the hydrodynamic coefficients are clearly shown giving larger damping forces when the water becomes shallower. The value of the formula of the present study increases gradually at shallow water, and the values of Y_v, Y_r, N_v, N_r are similar with experiment results of Yasukawa when the $h/T \geq 1.5$. However, the values of Y_v, N_v, N_r are overestimated as well as Clarke's formulae and the value of Y_r is underestimated in the case of h/T=1.2 compared with the experiment results. It is confirmed that established empirical formulas have low accuracy at h/T=1.2. For these reasons, it is considered that these inaccuracies can derive overestimated maneuvering simulation results. Therefore, a sensitivity analysis for the shallow water maneuvers is conducted on the case of h/T=1.5.

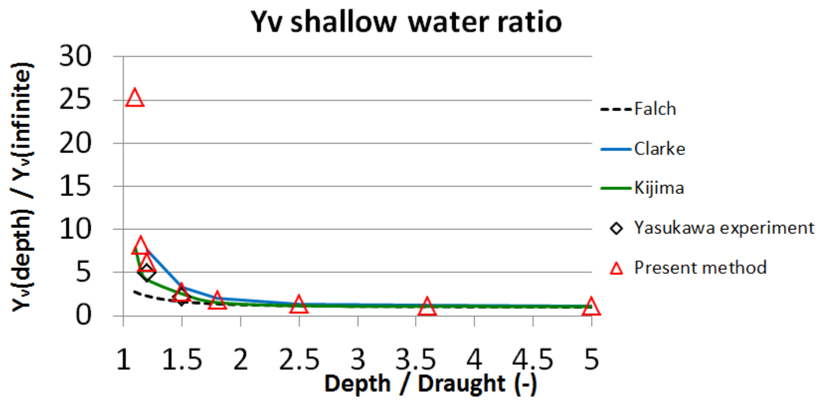

Fig. 8 Shallow water ratio of Y_v

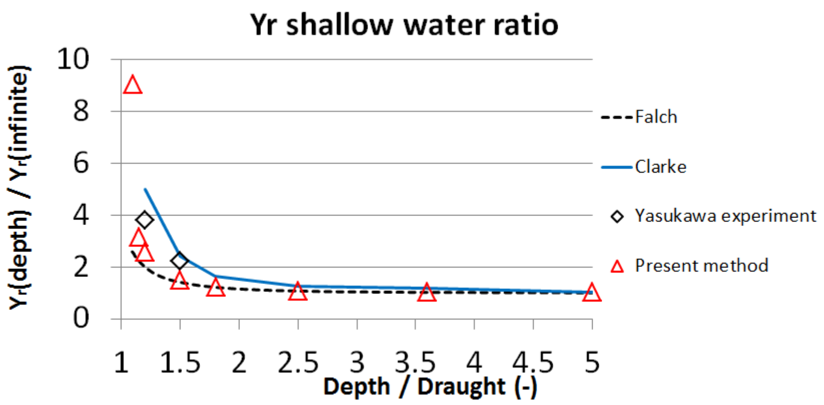

Fig. 9 Shallow water ratio of Y_r

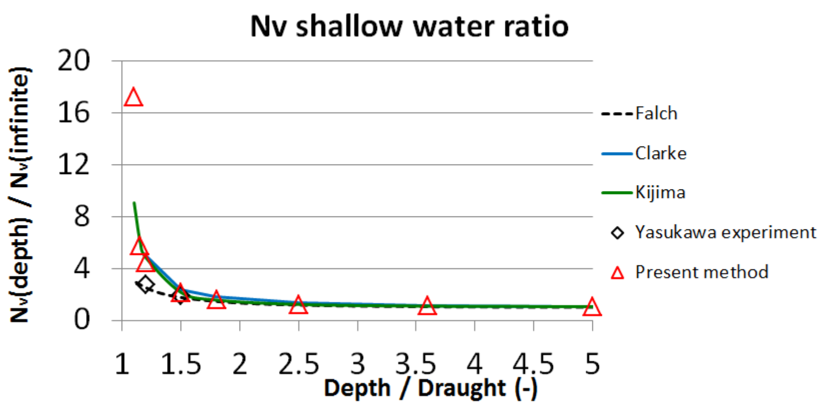

Fig. 10 Shallow water ratio of N_v

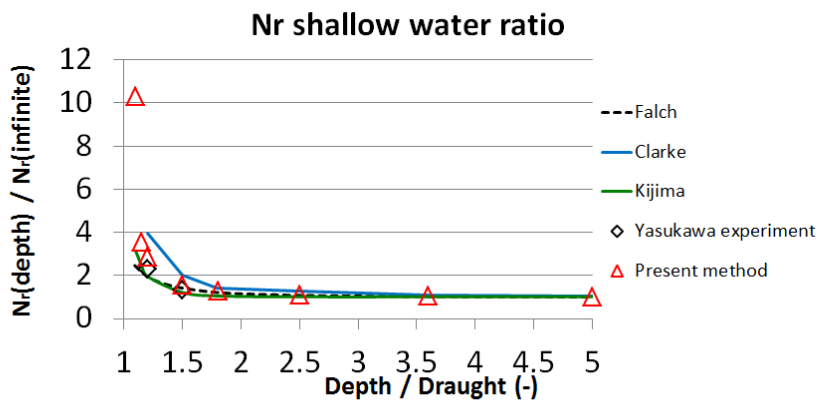

Fig. 11 Shallow water ratio of N_r

6. Sensitivity analysis method and results

The sensitivity analysis for deep water maneuvers is performed to compare the sensitivity index with that for shallow water maneuvers. In order to conduct sensitivity analysis, the original value of the coefficient is increased and decreased by 20%, and was used into simulate same maneuvers. Each coefficient is changed separately while the evaluation of its sensitivity is measured from the simulator maneuver. The simulated maneuvers performed in the sensitivity analysis are turning circles and zig-zag maneuvers. In case of sensitivity analysis for shallow water, the same sensitivity analysis method is applied as that used in the sensitivity analysis of the deep water maneuvering simulation. The simulated maneuvers performed in the sensitivity analysis are 35° turning circles, 10°/2.5°, and 10°/5°, zig-zag maneuvers with an h/T ratio of 1.5 since the maneuvers with an h/T ratio of 1.2 are overestimated.

6.1 Sensitivity analysis method and characteristics value

The sensitivity represents the output variations according to the input data variations. Correspondingly, the sensitivity analysis is necessary to grasp the contribution of each input parameter on the entire system. The method of Sen (2000) is adopted in this study to verify the variation of the output caused by changes in the each of the input variables.

The values of the hydrodynamic derivatives are used as input parameters, and the advance, tactical diameters, and the overshoot angle, which are derived from the numerical simulations of turning and zig-zag tests, are used as the output data. A Sensitivity index S is defined in accordance with Eq. 10.

$$S = \frac{\left|R - R^*\right| / R^*}{\left|H - H^*\right| / H^*} \tag{10}$$

where H^* represents the basic set of coefficient values that have been determined from theory or experiment, and R^* are the corresponding maneuvering response parameters. Therefore, S provides a measure of the changes in the response R resulting from corresponding changes in the input coefficients H.

$$\begin{aligned} &H = \{h_j\}, \qquad R = \{r_i\} \\ &\{h_j\} = \{h^*\} \times \{c_m\} \\ &c_m = \begin{cases} 1 & m \neq j \\ (1 + k/100) & m = j \end{cases} \end{aligned} \tag{11}$$

i and j are the number of coefficients in the mathematical model and the different maneuvering response parameters, respectively. For a particular type of definitive maneuvering with a given combination of initial conditions and control parameters, S is a matrix with elements S_{ij} denoting the sensitivity of the i^{th} response parameter to the j^{th} coefficient. The different values of the response parameters r_i can be estimated from simulating the maneuvering motion. To determine S_{ij} for a k% change in the j^{th} coefficient, a maneuvering simulation is performed by changing the coefficient by the required amount so that all the output parameters are determined.

$$S_{ij} = \frac{\left|r_i - r_i^*\right| / r_i^*}{c_j - 1} = \frac{\left|r_i - r_i^*\right| / r_i^*}{k/100} \tag{12}$$

The value of k, which determined the variation of hydrodynamic derivatives, is taken to be equal to 20% for the sensitivity analysis of the present study, because the hydrodynamic forces and derivatives are predicted within 20% of error by using CFD tool and viscous flow calculations in generally. (Zuo, et al., 2010, Toxopeus et al., 2013, Sung, et al., 2015) Furthermore, the sensitivity index is identical because the variation of response parameters is linearly increased or decreased when the k is increased or decreased according to the study of Furukawa (2016).

6.2 Sensitivity analysis results of turning manoeuvre in deep water

The following table presents only a part of the large sensitivity index values that are derived from the sensitivity analysis results of the advance and tactical diameters of the turning maneuver in deep water. From Figs. 12~ 13, it is confirmed that the values of N_r', N_v', N_d' wield a significant influence upon execution of the turning maneuver, Also Y_v', N_{ud}', Y_r' have a relatively major influence. These indicate that damping terms have a more significant effect on the turning maneuver than added mass terms. Additionally, the tactical diameter is more affected by the variation of the hydrodynamic derivatives than advance in the case of the turning test.

Table 6 Maximum sensitivity indices of turning maneuver in deep water

Advance		Tactical Diameter	
Derivative	Max. S.	Derivative	Max. S.
N_r'	0.45	N_v'	0.57
N_v'	0.44	N_r'	0.49
N_d'	0.31	N_{ud}'	0.21
N_{ud}'	0.08	N_d'	0.21
Y_v'	0.08	Y_v'	0.16
X_0'	0.08	$N_{r\|v\|}'$	0.14
$Y_{\dot{v}}'$	0.07	Y_r'	0.13
Y_r'	0.07	X_{vr}'	0.10
$N_{r\|v\|}'$	0.07	Y_d'	0.10
Y_d'	0.067	X_0'	0.09

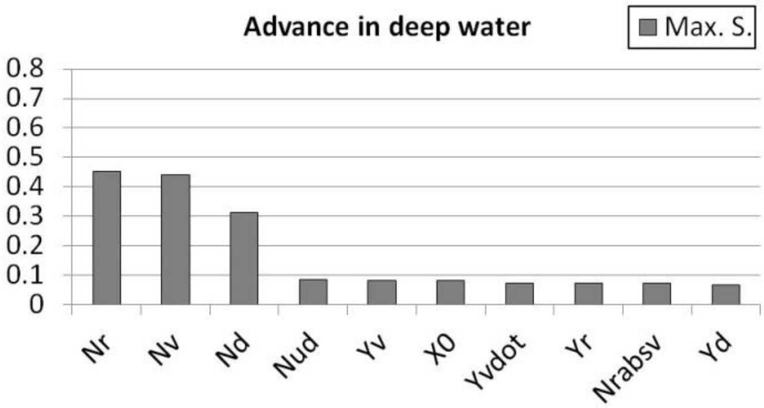

Fig. 12 Maximum sensitivity indices of advance in deep water

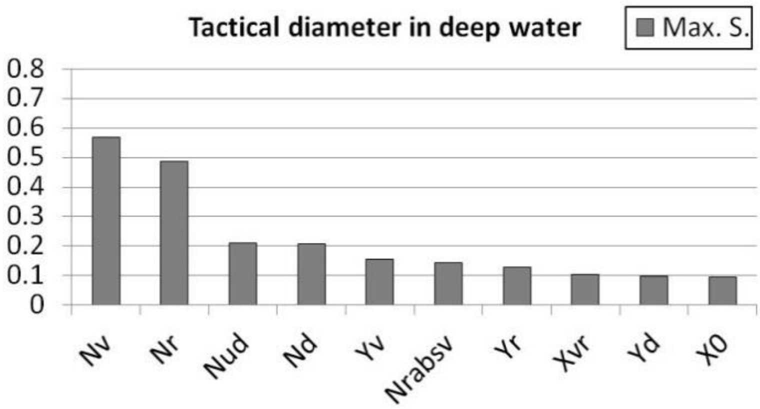

Fig. 13 Maximum sensitivity indices of tactical diameter in deep water

6.3 Sensitivity analysis results of zig-zag manoeuvre in deep water

The following table presents only part of the large sensitivity index values that are derived from the sensitivity analysis results of the 1st and 2nd overshoot angles of the 10°/10° zig-zag maneuver, and the 1st overshoot angle of the 20°/20° zig-zag maneuver in deep water. Figs. 14~16 confirm that not only the values of N_v', N_r', Y_v', Y_r' but also Y_d', N_d' have a significant effect on the zig-zag maneuver. Based on these results, the values of the linear hydrodynamic derivatives have a significant impact on the zig-zag maneuvers. Furthermore, the added mass and the added moment of inertia terms have more effect on the zig-zag maneuvers than the turning maneuver. Thus, it is verified that the zig-zag maneuvers are more sensitive to changes in the hydrodynamic derivatives than the turning maneuver. Through the results that were derived from the sensitivity analysis of each maneuvering motion, the 35° turning maneuver and the 20°/20° zig-zag maneuver have lower sensitivity index values than the 10°/10° zig-zag maneuver. Consequently, it is verified that the effect of the nonlinear hydrodynamic derivatives on the maneuvering motion is smaller in the case of the large rudder angle maneuvering motion.

Table 7 Maximum sensitivity analysis indices of zig-zag maneuvers in deep water

10°/10° zig-zag				20°/20° zig-zag	
1st Overshoot		2nd Overshoot		1st Overshoot	
Derivative	Max. S.	Derivative	Max. S.	Derivative	Max. S.
N_v'	2.65	N_v'	3.27	N_v'	1.65
N_r'	2.25	N_r'	2.58	N_r'	1.48
Y_v'	1.32	Y_v'	1.61	Y_v'	0.63
Y_r'	0.80	Y_r'	0.91	Y_r'	0.40
N_d'	0.29	$N_{\dot{r}}'$	0.23	Y_d'	0.17
$Y_{\dot{v}}'$	0.20	$N_{r\|v\|}'$	0.21	$N_{r\|v\|}'$	0.16
$N_{\dot{r}}'$	0.20	$Y_{v\|v\|}'$	0.19	$N_{\dot{r}}'$	0.16
Y_d'	0.19	Y_d'	0.19	$Y_{\dot{v}}'$	0.10
$N_{r\|v\|}'$	0.13	X_0'	0.16	$Y_{v\|v\|}'$	0.10
N_0'	0.11	N_d'	0.15	$Y_{r\|v\|}'$	0.07
$Y_{v\|v\|}'$	0.11	$Y_{r\|v\|}'$	0.12	N_{dd}'	0.06
$Y_{r\|v\|}'$	0.08	N_{uv}'	0.11	Y_{vrr}'	0.05

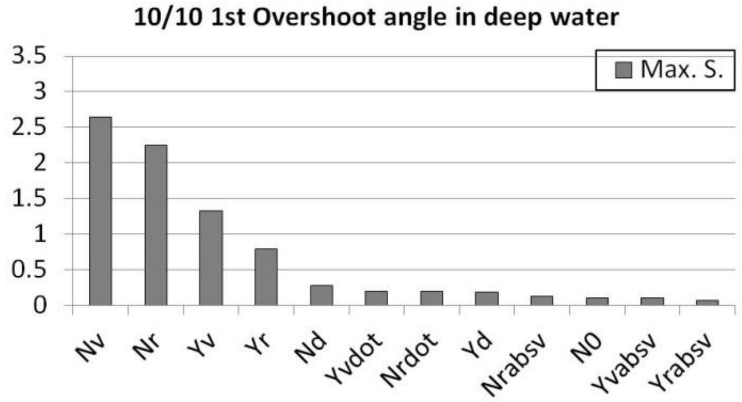

Fig. 14 Maximum sensitivity indices of 1st overshoot angle in deep water

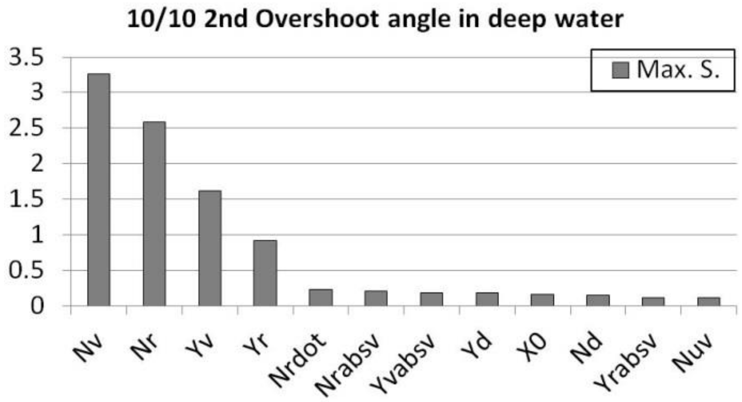

Fig. 15 Maximum sensitivity indices of 2st overshoot angle in deep water

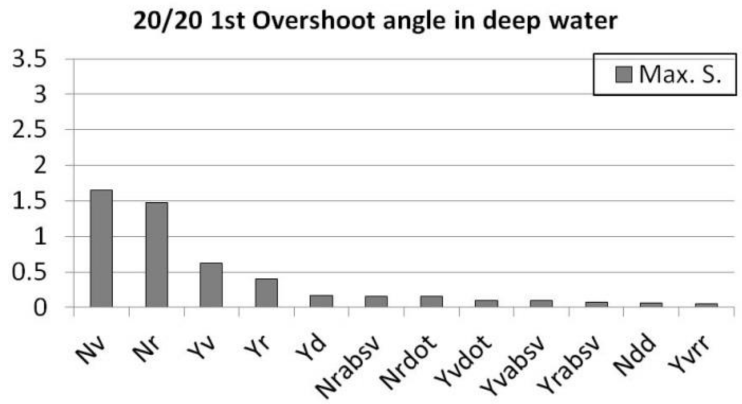

Fig. 16 Maximum sensitivity indices of 1st overshoot angle in deep water

6.4 Sensitivity analysis results of turning manoeuvre in shallow water

The following table presents only a part of the large sensitivity index values that is derived from the sensitivity analysis results of the advance and tactical diameters of the turning maneuver in shallow water. Figs. 17~18 confirm that the values of N_v', N_r', N_d' have a significant effect on the shallow water turning maneuver in the same manner the deep-water turning maneuver does. Based on the results, all of the sensitivity index values are increased in comparison to the deep water turning maneuver. Particularly, the values of Y_v', Y_r', Y_d' are significantly increased but the hydrodynamic derivatives of the added inertia terms are decreased exceptionally.

Table 8 Maximum sensitivity indices of turning maneuver in shallow water

Advance		Tactical Diameter	
Derivative	Max. S.	Derivative	Max. S.
N_r'	0.63	N_r'	0.71
N_v'	0.48	N_v'	0.53
N_d'	0.43	Y_v'	0.31
Y_v'	0.20	N_d'	0.28
Y_r'	0.17	Y_r'	0.25
Y_d'	0.16	N_{ud}'	0.20
X_0'	0.11	X_0'	0.17
N_{ud}'	0.10	Y_d'	0.16
N_{dd}'	0.07	X_{vr}'	0.11
$Y_{\dot{v}}'$	0.06	X_u'	0.08

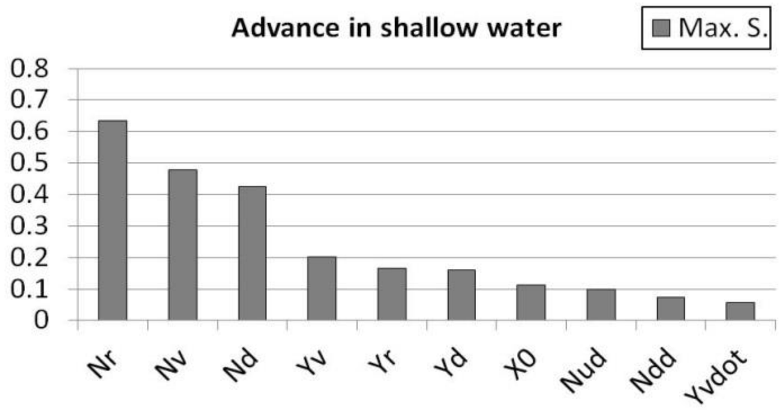

Fig. 17 Maximum sensitivity indices of advance in shallow water

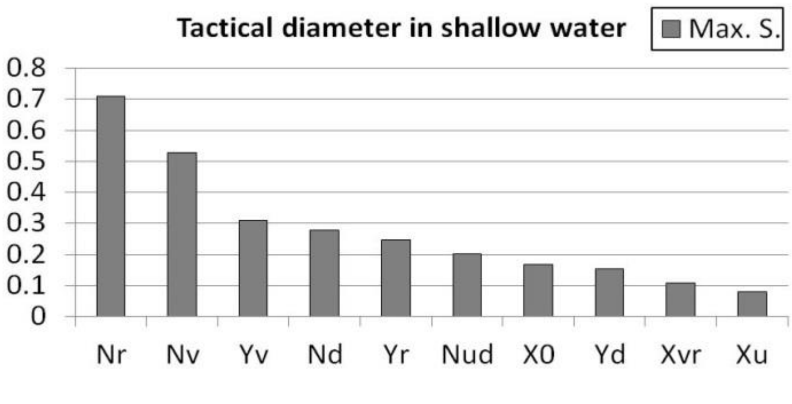

Fig. 18 Maximum sensitivity indices of tactical diameter in shallow water

6.5 Sensitivity analysis results of zig-zag manoeuvres in shallow water

The following table presents only a part of the maximum sensitivity index values that are derived from the sensitivity analysis results of the 1st and 2nd overshoot angles of the 10°/2.5° and 20°/5° zig-zag maneuvers in shallow water. The results of Figs. 19~22 confirm that the values of N_v', N_r', Y_v', Y_r' have a significant effect on the zig-zag maneuver in a manner similar to the turning maneuver in shallow water. Through the results, all of the sensitivity index values are decreased compared to the deep water zig-zag maneuver. Specifically, the hydrodynamic derivatives of the rudder force and inertia terms, such as $Y_d', \dot{N}_r'$, are maintained at similar or slightly increased values.

Table 9 Maximum sensitivity analysis indices of zig-zag maneuvers in shallow water

10°/2.5° zig-zag				20°/5° zig-zag			
1st Overshoot		2nd Overshoot		1st Overshoot		2nd Overshoot	
Derivative	Max. S.	Derivative	Max. S.	Derivative	Max. S.	Derivative	Max. S.
N_r'	1.68	N_r'	2.46	N_r'	1.55	N_r'	2.11
N_v'	1.07	N_v'	1.53	N_v'	0.98	N_v'	1.30
Y_v'	0.65	Y_v'	1.06	Y_v'	0.56	Y_v'	0.82
Y_r'	0.48	Y_r'	0.77	Y_r'	0.41	Y_r'	0.62
$N_{\dot{r}}'$	0.33	$N_{\dot{r}}'$	0.45	Y_d'	0.33	$N_{\dot{r}}'$	0.40
Y_d'	0.31	Y_d'	0.45	$N_{\dot{r}}'$	0.29	Y_d'	0.32
$Y_{\dot{v}}'$	0.17	$Y_{\dot{v}}'$	0.14	N_d'	0.16	N_d'	0.13
N_0'	0.12	N_d'	0.12	$Y_{\dot{v}}'$	0.13	N_{dd}'	0.08
N_{dd}'	0.07	N_0'	0.10	N_{dd}'	0.10	$Y_{\dot{v}}'$	0.07
$Y_{\dot{r}}'$	0.06	Y_0'	0.07	N_0'	0.06	$N_{\dot{v}}'$	0.07
Y_0'	0.06	$N_{\dot{v}}'$	0.07	$N_{r\|v\|}'$	0.05	$N_{r\|v\|}'$	0.03
$N_{\dot{v}}'$	0.05	Y_{ud}'	0.06	$Y_{\dot{r}}'$	0.04	$Y_{r\|v\|}'$	0.03

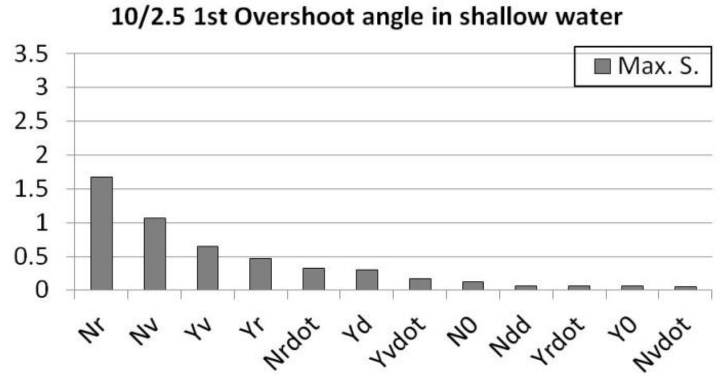

Fig. 19 Maximum sensitivity indices of 1st overshoot angle in shallow water

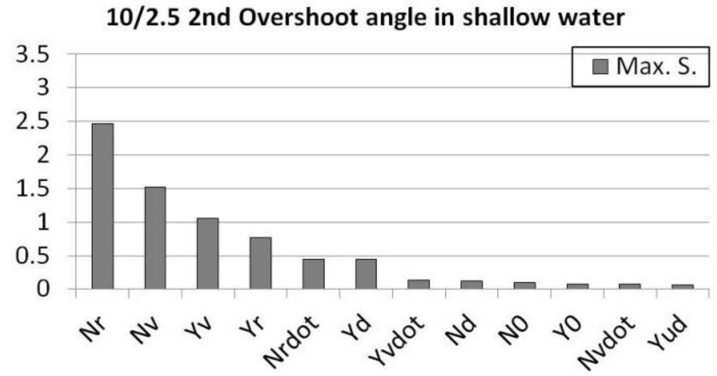

Fig. 20 Maximum sensitivity indices of 2nd overshoot angle in shallow water

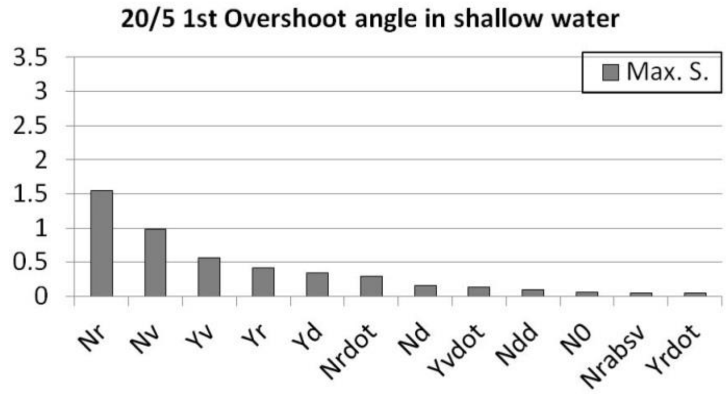

Fig. 21 Maximum sensitivity indices of 1st overshoot angle in shallow water

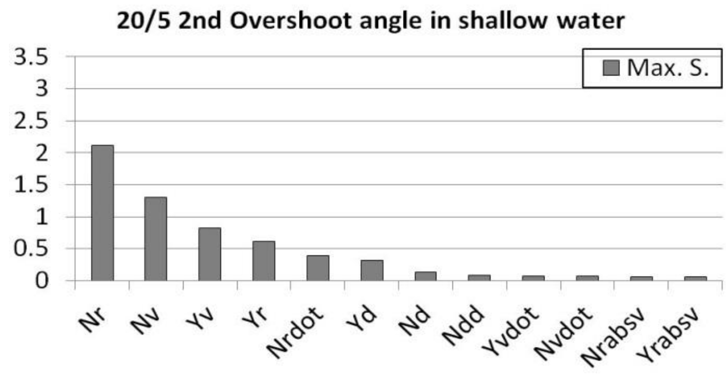

Fig. 22 Maximum sensitivity indices of 2nd overshoot angle in shallow water

6.6 Discussion of sensitivity analysis results

The sensitivity analysis results for deep water maneuvers are compared with the sensitivity index with that for shallow water maneuvers. The simulated maneuvers performed in the sensitivity analysis are turning maneuvers and zig-zag maneuvers with the h/T ratio of 1.5. In case of sensitivity analysis for shallow water, 7knots approach speed is applied as simulation condition to consider the low operating speed of the ship in the shallow water.

In an event of turning maneuver, the advance reacts sensitively to the tactical diameter in the turning maneuver. The sensitivity analysis results of turning maneuver in shallow water are indicated as similar to these in deep water. Additionally, most of sensitivity index values are increased in comparison to the deep water turning maneuver but the hydrodynamic derivatives of the added inertia terms are decreased exceptionally. From the results of sensitivity analysis on the zig-zag maneuvers, it is confirmed that 2^{nd} overshoot angle is more affected by the variation of hydrodynamic derivatives that 1^{st} overshoot angle and zig-zag maneuvers are more sensitive to variation of the hydrodynamic derivatives than turning maneuver. The sensitivity analysis results of zig-zag maneuvers in shallow water are indicated as similar to these in deep water. Furthermore, most of sensitivity index values are decreased compared to the deep water zig-zag maneuver, but the hydrodynamic derivatives of the rudder force and inertia terms are maintained at similar or slightly increased.

7. Conclusion

This study performed a sensitivity analysis for deep water and shallow water, and the influence of the hydrodynamic derivatives on the maneuverability of KVLCC2 is determined. An Abkowitz-type mathematical model was used to simulate maneuvers and maneuverability prediction, and elicited results in deep water were compared to the study of Otzen et al.(2008) in order to verify the maneuvering simulation model. A shallow water model was selected to include the shallow-water effect in the hydrodynamic derivatives, and was shown to significantly affect maneuvering based on the sensitivity analysis results. In order to conduct the sensitivity analysis, the maneuvering simulation was performed by changing the input parameters, and the characteristic values of the maneuvers were compared at each case.

The maneuverability of the ship in shallow water was investigated by formulating the mathematical model for shallow water and low-forward speeds. The simulation results showed that it is necessary to revise the shallow-water model since the hydrodynamic derivatives are overestimated for h/T=1.2. The sensitivity analysis showed that zig-zag maneuvers are more sensitive to variations of the hydrodynamic derivatives than the turning maneuver. In the turning maneuver, advance reacts sensitively to the tactical diameter. In the zig-zag maneuvers, the 2nd overshoot angle was more affected by the variation of the hydrodynamic derivatives than the 1st overshoot angle. Accordingly, it was shown that the zig-zag maneuver with a small rudder angle was sensitive to the variation of the hydrodynamic derivatives. Furthermore, the sensitivity index values of N_r', N_v', Y_v', Y_r' on the turning maneuver in shallow waters were larger compared to deep waters. Particularly, the sensitivity index values of Y_r', Y_v', Y_d' were found to be significantly increased. The sensitivity index values of N_r', N_v', Y_v', Y_r' on the zig-zag maneuver in shallow water were smaller than in deep water but the sensitivity index values of $Y_d', \dot{N}_r'$ were maintained at similar or slightly increased values. The sensitivity analyses results show that the high importance of the estimation of the maneuverability could be found through the sensitivity index of the hydrodynamic derivatives at various low-forward speeds in shallow water.

In future studies, it is necessary to establish a mathematical model that accurately accounts for the shallow-water effect. Therefore, a study based on the additional consideration of hydrodynamic derivatives is required. Furthermore, if the study on the shallow-water effect of the various ship types would be conducted, it is considered that the accuracy of the mathematical model for shallow water and low-forward speeds will be improved.

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Dong Young Kim, yellowspoon23@gmail.com
Corresponding author: Sang-Hyun Kim, kimsh@inha.ac.kr
Ji-Soo Han
Su-Jeong Kim
Kwang-Jun Paik
Inha University, 100, Inha-ro, Nam-gu, Incheon, Republic of Korea