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Numerical study on the maneuvering of a container ship in shallow water waves

Premchand Mallampalli[1,*], Sheeja Janardhanan[2], Kesavadev.V.K[3]

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ABSTRACT

Numerous practical and mathematical techniques have been piloted for studying the ships' behavior in deep water conditions with and without waves, and shallow water conditions without waves, while limited investigations have only been carried out for the assessment of ships' behavior in shallow waters with wave conditions as the flow around stern region, appendages and interaction effects are intricate. Therefore, an attempt has been made to understand the infrequently reconnoitered subset i.e. a vessel's behavior in regular waves in shallow water condition (channel depth to ship draft ratio taken as 1.5). A container ship (S175) model of scale ratio 1:36 has been considered for numerical studies which is subjected to static and dynamic maneuver simulations in head sea condition. The waves have been induced using the dispersion relationship of waves in a given depth. The trends of forces and moments acting on the hull while undergoing maneuvering motions have been obtained using smooth particle hydrodynamics based CFD solver. The resulting periodic trends of forces and moments were analyzed using Fourier series method to extract the Fourier coefficients and in turn calculate the hydrodynamic derivatives.

The trajectories in turning circle and zig-zag maneuvers have also been simulated using a MATLAB code. This paper demonstrates an increase in trajectory parameters and improvement in counter maneuverability owing to the complex flow physics around the hull while encountering regular waves in shallow water condition when compared to those with waves in deep water and without waves in shallow waters.

1. Introduction.

In regular or irregular waves, a vessel at sea is subjected to linear (surge, sway and heave) and rotational (roll, pitch and yaw) motions which constitutes as the six degrees of freedom. The motions (surge, sway and yaw) in horizontal plane i.e. waterplane / XY plane; (refer Figure (1) for the coordinate system) are of particular interest as far as the vessel's maneuverability is concerned.

The equations of motion in these motions are usually solved to predict the vessel's trajectory using suitable mathematical model. These hydrodynamic derivatives are intrinsic properties of the ship's under water hull-form and is influenced by the geometry of hull, attached appendages, hull-propeller-rudder interaction and the environmental effects. An effort has been made in this paper to study the influence of waves a subset of environmental dynamic forces on the maneuverability of hull-form in restricted water depths.

The introduction must be the first section of the text. It is important that it clearly describes the purpose and objectives

[1]Assistant Professor, Indian Maritime University, School of Naval Architecture and Ocean Engineering, Sabbavaram Mandal, Visakhapatnam ? 531035, Andhra Pradesh, India.

[2]Associate Professor, Indian Maritime University, School of Naval Architecture and Ocean Engineering, Sabbavaram Mandal, Visakhapatnam ? 531035, Andhra Pradesh, India. Tel. (+91) 8281943531. E-mail Address: sheejaj@imu.ac.in.

[3]3Professor, Indian Maritime University, School of Naval Architecture and Ocean Engineering, Sabbavaram Mandal, Visakhapatnam ? 531035, Andhra Pradesh, India. Tel. (+91) 9745676076. E-mail Address: vkkesavadev@imu.ac.in.

*Corresponding author: Premchand Mallampalli. Tel. (+91) 8129117117. E-mail Address: pcmallampalli@imu.ac.in.

of the work. It should also contain a review of the state of the art that is references to the most relevant works reported in the literature in recent years.

Normally, at the end of the introduction, the structure of the text of the article is described. For this specific document, Section 2 is devoted to explaining how to format the text, Section 3 gives recommendations on style and structure, Section 4 explains how to present the supplements to the text, that is, the Figures, Tables and Equations. Section 5 deals with the subject of intellectual property and, finally, the conclusions are presented.

The objective of the International Maritime Organization (IMO), was to regulate international shipping with an aim to promote safer shipping and cleaner oceans. The 71st session of Marine Environment Protection Committee (MEPC) was concerned about the minimum power requirements, maneuverability under adverse weather conditions (i.e., in waves, wind and currents) and stability in waves. Estimation of maneuvering qualities of the hullform at an early stage of design is the most challenging task, as these require estimation of various hydrodynamic coefficients (say, inertia, damping and restoring terms) to solve the maneuvering equations of motion and to predict the vessel's trajectory.

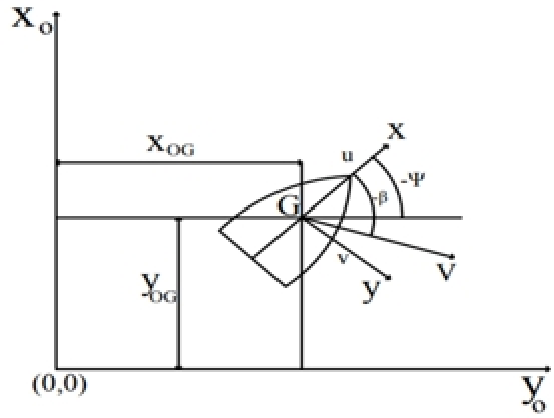
The effects of wave length and encounter angle to waves as well as the effect of loading condition on the maneuverability based on the experimental data were studied in [1] and predicted the drifting distance and drifting direction. Large drift was observed for short wavelengths and the drifting direction was observed to be different from the incoming wave direction.

The bare hull forces and vortices around the KRISO Very Large Crude Carrier (KVLCC) tanker hullform during steady drift test in deep and shallow water were examined by [2] and [3]. The work demonstrated the variation in hull pressure in shallow water, and in turn its affect on the hydrodynamic forces in forward motion as well as static drift. An estimation of the ship maneuvering performance in waves was obtained using a 3D panel method in [4]. In this study, maneuvering performance in waves was calculated using B-spline Rankine panel method.

The affects of the wave amplitude and wave length on the maneuverability of KVLCC model were studied in [5], the results indicate that second order wave force has dominant influence on turning trajectory and zig-zag maneuver. Studies to determine the sway velocity dependent linear and non-linear hydrodynamic derivatives of a container ship by simulating straight line tests using RANSE equations for wider range of drift angles without waves were carried out in [6].

[7] conducted experiments and measured ship motions in head waves and beam waves and concluded that increase in hull drift angle influence lateral motions such as sway, roll and yaw and increase their amplitudes. However, the influence of hull drift angle on motions of surge, heave and pitch is not remarkable. As per [8], to predict maneuvering performance of hull in waves, several methods were derived based on 2D strip method to calculate wave induced motion.

Figure 1: Earth fixed coordinate system and ship fixed coordinate system.



Source: Authors.

As in [9], a lot of technical difficulties related to analysis of ship maneuvering in waves are prevailing, due to inadequacy of turbulence models for large angle of attack, cross flow shed vortices etc. In [10], a time-domain body exact strip theory was developed to predict maneuvering of a vessel in a seaway. Results are presented for the turning circle maneuver of the containership S-175 in calm water and in the presence of regular waves. The results are compared with available experimental results. The general qualitative aspects of the maneuver are captured by the numerical model, in particular for longer waves. However, the accuracy could drop as the wave steepness increases.

Numerical simulations of Planar Motion Mechanism (PMM) tests on container (S175) hullform in regular waves in head sea conditions were conducted in [11] have shown that the estimated hydrodynamic derivatives have substantial variations in comparison with those in still water, which in turn influenced the steady turning and zigzag trajectory parameters. In [12], scaled KVLCC2 free running model tests are performed in regular waves. The effects of wave conditions such as wave directions, lengths, and heights on the turning trajectories are investigated and observed that are reduced by about half of calm water speeds in head waves, but there are little loss of speed in beam waves. When the wave lengths are below the ship length, drifting distances of trajectories are relatively large. Relative drifting angles between wave propagation direction and trajectory drifting direction are largest when the wave lengths equal to the ship length.

According to [13], the sway force, roll and yaw moments for a scaled model of Ultra Large Container Ship (ULCS) was tested in shallow water condition (i.e., 50% UKC) for a limited combination of drift angles, wave amplitudes and wave lengths. The influence of waves (i.e., sway, roll and yaw) at lower speeds are predominant than the larger speeds. [14] carried out oblique tests on a fixed KCS ship model in regular waves. Hence, the measured forces represent the sum of hull forces and wave induced forces.

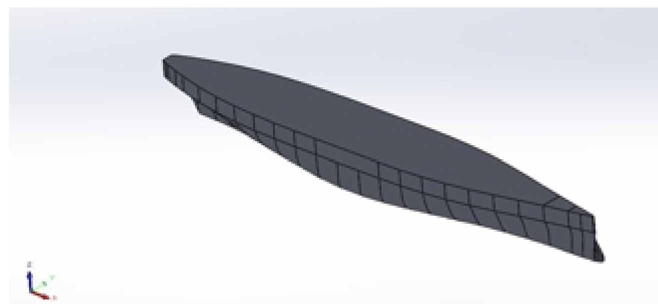
The KRISO container ship (KCS) hullform was studied to understand the maneuvering performance, when the ship operates in normal and propulsion failure conditions during maneuvering in calm water and regular waves in [15]. It was observed that the propulsion failure has a significant influence on the course keeping capability, seakeeping performance, and ship maneuverability in a real seaway. The turning behavior of the ship considerably differed according to the presence or absence of the propulsion power, which caused substantial changes in not only the turning trajectories but also the critical maneuvering indices. It was revealed that the loss of propulsion power led to noticeable in-creases in the advance, the transfer, and the time to turn by 90^0 due to the insufficient rudder lift. It is interesting to note that a 180^0 turn could not even be achieved under the propulsion loss condition, which implies the poor turning ability of the ship.

In [16], a new fast running hybrid method that allows for the study of maneuvering in regular waves was formulated. Multiple numerical methods and force models used for efficient computation of the total hydrodynamic force acting on the vessel maneuvering in waves. The computational savings of the hybrid method are shown to be appreciable over a comparable simulation using the nonlinear VOF method, as it offers an efficiency gain by at least a factor of 10 over using a VOF method with free surface capturing. The proposed hybrid simulation method is tested in two case studies: maneuvering of the Duisburg Test Case hull form and maneuvering of the KRISO Container Ship. The comparable accuracy and reduced computational expense highlight the hybrid method as an attractive option for prediction of ship maneuvering performance in waves.

As per IMO and Maritime Safety Committee (MSC), at the time of initial design stage of a ship itself it is essential to predict maneuvering characteristics for safe navigation in deep seas and harbor conditions. It is known fact that hydrodynamic coefficients are intrinsic properties of a hull-form, can potentially dictate the ship's trajectory; while detailed study of a ship's performance in both deep seas and harbor conditions is challenging and quite a quantum of research have been carried out. However, the studies carried out with respect to harbor conditions are paucity; except for the model tests conducted by [13] on a scaled model of ULCS for a combination of wave parameters, drift angles and shallow water conditions.

This work proposes a novel methodology for predicting the maneuvering behavior of hullform in shallow water regular waves, which represent virtually realistic harbor conditions. The waves assumed as regular, non-breaking and propagating in intermediate water depth [described in section 2]. The wave parameters such as wave height and frequency have been worked out from the dispersion relationship of water waves for a given water depth. The S175 hullform is subjected to static and dynamic simulations in order to mimic the typical towing tank maneuvering tests such as steady drift and Planar Motion Mechanism (PMM) tests respectively using a high fidelity Computational Fluid Dynamics (CFD) solver. The numerically simulated bare hull forces and moments measured at midship have been compared with the published results in deep and shallow calm water conditions. The method espoused in this work was able to replicate the existing published results, proving its efficacy. The studies mentioned above were addressed to predict the maneuverability in deep calm water, shallow calm water and deep water regular wave conditions. Studies on the effects of restricted water depths on maneuvering behavior of the hullform in wave conditions are indeed scarce in the open literature. In this context, the present study focuses on predicting the ship's maneuvering behaviour and trajectories during maneuvering motions to demonstrate an increase in trajectory parameters and an improvement in counter maneuverability while encountering regular waves in shallow water condition. The hullform geometry and principal particulars used for the present study are given in Figure (2) and Table (1) respectively.

Figure 2: 3D scaled model of S175.



Source: Authors.

Table 1: Principal particulars of S175.

Parameters	Ship	Model
Scale ratio, λ	-	36
LBP, L(m)	175	4.86
Beam, B(m)	25.4	0.705
Fore draft, T_f (m)	8.0	0.22
End draft, T_a (m)	9.0	0.25
Mean draft, T_m (m)	8.5	0.236
Depth, D (m)	11.0	0.305
Displaced volume, $\nabla(m^3)$	21,222	0.4548
Block coefficient, C_b	0.559	0.559

Source: Authors.

2. Mathematical model and CFD solver.

Prediction of ship maneuvering behavior entails a mathematical model representing equations of motion in the horizontal plane. In the mathematical model represents a balance of rigid body terms with the hydrodynamic reaction forces and moments. The simplified equations of motion is given by ([17] (pp.29)) are represented by Equations (1) through (3)

$$(m - X_{\dot{u}})\,\dot{u} - X_u \delta u = 0 \tag{1}$$

$$(m - Y_{\dot{v}})\,\dot{v} - Y_v v + (m x_G - Y_{\dot{r}})\,\dot{r} + (m u_0 - Y_r)\,r = 0 \tag{2}$$

$$(m x_G - N_{\dot{v}})\,\dot{v} - N_v v + (I_z - N_{\dot{r}})\dot{r} + (m x_G u_0 - N_r) r = 0 \tag{3}$$

In the present work, a linear mathematical model proposed by Son and Nomoto [13] has been considered. The non-dimensional factors for forces and moment are 0.5ρLm2Um2 and 0.5ρLm3Um2 respectively. The computational domain limits are in line with the ITTC recommended procedures and guidelines [18] and the prescribed domain size is as per Table (2). The regular wave parameters are computed for intermediate depth (h), wherein the water depth to draft (h/Tm) ratio is 1.5, wavelength (λ) is assumed as equal to the ship length (LBP), depth to wavelength (h/λ) ratio is 0.0728. From the dispersion relation, wave frequency is 2.33 rad/sec. The wave height of the wave is calculated as 0.354m. The ratio of water depth to wavelength (h/λ=0.0728) falls into an intermediate depth region and as a result waves have been assumed regular in nature. On the other hand the size of the ship makes it encounter shallow waters. Hence the challenge in the present study is to predict the sluggishness of the vessel in shallow depths while encountering waves. The empirical relationships proposed by Son and Nomoto [19] have been simplified and used for rudder and propeller derivatives as given by ([17] (pp.44)).

The solver used for carrying out the present work is a CFD based Smooth Particle Hydrodynamics (SPH) code, based on a particle-based Lattice Boltzmann technology.

Governing Equations in SPH are given in Equations (4) through (10)

The Navier-Stokes equation of flow is given by Eq. (4)

$$\frac{dV}{dt} = \frac{-1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla.\nabla V + \frac{1}{\rho}F_{ext} + g \tag{4}$$

Table 2: Computational Domain size.

ITTC recommended (min.)	Domain		Dimensions (m)
$1.0{*}L_{BP}$	Upstream	$1.8{*}L_{BP}$	8.748
$2\text{-}4{*}L_{BP}$	Downstream	$3.6{*}\ L_{BP}$	17.496
$0\text{-}1{*}L_{BP}$	Top	$1.6{*}\ L_{BP}$	7.776
h/T < 3.0 (for shallow)	Bottom	h/T=1.5	0.354
$1\text{-}2{*}L_{BP}$	Traverse	$2.4{*}\ L_{BP}$	11.664

Source: Authors.

Each term in Equation (4) represents acceleration. The discretization term for each term is given by Equation (5) through (7)

The pressure term is

$$\left\langle \frac{-1}{\rho}\nabla p \right\rangle_i = \sum_j P_{ij} \nabla W\,(r_{ij}) \tag{5}$$

where,

$$P_{ij} = -\frac{m_j}{P_j}\left[\frac{p_i}{{\rho_i}^2} + \frac{p_j}{{\rho_j}^2}\right] \tag{6}$$

W is known as the weighting or Kernel function.

The viscosity term is represented as in Equation (7).

$$\left\langle \frac{-\mu}{\rho}\nabla.\nabla V \right\rangle_i = \sum_j V_{ij} \nabla^2 W\,(r_{ij}) \tag{7}$$

where,

$$V_{ij} = -\mu \frac{m_j}{P_j}\left[\frac{V_i}{{\rho_i}^2} + \frac{V_j}{{\rho_j}^2}\right] \tag{8}$$

Hence the total acceleration of i^{th} particle is given by Equation (9)

$$\frac{dV_i}{dt} = a^{pressure} + a^{viscosity} + a^{external} + a^{gravity} \tag{9}$$

It computes numerical acceleration of the boundary particles solving the particle interactions with fluid neighboring particles. We assume the same mass for all particles, m_i = m. The mass m is calculated by Equation (10).

$$m = \frac{\rho.v}{N} \tag{10}$$

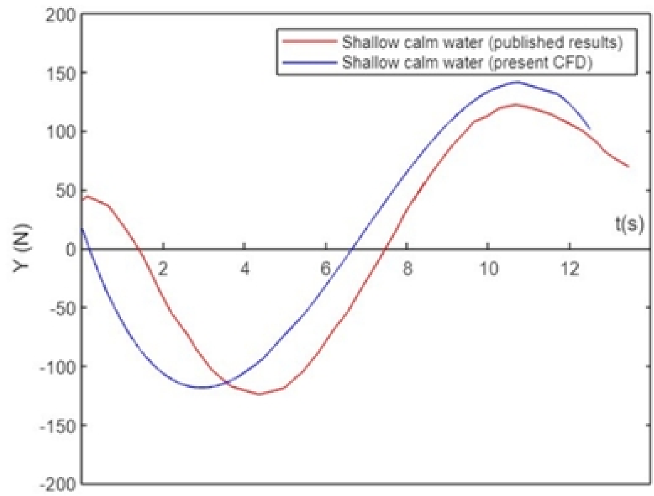
where v is the total volume of the computational domain and N is the total number of fluid particles. Fluid dynamics computation of forces and pressure are carried out from Equation (4).

3. Results.

In order to establish the efficacy of the SPH solver, shallow water dynamic simulations as in [17] have been accomplished and was observed to yield reasonably comparable predictions as shown in Figures (3) and (4).

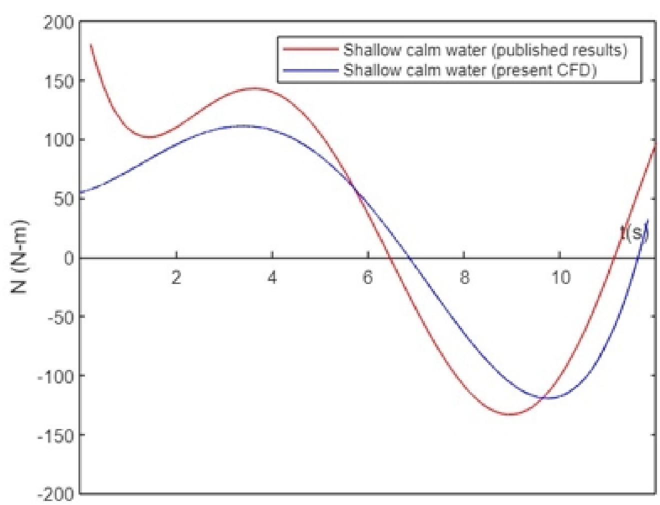
In fact the computational time and effort for SPH based CFD is 1.5 times lesser than that for a typical mesh-based solver.

Figure 3: Comparison of sway forces in a dynamic simulation present CFD vs published results from [17].



Source: Authors.

Figure 4: Comparison of yaw moment in a dynamic simulation present CFD vs published results from [17].



Source: Authors.

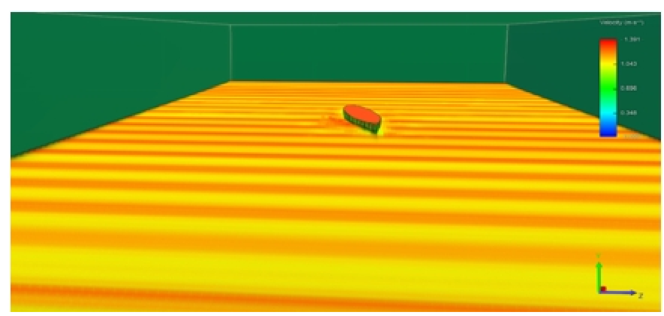
The numerically simulated forces and moments measured at midship have been non-dimensionalised. The bare hull forces of steady drift test in regular waves and dynamic simulations – Planar Motion Mechanism (PMM) test in regular waves have been carried out. The measured forces and moments have been compared with the published results. The present method was also able to reproduce the existing results in the literature proving its efficacy and reliability. Enhanced forces and moments estimated in the ship's hull in the present studies are considered as possible contributions from the wave induced forces and moments on the hull.

3.1. Static Drift test.

In the static drift test, hullform has been oriented at an angle to the centerline of computational domain (i.e. drift angle) to the incoming regular waves propagating at velocity of 1 m/sec. This drift angle leads to asymmetric flow conditions around the hullform. Thus it will behave like an aero foil shape to develop lift force and moment. Drift angles are varied from 0 to 10 deg in steps of 2.5 deg.

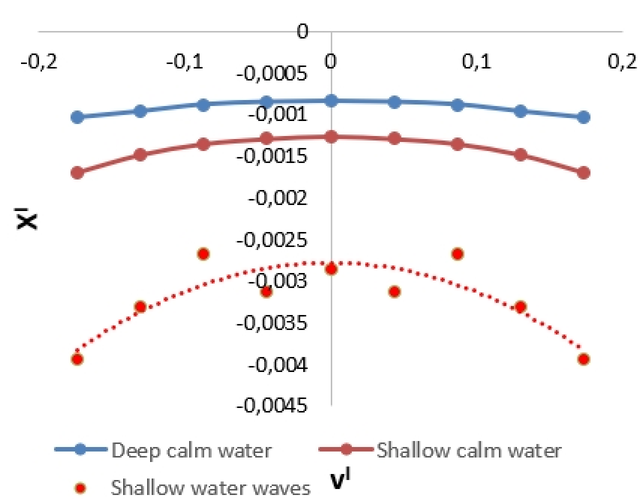
Computed forces or moments due to the variations in drift angle are plotted against the non-dimensionalised (linear) velocity (v'= -sinβ) to determine the sway-velocity dependent hydrodynamic derivatives using higher order curve fitting method and the results represented in Table (3) and Figures (6) through (8).

Figure 5: Water surface captured during drift test.



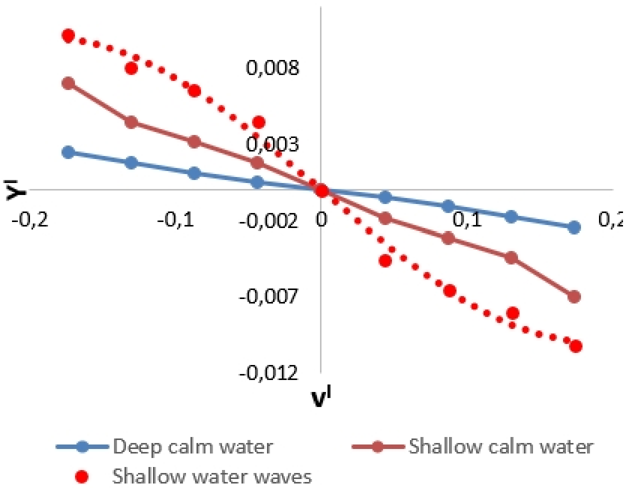
Source: Authors.

Figure 6: Drift test ? Non-dimensionalized surge force vs velocity.



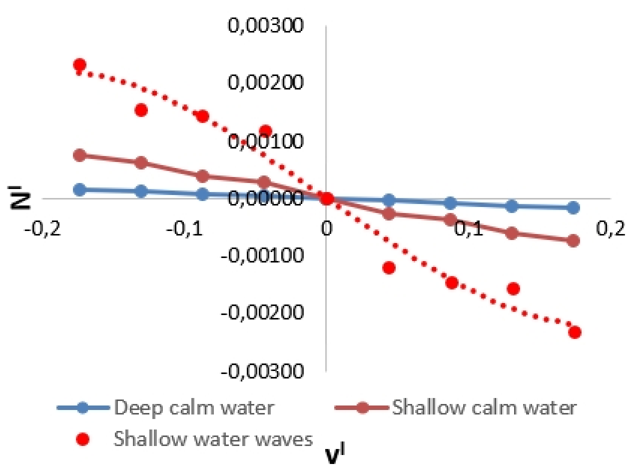
Source: Authors.

Figure 7: Drift test - Non-dimensionalized sway force vs velocity.



Source: Authors.

Figure 8: Drift test - Non-dimensionalized yaw moment vs velocity.



Source: Authors.

Table 3: Comparison of sway velocity dependent derivatives.

Derivative	Deep calm water ([19])	Shallow calm water ([17] (pp.117))	Shallow water waves (CFD)	Grading ([17] (pp.139-140))
Y'_v	-0.0116	-0.02	-0.0631	A
N'_v	-0.0039	-0.0047	-0.0174	A

Source: Authors.

3.2. Dynamic Simulations.

Planar Motion Mechanism (PMM) tests (pure sway and pure yaw) have been simulated to compute the hull forces and moments, this data helped to predict the hydrodynamic derivatives using mathematical expressions developed from Fourier series expansion method. The development of expressions for hydrodynamic derivatives in terms of Fourier coefficients are as in [17] (pp.184-188).

Pure sway test:

In pure sway simulation, the hullform considered is defined as rigid body and subjected to translation motion about y-axis along the trajectory shown in Figure (9). The hull imperiled to transverse displacement, y_o, velocity $\dot{y_o}$ and acceleration $\ddot{y_o}$ given by the Equations (11) through (13). The forward velocity is a non-zero value and forward acceleration, angular (yaw) displacement, velocity and acceleration are zero. By substitution of above mentioned values in the mathematical model presented in Equations (1) through (3), the equations of motion will reduce to Equations (14) and (15).

$$\text{Transverse displacement, } y_0 = -y_{0a}\sin\omega t = y \tag{11}$$

$$\text{Transverse velocity, } \dot{y}_0 = -y_{0a}\omega\cos\omega t = v \tag{12}$$

$$\text{Transverse acceleration, } \ddot{y}_0 = y_{0a}\omega^2\sin\omega t = \dot{v} \tag{13}$$

$$Y_{HY} = Y_{\dot{v}}\dot{v} + Y_v v \tag{14}$$

$$N_{HY} = N_{\dot{v}}\dot{v} + N_v v \tag{15}$$

In the present simulations amplitude of sway oscillations, y_{oa} is taken as 0.3m and the rigid body oscillation frequency, ω is taken as 0.47 rad/sec, corresponding to a time period, t_p of 13.33 sec [17].

Pure yaw test:

In pure yaw simulation, the hullform considered is defined as rigid body and subjected to rotational motion about z-axis, such that the surge velocity is always tangential to its oscillating path as shown in Figure (10). The angular displacement, velocity and acceleration given by Equations (16) through (18). The sway displacement, velocity and acceleration is zero. By substitution of Equations (16) through (18) in mathematical model, the equations of motion will only contain yaw dependent terms as shown in Equations (19) through (21).

$$\psi = -\psi_a\cos\omega t \tag{16}$$

$$\dot{\psi} = r = r_a\sin\omega t \tag{17}$$

$$\ddot{\psi} = \dot{r} = r_a\cos\omega t \tag{18}$$

$$X_{HN} = X_{\dot{u}}\dot{u} \tag{19}$$

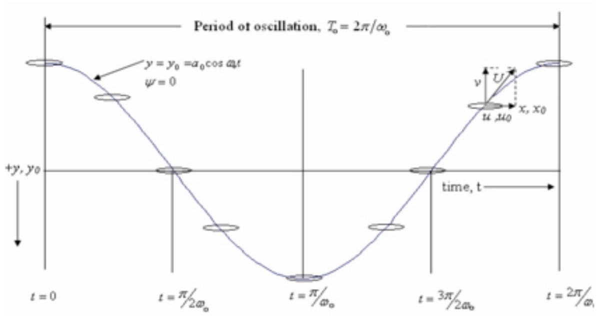
$$Y_{HN} = Y_{\dot{r}}\dot{r} + Y_r r \tag{20}$$

$$N_{HN} = N_{\dot{r}}\dot{r} + N_r r \tag{21}$$

In the present simulations amplitude of yaw angular oscillations, ψ_a is taken as 10 deg and the rigid body oscillation frequency, ω is taken as 0.47 rad/sec, corresponding to a time period, t_p of 13.33 sec [17].

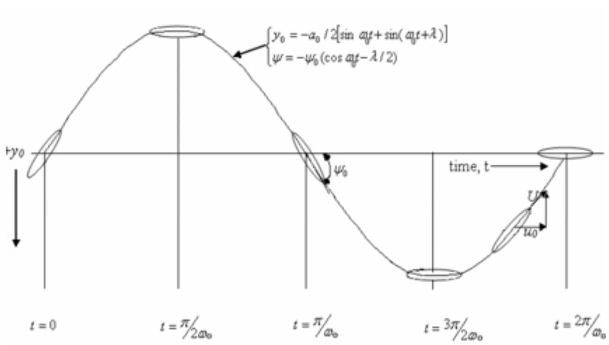
The time histories of sway force and yaw moment plotted in Figures (13) through (16). Using the equations given in [17] (pp.184-188), the Fourier constants have been obtained by numerical integration of forces and moments using trapezoidal rule or Simpson's rule and consequently the non-dimensionalised hydrodynamic derivatives have been predicted. The predicted hydrodynamic derivatives (for shallow regular wave conditions) have been compared with the published results of shallow calm water hull derivatives, as the experimental results for former data not available. The relevance of the predicted derivatives on various trajectories and various maneuvers given in Table (4).

Figure 9: Pure sway trajectory ([17] (pp.75)).



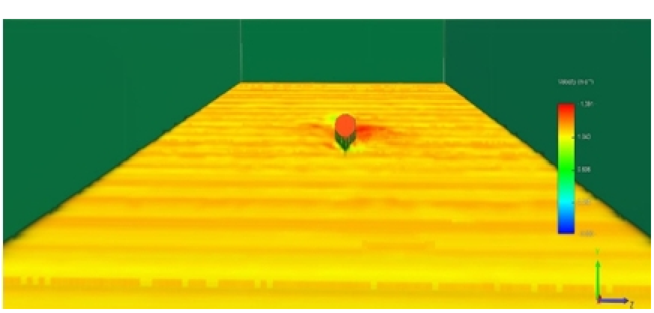
Source: Authors.

Figure 10: Pure yaw trajectory ([17] (pp.76)).



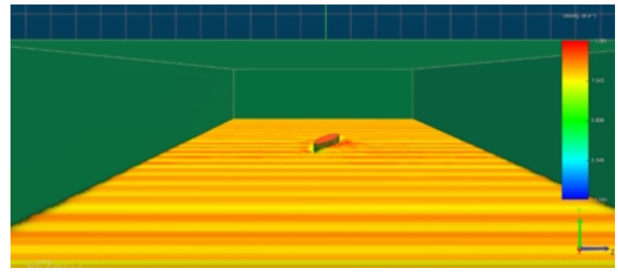
Source: Authors.

Figure 11: Water surface captured during pure sway test



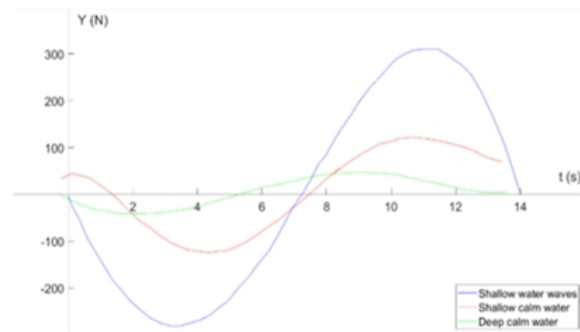
Source: Authors.

Figure 12: Water surface captured during pure yaw test



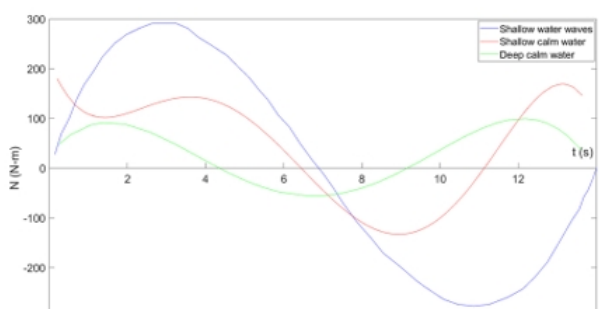
Source: Authors.

Figure 13: Pure sway test - sway force time history



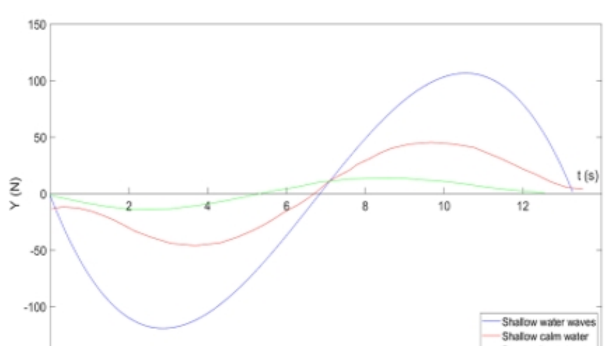
Source: Authors.

Figure 14: Pure sway test - yaw moment time history



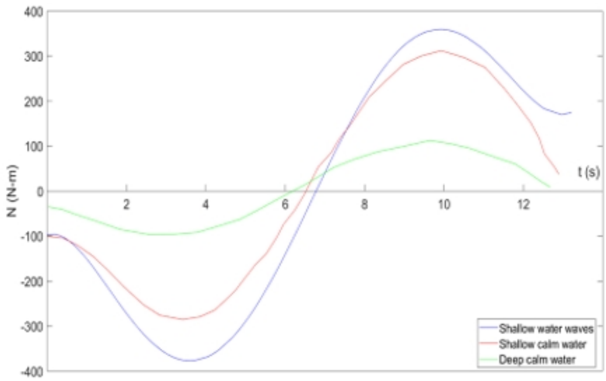
Source: Authors.

Figure 15: Pure yaw test - sway force time history



Source: Authors.

Figure 16: Pure yaw test - yaw moment time history



Source: Authors.

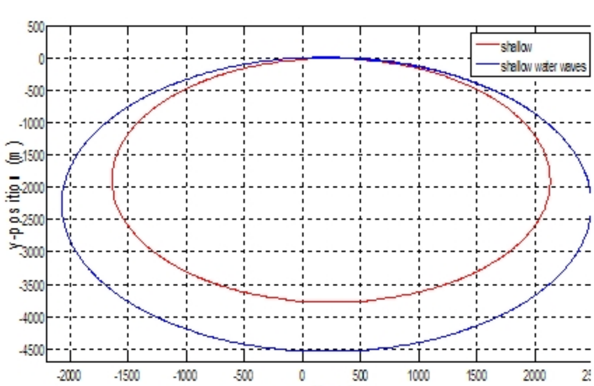
Table 4: Hydrodynamic derivatives predicted from dynamic maneuver simulations in shallow water regular wave condition

Derivative	Deep calm water ([19])	Shallow calm water ([17] (pp.139-140))	Shallow water waves (CFD)	Grading ([17] (pp.139-140))
Y'_v	-0.0116	-0.0179	-0.05577	A
N'_v	-0.0039	-0.00761	-0.0082	A
Y'_v	-0.007049	-0.01845	-0.03761	A
N'_v	-0.00035	-0.00052	-0.00095	A
Y'_r	-0.00035	-0.00058	-0.00117	A
N'_r	-0.000419	-0.00067	-0.00072	A
N'_r	-0.00222	-0.0065	-0.00964	A
Y'_r	0.00242	0.00783	0.027834	A

Source: Authors.

Trajectories in turning circle, zig-zag maneuver have been simulated using a MATLAB code and have also been compared with those in shallow calm water simulations shown in Figures (17) through (19).

Figure 17: Turning trajectory in shallow calm water and shallow water wave conditions



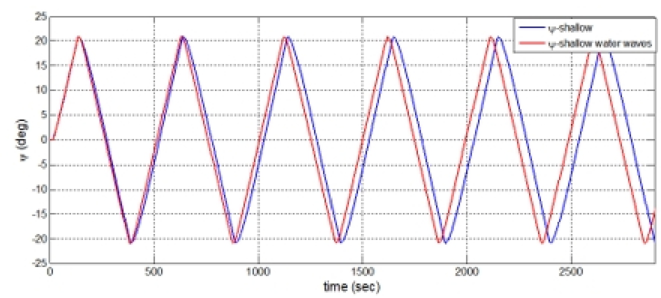
Source: Authors.

Table 5: Turning trajectory parameters in shallow calm water and shallow water wave conditions

	Shallow calm water (m)	Shallow water wave (m)	percentage deviation
Rudder execute (X-coordinate)	119	122	
Steady turning radius (m)	1886	2279	20.84
Transfer (m)	1814	2168	19.51
Advance (m)	2012	2363	17.45
Tactical diameter (m)	3773	4536	20.22

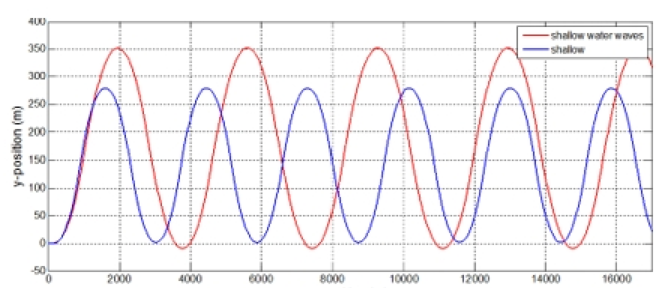
Source: Authors.

Figure 18: Z-maneuvre in shallow calm water vs shallow water wave conditions



Source: Authors.

Figure 19: Yaw width in shallow calm water vs shallow water wave conditions



Source: Authors.

4. Discussion.

The results presented by [6] conveys the effect of water depth on the hull-form maneuvering behavior and the results discussed by [11] in regular waves were limited to deep water conditions only; present study is an attempt to emphasize the effect of water depth on hullform maneuvering behavior in regular waves in head sea condition. In static and dynamic simulations, it's clearly envisaged that the water depth will impact the hydrodynamic derivatives, which translates the increase in standard trajectory parameters as reported by [6]; while the influence of regular waves in head sea shallow water condition leads to further augmentation of hydrodynamic derivatives and its repercussions mentioned below:

- Inclusive improvement in directional stability;
- Approximate enhancement of 20% in turning trajectory parameters;
- Improvement in counter maneuverability as hypothesized from the Zig-zag maneuver simulations.

The results presented in Figures (13) through (19) postulate the impact of water depth and wave force on the hydrodynamic derivatives.

The time dependency of hydrodynamic derivatives in waves have been neglected in this study. Investigations have been carried out for the augmented forces and moments acting on the hull during maneuvering motions in waves. The hydrodynamic derivatives evaluated through a Fourier series method as in [17] are considered to be constants as the amplitude of the waves are considered to be small and the waves to be linear.

Conclusions.

The present work can be protracted to predict the effect of wave parameters and wave propagation directions on the maneuvering performance of hull-form of the vessel, therefore it is believed to help understand the hullform's performance in a restricted environment where maneuverability of a vessel is of paramount importance at the early stages of design exercise.

CFD based smooth particle hydrodynamics has proved its efficacy in predicting the ship's maneuverability in shallow water with waves both qualitatively and quantitatively. Such predictions are very crucial as it offers realistic predictions leaving the helmsman with adequate anticipation while maneuvering the vessel in a harbor or restricted environment.

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Nomenclature.

m body mass/integer for determining harmonic of Fourier series.
$X_{\dot{u}}$ hydrodynamic uncoupled derivative in surge force with respect to surge acceleration.
X_u hydrodynamic linear uncoupled derivative of surge force with respect to sway velocity.
$Y_{\dot{v}}$ hydrodynamic uncoupled derivatives in sway force with respect to sway acceleration.
Y_v hydrodynamic linear uncoupled derivatives of sway force with respect to sway velocity.
u forward velocity in ship-fixed co-ordinate system.
$\dot{u}$ surge acceleration.
v sway velocity in ship-fixed co-ordinate system.
$\dot{v}$ sway acceleration.
u_0 forward velocity in earth-fixed co-ordinate system.
x_G distance of origins of earth and ship fixed co-ordinate systems.
Y forces in transverse direction in ship-fixed co-ordinate system.
y_0 Transverse displacement.
$\dot{y}_0$ Transverse velocity.
$\ddot{y}_0$ Transverse acceleration.
y position in transverse direction in ship-fixed co-ordinate system.
y_{0a} amplitude of sway motion.
ω specific dissipation of energy per unit volume.
δ rudder angle.
ψ heading /yaw angle.
$\dot{\psi}$ yaw rate.
$\ddot{\psi}$ yaw acceleration.
ψ_a amplitude of yaw angular motion.
t instantaneous time.
N_v non-dimensional hydrodynamic linear coupled derivative of yaw moment with respect to sway velocity.
$N_{\dot{v}}$ non-dimensional hydrodynamic coupled derivative of yaw moment with respect to sway acceleration.
r yaw rate.
$\dot{r}$ yaw acceleration.
r_a amplitude of yaw rate.
Y_r hydrodynamic linear coupled derivative of sway force with respect to yaw rate.
$Y_{\dot{r}}$ hydrodynamic coupled derivative of sway force with respect to yaw acceleration.
N_r hydrodynamic linear uncoupled derivative of yaw moment with respect to yaw rate.
$N_{\dot{r}}$ hydrodynamic uncoupled derivative of yaw moment with respect to yaw acceleration.
I_z mass moment of inertia about z-axis.
X_{HN} hydrodynamic reaction force of surge in pure yaw mode.
Y_{HN} hydrodynamic reaction force of sway in pure yaw mode.
Y_{HY} hydrodynamic reaction force of sway in pure sway mode.
N_{HN} hydrodynamic reaction moment in yaw in pure yaw mode.
N_{HY} hydrodynamic reaction moment in yaw in pure sway mode.
V is the velocity field.
ρ is the fluid density.
p is the fluid pressure.
μ is the dynamic viscosity of fluid.
F_{ext} is the external force in.
g is the acceleration due to gravity

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